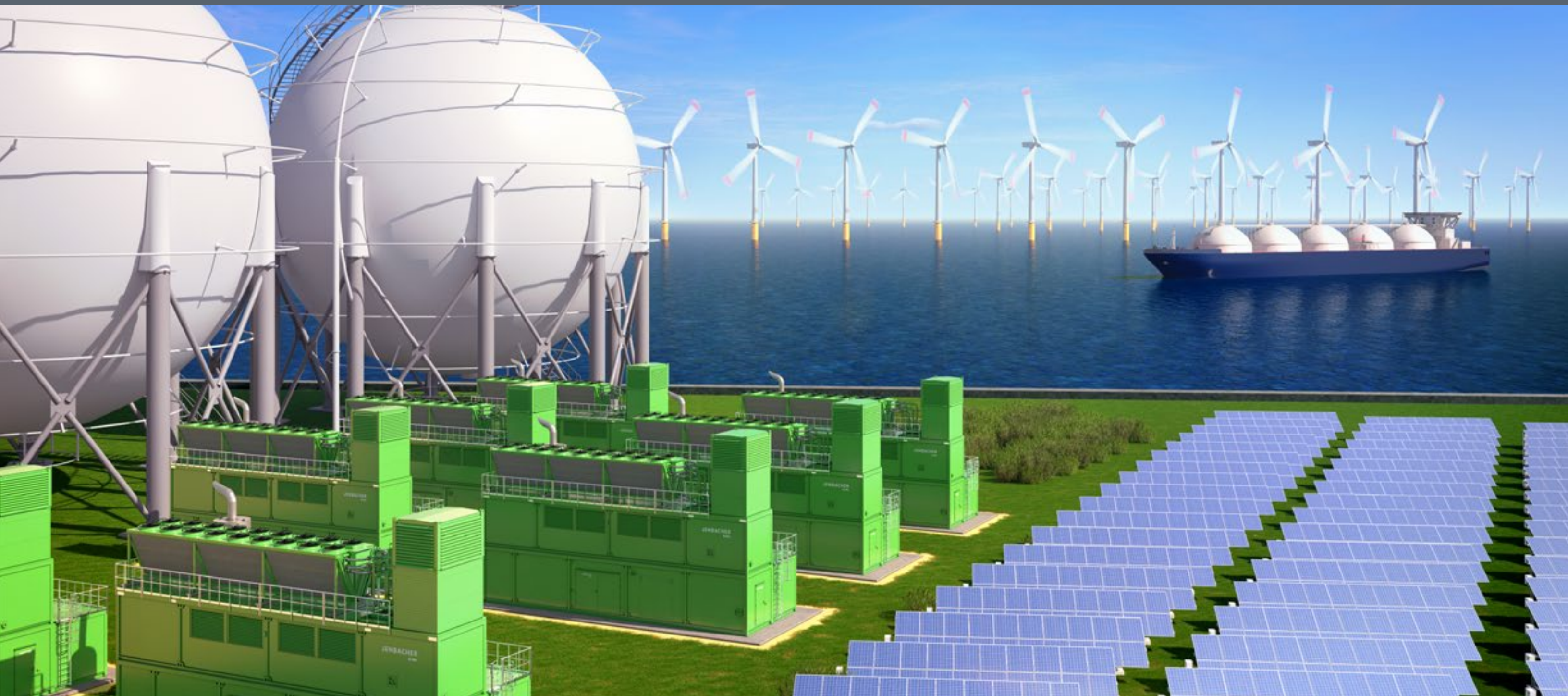
JENBACHER

HYDROGEN-BASED POWER GENERATION

II. A Net-Zero Backup Solution for Green Ammonia Hubs

This white paper details the use of hydrogen engines for decarbonizing the backup power supply of green ammonia hubs. By outlining the techno-economic specifications of this technology in general and INNIO Group's Jenbacher solutions in particular, the paper can be used to aid project developers and EPCs in their decision-making when selecting a suitable backup solution for their green ammonia production facilities.



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1.

INTRODUCTION

1. INTRODUCTION

The global pursuit of clean and sustainable energy solutions, together with the goal of meeting the 2050 Paris agreement, has brought hydrogen into the spotlight as a key player in reducing carbon emissions and mitigating climate change. Green hydrogen, produced by renewable energy resources (RES), is gaining prominence as a clean energy carrier for various applications in different sectors. On one hand, hydrogen-based solutions show great potential in tackling the challenge for highly decarbonized energy systems, but on the other hand, the hydrogen economy presents challenges when looking at efficient storage, transportation, and distribution over long distances. A main reason for this is that hydrogen is the lightest element in the periodic table, reflecting the volatility of this gas and its low energy density when looking at volume basis.

Among the different possibilities for transporting green hydrogen—and considering the various commercial and technical challenges—green ammonia seems to be the most promising alternative chosen by various project developers at this stage. Indeed, ammonia (NH_3) shows a high hydrogen density by volume. This inherent advantage makes ammonia an efficient and compact carrier for transporting and storing hydrogen, enabling greater energy density per unit volume.

Another key advantage of green ammonia is the presence of a well-established global infrastructure for ammonia production, transportation, and storage. The already existing ammonia industry provides a network of pipelines, storage tanks, and distribution systems that can be harnessed to transport and distribute green hydrogen derived from ammonia, decreasing the need for costly and time-consuming infrastructure development.

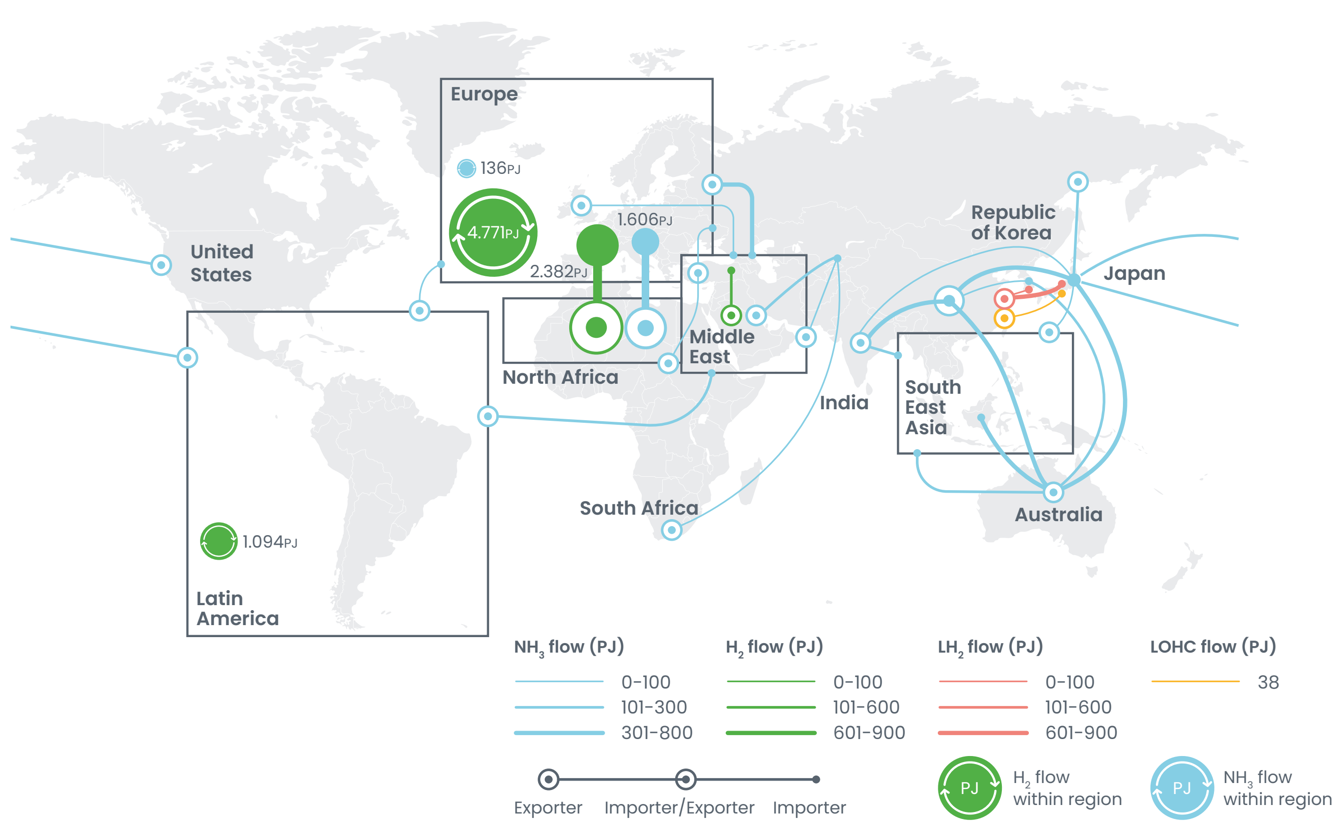

Figure 1: Major transportation routes for NH_3; illustration based on IRENA

As a game-changing technology, green ammonia can facilitate the production, transportation, and utilization of renewable energy resources (RES) and foster international cooperation in the renewable energy sector, accelerating the growth of the green hydrogen market.

In fact, the global green ammonia volume valued at $0.3 billion in 2023 is predicted to reach $17.9 billion in 2030, growing at a compound annual growth rate of 72.9% (Deloitte, 2023). Numerous global projects aimed at establishing green ammonia production facilities are set to commence operations during the middle of the current decade. These projects comprise four key components: a wind/solar farm for supplying green electricity, an electrolyzer for green hydrogen production, an ammonia synthesis plant section to produce ammonia from hydrogen, and a refueling facility for maritime transport.

However, a major challenge for project developers at present are the regulatory standards for the lifetime emissions for hydrogen imports. Indeed, as further explained in section 2.1, these standards are emerging in key regions with the highest hydrogen demand.

Many of the planned green ammonia production sites are designed as off-grid initiatives, featuring dedicated wind and solar farms. This is primarily due to either the lack of an existing power grid to handle the substantial power requirements or the absence of internationally standardized certification systems for procuring green energy from the grid. While hydrogen production via electrolysis can be operated flexibly to a certain extent according to the local supply of volatile renewable electricity, the advanced Haber-Bosch process for ammonia production typically requires almost constant operation and a corresponding base load power supply for optimum operation.

Therefore, to close the last decarbonization gaps, net-zero backup solutions are necessary on site. Due to existing synergies, such as the availability of high storage capacities for hydrogen in green ammonia facilities, hydrogen-fed energy converters such as reciprocating internal combustion engines (ICE) and fuel cells represent a valuable techno- economic alternative among the existing technologies for backup power. Besides the avoided storage costs, when looking at ICE fed by hydrogen, they are characterized by low power-specific capital costs, high operating flexibility, fast response time, low hydrogen purity requirements, and non- effortful scalability compared to competing technologies.

The present study provides a comparative evaluation of hydrogen engines with alternative storage and backup power solutions according to economic key performance indicators (KPI) specifically for off grid-utilization in existing and future green ammonia production facilities. By providing a detailed analysis of the economic assessment and the related feasibility of these solutions, this paper highlights the potential of hydrogen engines to play a critical role in enabling the widespread adoption of green ammonia production facilities.

Special thanks to Prof. Stefano Mazzoni from the University of Roma Tor Vergata for his valuable contribution to the economic evaluation and revision of this white paper.

1.1 Global hydrogen outlook

The global green hydrogen export outlook is becoming an increasingly important topic in discussions surrounding the transition to a sustainable and clean energy future. Green hydrogen, produced through water electrolysis using renewable energy sources, offers a versatile and low-carbon energy carrier.

The significance of green hydrogen exports

- **Carbon neutrality:** Exporting green hydrogen allows regions with abundant RES to share their surplus with regions that may have limited access to clean energy.
- **Energy security:** By importing green hydrogen, countries can diversify their energy sources, reducing reliance on fossil fuels and enhancing energy security. This, in turn, can mitigate geopolitical tensions and trade imbalances related to energy resources.
- **Economic opportunities:** The production, export, and transportation of green hydrogen can stimulate economic growth, create jobs, and foster international cooperation. It can become a valuable export com-modity, supporting local economies, and reducing trade deficits.
- **Global cooperation:** Green hydrogen exports promote international cooperation and trade, fostering diplomatic ties and shared interests in clean energy solutions.

Current trends in green hydrogen exports

- **Pilot projects:** Several pilot projects have been launched to explore the feasibility of green hydrogen export. These projects aim to establish the infrastructure, regulations, and regional dynamics for the green hydrogen trade. For instance, South America, Australia and the Middle East are frontrunners in exporting green hydrogen to Asia, with multiple pilot projects and ambitious plans.
- **International collaboration:** Countries are increasingly collaborating on green hydrogen production and trade. Memorandums of understanding, agreements, and partnerships are being formed to facilitate the exchange of knowledge, technology, and expertise.
- **Transportation infrastructure:** The development of infrastructure for transporting green hydrogen, such as pipelines and ships, is gaining momentum. This infrastructure is vital for making green hydrogen a viable and cost-effective export option.
- **Policy support:** Governments worldwide are implementing policies and regulations to support green hydrogen exports. This includes setting emission reduction targets, providing financial incentives, and promoting research and development in the green hydrogen sector.

Unlocking the potential benefits of green hydrogen exports requires tackling several challenges. These encompass achieving cost competitiveness, establishing international standards, scaling up production, and securing a reliable and cost-effective supply of renewable energy.

1.2 Technologies for hydrogen transportation

The transportation of green hydrogen over long distances presents several challenges:

1. **Energy efficiency:** Hydrogen, as a low-density energy carrier by volume, necessitates considerable energy for its transportation. It is imperative to address substantial energy losses during this process and reduce inefficiencies.
2. **Safety:** Hydrogen, characterized by its high volatility and flammability, presents inherent safety risks during transportation. The economically crucial dimension lies in establishing secure containment and handling protocols to mitigate these potential hazards.
3. **Infrastructure development:** Building the necessary infrastructure, such as pipelines or high-pressure storage and transportation systems, requires substantial investments.

Numerous alternatives exist for transporting hydrogen across varying distances, each situated at distinct points along the technological maturity spectrum.

Hydrogen compressed gas tubes, or tube trailers, are used to transport hydrogen in gaseous form. These trailers are used for gas transportation over short distances to supply industrial users or hydrogen refueling stations.

Hydrogen pipelines are one of the most efficient and cost-effective methods for transporting hydrogen over long distances. These pipelines typically are made of materials that can safely contain hydrogen. To optimize efficiency, compressor stations are placed strategically along the pipeline routes to maintain pressure and control flow.

Liquefied hydrogen (LH_2) can be transported in specially designed cryogenic containers. By cooling hydrogen to extremely low temperatures (-253°C or -423°F), it becomes a dense liquid that occupies less space. Specialized tankers and containers are used for this purpose. Although energy-intensive due to the liquefaction process, LH_2 transportation can be a viable option for long-distance transport.

Liquid organic hydrogen carriers (LOHC) are organic compounds that can absorb and release hydrogen through chemical reactions. Therefore, LOHCs can be used as storage and transportation media for hydrogen. LOHCs enable long-distance hydrogen transportation under ambient temperature and pressure conditions without significant losses. On energy or hydrogen demand, the hydrogen-rich LOHC molecule is heated to the dehydrogenation temperature and allowed to be in contact with the dehydrogenation catalyst. The most critical aspects regarding LOHC handling are the potential exposure to the environment and the potential fire risks at the sites, since LOHC is a flammable hydrocarbon.

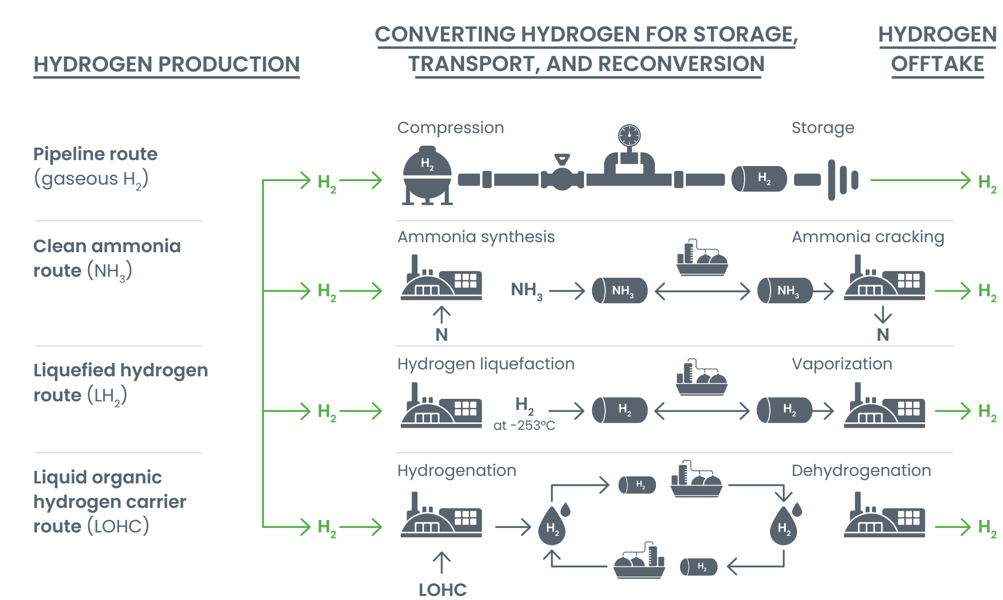

Figure 2: Hydrogen transportation routes (Roland Berger)

Ammonia (NH_3) has historically played a pivotal role in various industries. However, more recently, it has garnered attention as a promising hydrogen carrier due to its well-established international trade networks. This newfound interest stems from several key factors. First and foremost, despite both ammonia and hydrogen being gaseous at standard conditions, the former surpasses the latter when it comes to efficiently delivering hydrogen over long distances after liquefaction. The reason lies in the fact that a liter of liquid ammonia contains a greater mass of hydrogen than a liter of liquid hydrogen itself. This is because ammonia shows a superior capability for self-packing compared to hydrogen. Consequently, liquefied ammonia boasts a density nearly 10 times that of liquid hydrogen, approximately 686 kg/m³ versus 71.1 kg/m³. Under these conditions, while its hydrogen content by weight is only 17.65 wt% compared to the 100 wt% of liquid hydrogen, its hydrogen content by volume significantly exceeds that of liquid hydrogen, with values around 107.7 kg_{H2}/m^3 versus 70.8 kg_{H2}/m^3. In fact, both the gravimetric and volumetric hydrogen contents of liquid ammonia outperform those of LOHC (6.1 wt% and 47.1 kg_{H2}/m^3), making it a more efficient hydrogen carrier in comparison.

In contrast to hydrogen, ammonia boasts a much higher boiling point (-33.34 °C), requiring less energy for its conversion and preservation in liquid form. This elevated boiling temperature also results in lower boil off gas (BOG) losses during storage and transportation, enabling a greater amount of hydrogen to be delivered in the form of ammonia rather than directly as hydrogen. However, in contrast to LOHC and methanol, which are already in liquid form under standard conditions, ammonia necessitates an additional step in the value chain: liquefaction. This extra step entails additional energy consumption and costs in the overall process.

The flammability of ammonia is lower compared to other hydrogen energy carriers and carbon-based fuels because of the high flash point.

While ammonia is one of the comparatively safe hydrogen carrier options regarding flammability and explosion hazard, conversely its toxicity poses a safety risk. However, with the transportation infrastructure for ammonia having been established for decades as the world's second most frequently produced chemical, far-reaching safety standards already have been established for the worldwide transportation of ammonia.

1.3 Green ammonia production

Green ammonia production is based on a catalytic reaction of hydrogen and nitrogen. The primary steps for green ammonia production are:

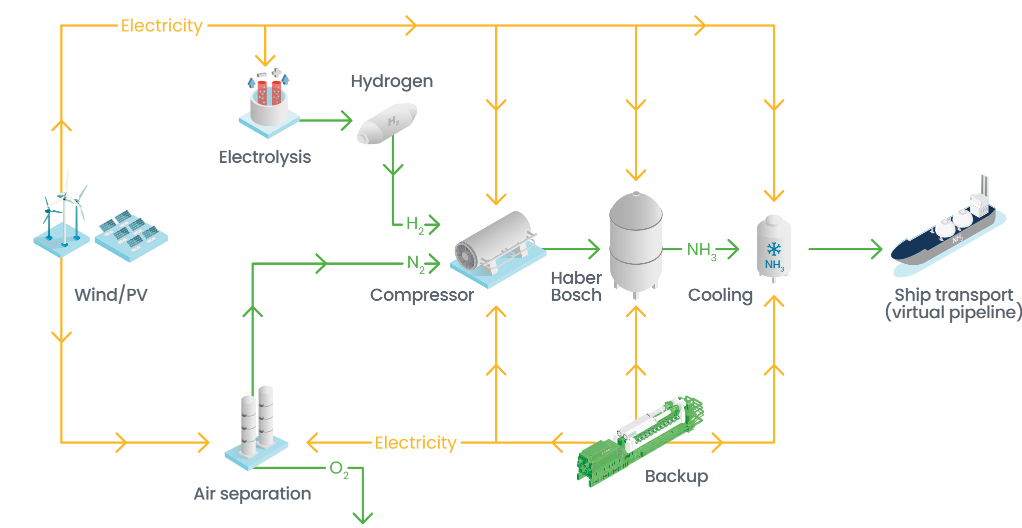

Figure 3: Basic setup of a green ammonia production facility

1. **Nitrogen extraction:** The first step is to source nitrogen, typically from the air using an air separation unit (ASU). The ASU separates nitrogen from other gases, producing a high-purity nitrogen stream. Nitrogen also can be sourced from organic waste or other sustainable methods, reducing the environmental footprint.

2. **Hydrogen production:** Green ammonia facilities use renewable energy sources, such as wind or solar power, to generate electricity. This electricity then is used in the electrolysis of water to produce hydrogen. Electrolyzers split water into hydrogen and oxygen, and the hydrogen is collected for further processing.

3. **Ammonia synthesis:** The hydrogen and nitrogen are combined in a reactor. The reactor is the heart of the ammonia production process. It should be constructed using materials that can withstand high pressures and temperatures, and the catalysts must be carefully selected to maximize conversion efficiency. This process is known as the Haber-Bosch (HB) synthesis, and it converts nitrogen and hydrogen into ammonia (NH_3).

4. **Ammonia separation and purification:** The ammonia produced in the synthesis process then is separated from unreacted nitrogen and hydrogen and purified to meet the desired product specifications.

5. **Ammonia storage and transportation:** Green ammonia typically is stored in tanks or converted into liquid ammonia for easier handling and transportation. This stage requires careful consideration of safety procedures and infrastructure.

The setup of a green ammonia production facility is not without challenges. Those include the cost of renewable energy, maintaining highly efficient electrolyzers and reactors, and ensuring safe and environmentally responsible operations. However, advancements in renewable energy technologies, improvements in catalysts, and increased investments in sustainable practices hold the promise of overcoming these challenges.

2.

REGULATORY CONDITIONS FOR LOW-CARBON REQUIREMENTS

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To achieve climate neutrality by 2050, the clean hydrogen capacity can grow to 170 million tons (Mt_{H2eq}) in 2030 and to 600 Mt_{H2eq} in 2050. Demand is expected to initially build on the decarbonization of existing industrial uses of hydrogen (95 Mt_{H2eq}), most notably for fertilizer production. A short-term ramp-up of demand for clean hydrogen is expected in industrialized economies (figure 4).

Therefore, the national and regional developments regarding regulatory requirements for clean hydrogen in these markets are being followed particularly closely by project developers for green hydrogen hubs.

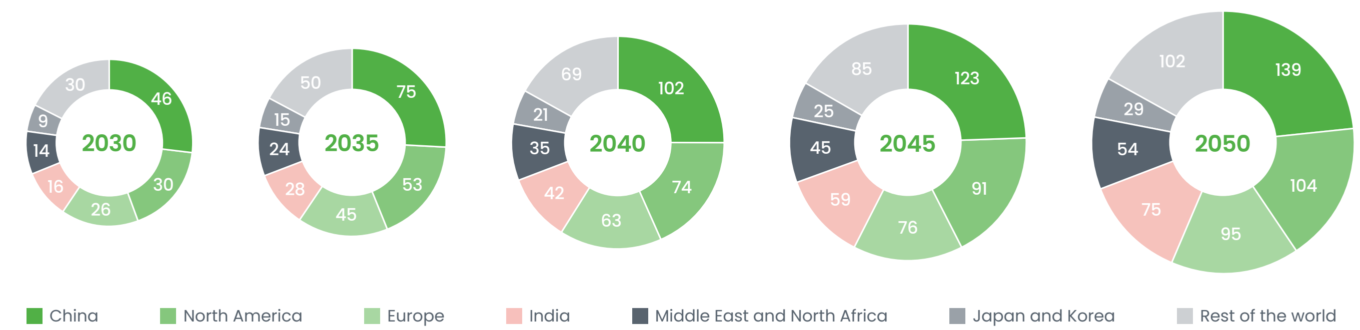

Figure 4: Regional demand (Mt_{H2eq}) for clean hydrogen and its derivatives, 2030 to 2050 (Deloitte)

		Production method	Scope	Year issued	Current Status	Emissions intensity [kg_{CO2}/kg_{H2}]
EU	EU Taxonomy	All	Well to gate	2021	Operational	3.0
	RED II	Renewable electricity, low carbon electricity (<65 $g_{CO2,eq}$/kWh)	Well to wheel	2023	Under development	3.4
UK	UK Low Carbon Hydrogen Standard	Electrolysis, natural gas with CCUS, biomass and waste	Well to gate	2022	Operational	2.4
	Renewable Transport Fuel Obligation (RTFO)	Renewable energy, excluding bioenergy	Well to point of delivery	2021	Operational	4.0
U.S.	Clean Hydrogen Production Tax Credit	All	Well to gate	2022	Under development	2.5 - 4 1.5 – 2.5 0.45 – 1.5 <0.45
Canada	Clean Hydrogen Investment Tax Credit	Electrolysis, natural gas with CCUS	Well to gate	2022	Under development	2 – 4 0.75 – 2 <0.75
France	France Ordinance No. 2021 - 167	All	Well to gate	2021	Under development	3.38
Japan	Clean Hydrogen Standard	All	Well to gate	2023	Under development	3.4

Table 1: Low-carbon hydrogen emission intensity reference values by country

2.1 National regulations in key regions

Legislative institutions in high-demand regions around the world are working on different standards for the CO_2 impact of clean hydrogen. The aim is to find a compromise that enables an economically viable import ramp-up and at the same time sufficiently preserves the climate protection effect of hydrogen. A summary of the most globally relevant legislative initiatives is listed in table 1.

European Union

The current Renewable Energy Directive (EU) 2018/2001 (RED II) requires 32% of the energy consumed within the EU to be renewable by 2030. The directive mentions renewable fuels of non-biological origin (RFNBOs) only in their role as transport fuels and defines them as "liquid or gaseous fuels which are used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass."

In practice, this generally covers hydrogen produced by electrolysis and hydrogen-derived fuels. RED II also provides that as of January 1, 2021, RFNBOs must deliver greenhouse gas emission savings of 70% compared to fossil fuels; this is equivalent to 3.38 kg_{CO2}/kg_{H2} in life-cycle emissions. If it meets this requirement, it counts toward the member states' renewable energy targets. Under RED II, the Commission adopted a delegated act on GHG savings and calculation of life-cycle emissions by January 2023.

The Commission's July 2021 proposal to revise the Renewable Energy Directive (RED III) widens the definition of RFNBOs by removing the transport sector aspect used in RED II. The proposal also clarifies that as a result of the modified definition, RFNBOs would count as renewable energy regardless of the end-use sector.

Furthermore, the revised RED III sets a general rule that RFNBO produced with electricity from the grid are deemed renewable in proportion to the average share of electricity from renewable sources in the country of RFNBO production, as measured two years before the year in question. However, electricity can be deemed to be 100% renewable in case of a direct connection between the renewable electricity generator and the RFNBO producer, provided that no electricity from the grid is used for RFNBO production and the renewable electricity generator comes into operation at the same time or after the RFNBO producer.

Japan

The Japanese government has promoted the establishment of international hydrogen supply chains in cooperation with countries in the Indo-Pacific, Europe, and the Middle East. Both the public and private sectors in Japan have developed partnerships with countries such as Australia and the United Arab Emirates.

The Japanese government considers hydrogen to be an industrial sector that can make a one-shot triple achievement of decarbonization, stable energy supply, and economic growth. In this context, the Japanese administration announced Japan's new hydrogen strategy, its first in six years.

In essence, the 2023 Hydrogen Strategy of Japan has four goals:

1. Increase the supply of hydrogen and ammonia in Japan from 2 million tons to 3 million tons by 2030, then to 12 million tons by 2040, and reach 20 million tons by 2050.

2. Reduce hydrogen supply costs in Japan from 100 円/m^3_{STP} to 30 円/m^3_{STP} by 2030 and to 20 円/m^3_{STP} by 2050.

3. Expand the amount of water electrolysis equipment made by Japanese companies to approximately 15 GW by 2030 on a global scale.

4. Attract public and private investments into the hydrogen and ammonia supply chain sector, setting a goal of more than 15 trillion yen ($107.5 billion) over the next 15 years.

The new hydrogen strategy also makes it clear that the Japanese government will subsidize the establishment of the hydrogen supply chain and the development of infrastructure based on carbon intensity. This means that the Japanese government will subsidize projects based on threshold of clean hydrogen and on its carbon footprint, rather than "color" of hydrogen. The threshold of clean hydrogen is defined as 3.4 kg_{CO2}/kg_{H2} on a Well-to-Gate basis, and the threshold for ammonia is defined as 0.84 kg_{CO2}/kg_{NH3} on a Gate-to-Gate basis. To promote Japan's policy toward hydrogen and ammonia, the Ministry of Economy, Trade and Industry established a new division for hydrogen and ammonia policy separately from the hydrogen and fuel cells strategy office in July 2023.

United Kingdom

As outlined by the British Energy Security Strategy (BESS) in 2022, the UK government set out its doubled ambition to deliver up to 10 GW of low carbon hydrogen production capacity by 2030, subject to affordability and value for money, with at least half of this from electrolytic hydrogen.

To help ensure that the hydrogen ramp-up significantly contributes to carbon reduction targets in the United Kingdom, the Low Carbon Hydrogen Standard Policy has defined a Low Carbon Hydrogen Standard.

The Low Carbon Hydrogen Standard sets a maximum threshold for the amount of greenhouse gas emissions allowed in the production process for hydrogen to be considered "low carbon hydrogen."

The standard requires hydrogen producers to:

1. Meet a greenhouse gas (GHG) emissions intensity of $20g_{CO2}e/MJ_{LHV}$ of produced hydrogen or less for the hydrogen to be considered low carbon.

2. Calculate their GHG emissions up to the Ω"point of production."

3. Set out a risk mitigation plan for fugitive hydrogen emissions.

4. Meet additional requirements for the use of biogenic inputs, where relevant and as appropriate for the feedstock source and classification.

North America

The Clean Hydrogen Production Tax Credit as part of the Inflation Reduction Act (IRA) in the United States and the Clean Hydrogen Investment Tax Credit as part of Canada's climate protection initiative have provided the most far-reaching incentives to date for developing a net-zero hydrogen supply infrastructure. Analogous to the Japanese hydrogen strategy, a technology-neutral funding approach has been chosen in North America, which is primarily based on the carbon intensity of the hydrogen produced. Accordingly, limits have been defined that provide for a maximum lifetime CO_2 load of 4 $kg_{CO2}/kg/_{H2}$ over the production process. No standards have yet been defined in the regions for accounting for the decarbonization effect of imported hydrogen. However, it can be assumed that these will be based on future domestic production limits.

2.2 Challenges for project developers

These comparatively strict regulations on lifetime emissions in the most attractive target regions for the import of green hydrogen in the medium term represent a key challenge for project developers.

In many cases, the priority development of green ammonia hubs means a high level of dependence on the local supply of renewable electricity, first because the local electricity grid supply is not designed for large projects in the scale of GWe and second because the corresponding proof of electricity procurement required for regulatory certification is not possible in most regions.

However, the use of established backup technologies, such as diesel engines, is at the expense of the lifetime emissions of the hydrogen produced. A backup share of 25% results in emissions of more than 3 kg_{CO2}/kg_{H2} (figure 5). The limit values discussed in chapter 2.1 do not allow any further leeway for emissions via the supply chain, such as ship transportation.

As an alternative to the cost-intensive provision of high RES surplus capacities to reduce undersupply, the implementation of climate-neutral backup systems can be crucial for project developers to ensure the economic viability of green ammonia hubs. Due to the already existing hydrogen production and storage capacities in these hubs, hydrogen-based energy solutions are a particularly reasonable backup technology.

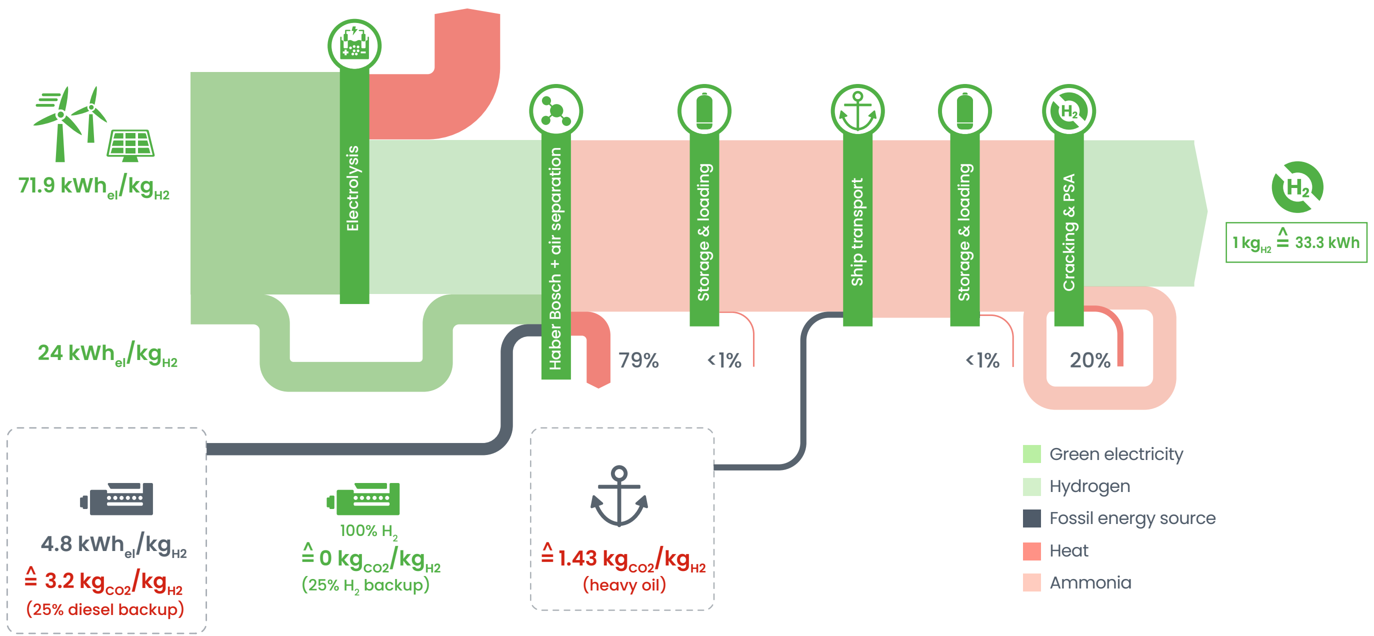

Figure 5: Major CO_2 sources along the value chain of green ammonia-based hydrogen transport (DVGW)

3.

RELIABLE BACKUP POWER AND A REDUCED CARBON FOOTPRINT WITH JENBACHER TECHNOLOGY

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3.1 H2-Engines

As a green technology pioneer and an integral part of the energy transition, INNIO Group has launched its "Ready for H_2" portfolio that includes 100% hydrogen-powered Jenbacher H2-Engines. INNIO Group's "Ready for H_2" engine portfolio is built on a long history of innovation with more than 30 years of experience and expertise in the use of renewable fuels and hydrogen-rich fuels, such as syngas and process gases for power generation.

As of today, Jenbacher Type 4 engines—with an approximate output of 800 to 1,500 kW—are available for operation with 100% hydrogen or mixtures of natural gas and hydrogen.

All new Jenbacher engine solutions are "Ready for H_2." In addition, Jenbacher models can be offered with the option to operate with up to 25% (vol) of H_2 in the pipeline gas. As hydrogen availability increases, all new plants and most of the currently installed Jenbacher natural gas-powered engines can be converted to run on 100% hydrogen.

Power Output (kWel) (0, 1,000, 2,000, 3,000, 4,000, 5,000, […], 10,000)		H_2 in pipeline gas		Gas/H_2 engine	100% H_2
		<5% (vol)	<25% (vol) optional	0-100% (vol)	100%
Type 9	J920 FleXtra	✓	✓	25	2025+
Type 6	J612, J616, J620, J624	✓	✓	60	2025
Type 4	J412, J416, J420	✓	✓	100	✓
Type 3	J312, J316, J320	✓	✓	60	2025+
Type 2	J208	✓	✓	60	2025+

Figure 6: Jenbacher "Ready for H_2" product portfolio

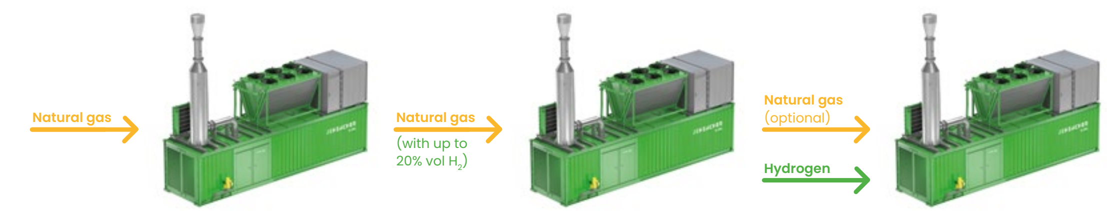

Figure 7: Demand-oriented conversion of INNIO Group's Jenbacher engines to hydrogen operation

Up to 60% (vol) of H_2 content can be admixed to pipeline gas for use in specific versions of Jenbacher Type 2, 3, 4, and 6 engines. Jenbacher Type 4 engines and CHP systems are available today as dual-gas-fuel solutions capable of running on 100% conventional gas, 100% hydrogen, or mixtures of pipeline gas and hydrogen.

Despite the lack of widespread availability of green hydrogen, INNIO Group can already look back on several commercial hydrogen projects worldwide for its young technology, underlining the technology leadership of INNIO Group with its Jenbacher solutions (figure 8).

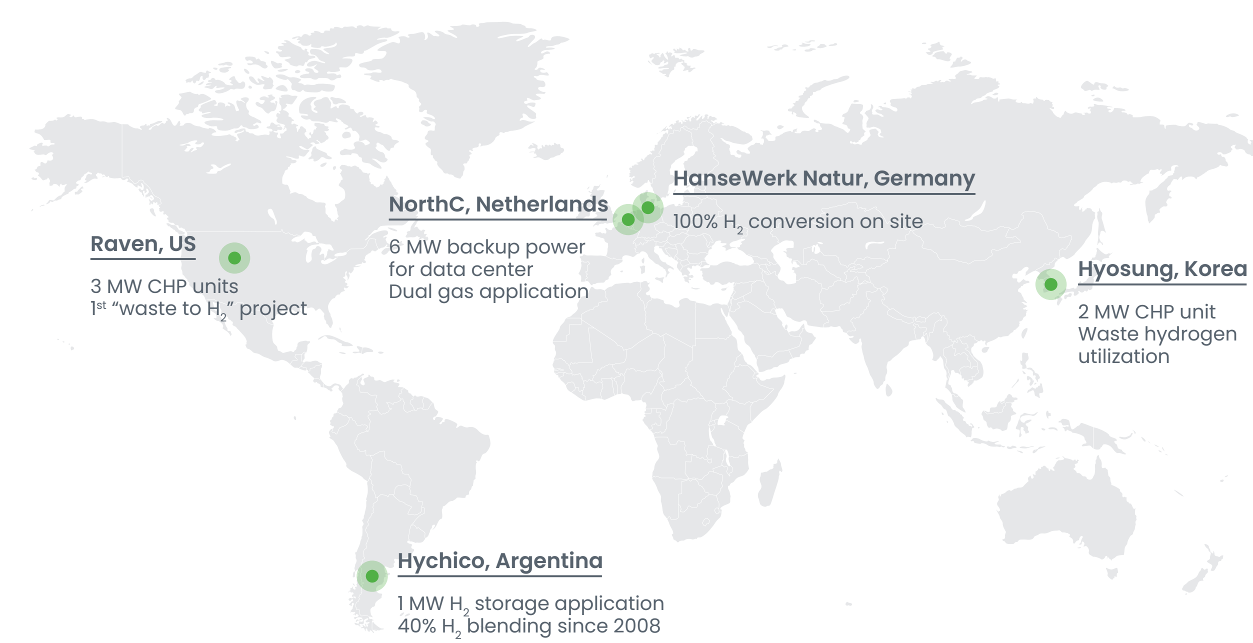

Figure 8: Selection of INNIO Group's Jenbacher H_2 projects worldwide

3.2 Microgrid solutions

Green ammonia hubs are energy-intensive facilities that, in most cases, are supplied almost entirely from on-site local renewable energy plants. Accordingly, these green ammonia hubs require a high degree of self-sufficiency. To support flexible, reliable, environmentally friendly and economically viable operations, a robust, resilient, and intelligent energy management system is crucial. In addition to the supply and implementation of net-zero technologies for power units, INNIO Group also offers digital solutions based on intelligent algorithms and machine learning to support off-grid or microgrid applications in this environment.

Energy management solutions for a sustainable regionally integrated energy supply

Decarbonization, decentralization, and digitalization pose major challenges for CHP plant operators today. INNIO Group recognizes the growing importance of complex energy-generating plants, especially in the context of constantly changing regulatory requirements. With the energy management solution myPlant Optimization, INNIO Group offers a tailor-made tool to increase overall profitability through a directly marketed, sustainably flexible and heat- as well as storage-oriented mode of operation in compliance with regulatory requirements. Based on precise electricity price forecasts as well as storage and heat forecasts, it enables the production and feed-in of electricity precisely when it is demanded in the grid, thus helping to improve the profitability of the plant and claim productivity gains through a high degree of automation. At the same time, precise design and mapping of the connected storage and heat networks contributes to high flexibility in power generation. For this purpose, the intelligent digital solution continuously compares new information (e.g., new regulatory guidelines, current electricity and gas prices, weather data, and calculated forecasts such as emissions) and uses self-learning algorithms to create economically optimized and resource-saving operating strategies within the framework of individual specifications and operating conditions. By integrating INNIO Group's innovative myPlant Optimization as an energy management solution, plant operators have the opportunity to make better operating decisions in a constantly changing environment and contribute to a sustainable heating, cooling, and power supply.

For more information, visit: https://www.jenbacher.com/en/services/myplant-energy-management, https://myplant.io/en/optimization

4.

COMPARATIVE TECHNO-ECONOMIC EVALUATION OF AVAILABLE BACKUP-POWER TECHNOLOGIES

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4.1 Technology comparison

Fuel cells
For hydrogen-based decentralized energy supply in almost all applications, the fuel cell and the hydrogen engine represent the dominant competing technologies. In the comparative assessment, both technologies show different advantages and challenges.

Advantages of hydrogen engines:

- **Simplicity:** Hydrogen engines are relatively simple and resemble conventional internal combustion engines, making them easier to understand and maintain. They can be adapted to existing infrastructure with fewer modifications.
- **CAPEX:** In particular, the need for rare earths and the energy-intensive production of the electro-chemical cell materials lead to significantly higher investment costs for the fuel cell compared to an internal combustion engine.
- **Thermal efficiency:** Due to the lower temperature level of the waste heat generated, the potential for waste heat utilization (for example in trigeneration systems) of most fuel cell technologies is significantly below that of internal combustion engines.
- **High power output:** Hydrogen engines can deliver high power output, making them suitable for applications where high torque and rapid acceleration are required, such as in heavy-duty vehicles or certain industrial settings.
- **Flexibility:** Hydrogen engines can be used with various fuels, including hydrogen produced from renewable sources or conventional fossil fuels. This flexibility allows for a transition from fossil fuels to cleaner alternatives over time.
- **Load ramps:** Sharp load ramps lead to accelerated aging and deterioration of the FC-stacks, whereas an engine is designed for rapid load cycles.
- **Grid stabilization:** Rotating mass in the generators are physical grid stabilizers that are not available in fuel cell-based generators, requiring power electronics.
- **Purity requirements:** Hydrogen engines are able to handle significantly higher impurity levels of hydrogen during combustion. Compared to fuel cell-based systems, this can be a significant cost advantage, for example due to the need for gas treatment or the use of cost-intensive compressors with a lower lube oil entrainment.

Challenges of hydrogen engines:

- **Efficiency:** Hydrogen engines have lower electrical energy efficiency compared to most fuel cells.
- **Emissions:** Hydrogen engines produce emissions, primarily in the form of nitrogen oxides (NO_x). While the NO_x emissions are significantly reduced compared to the use of other fuels, a low amount of NO_x emissions is not avoidable.

	H2-Fuel cell		H2-Engine
	PEM	SOFC	
Fuel flexibility	-	○	+
CAPEX	-	-	+
Efficiency	+	++	++
Cold start for grid stabilization	++	--	+
Load flexibility	+	-	+
Service life	--	++	++

Table 2: Comparison of H2-Engines and H2-Fuel cells

Among the advantages and challenges of the hydrogen engine compared to the fuel cell, the significantly lower investment costs on the one hand and the lower electrical efficiency on the other are particularly noteworthy from an economic perspective. As a result, hydrogen engines have significantly lower levelized cost of electricity (LCOE) at lower full load hours, where efficiency does not play a significant role, while capital costs are dominating.

Therefore, hydrogen engines show significantly higher economic efficiencies in corresponding applications, such as backup operation.

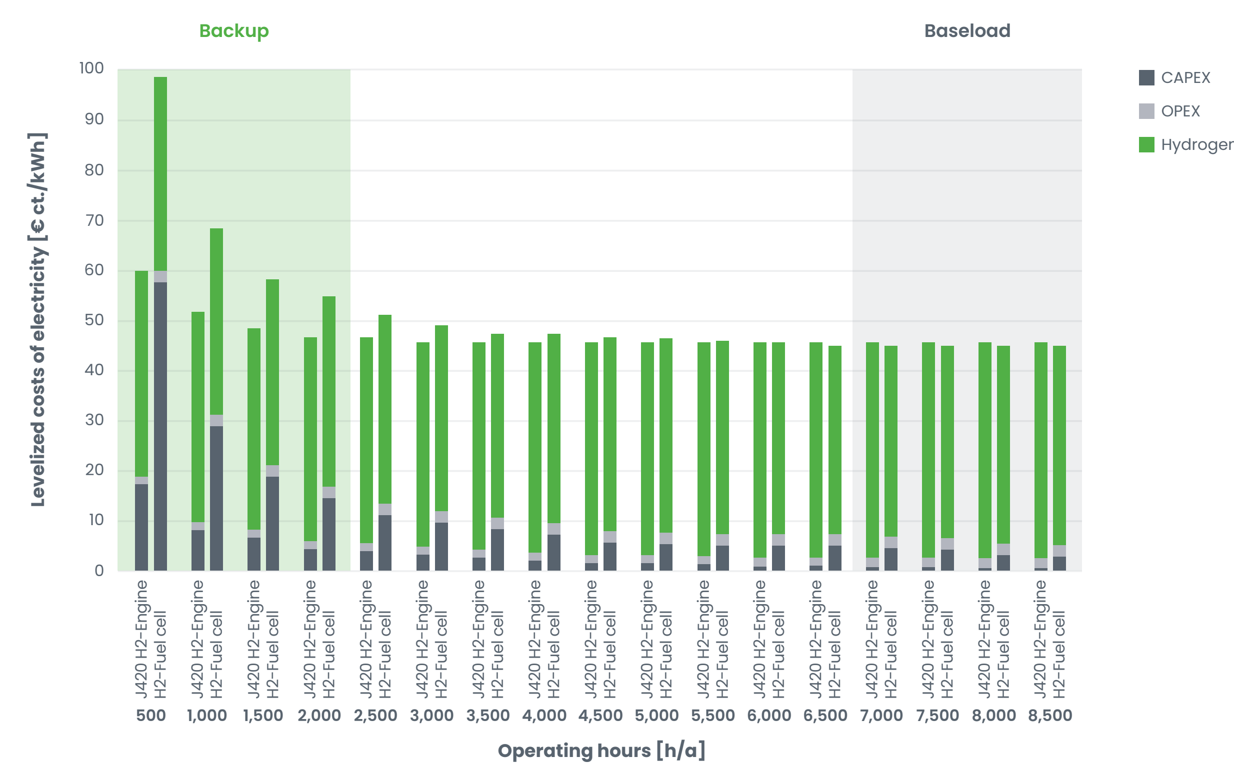

Figure 9: Levelized cost of electricity (LCOE) for H2-Engines and H2-Fuel cells

Battery electric backup
Electrochemical energy storages, commonly named battery energy storage systems (BESS), are accumulators that are used primarily to utilize surplus yields during the day in low-yield or non-yielding evening and night hours. The most commonly used accumulators in BESS are lithium-ion accumulators and lead-acid accumulators.

A decisive advantage of BESS is their very high round trip efficiency because the most up to date lithium-ion battery shows efficiencies today of up to 95%. The entire BESS package, including the inverters and transformers, still shows a very competitive efficiency of about 90%.

Another important advantage of battery technology is its fast response time. Within milliseconds, BESS can draw and store or release electrical energy, offering enormous flexibility for the power grid.

Figure 10 shows an overview of the storage capacity and release duration of various storage technologies. The withdrawal period indicates how long a storage system can supply energy. It is calculated from the ratio of withdrawable energy and withdrawal capacity.

While large-scale BESS can effectively balance short-term differences between supply and demand due to their high efficiency and quick response time, they are not the only solution. They are often used to balance the day/night fluctuation of PV systems, storing excess PV power during the day with minimal losses and making it available again in the evening.

However, for longer-term fluctuations and where large storage for seasonal application are required, hydrogen-based storage becomes a viable alternative. Despite the higher losses due to lower efficiency, hydrogen storage can compensate for these fluctuations effectively.

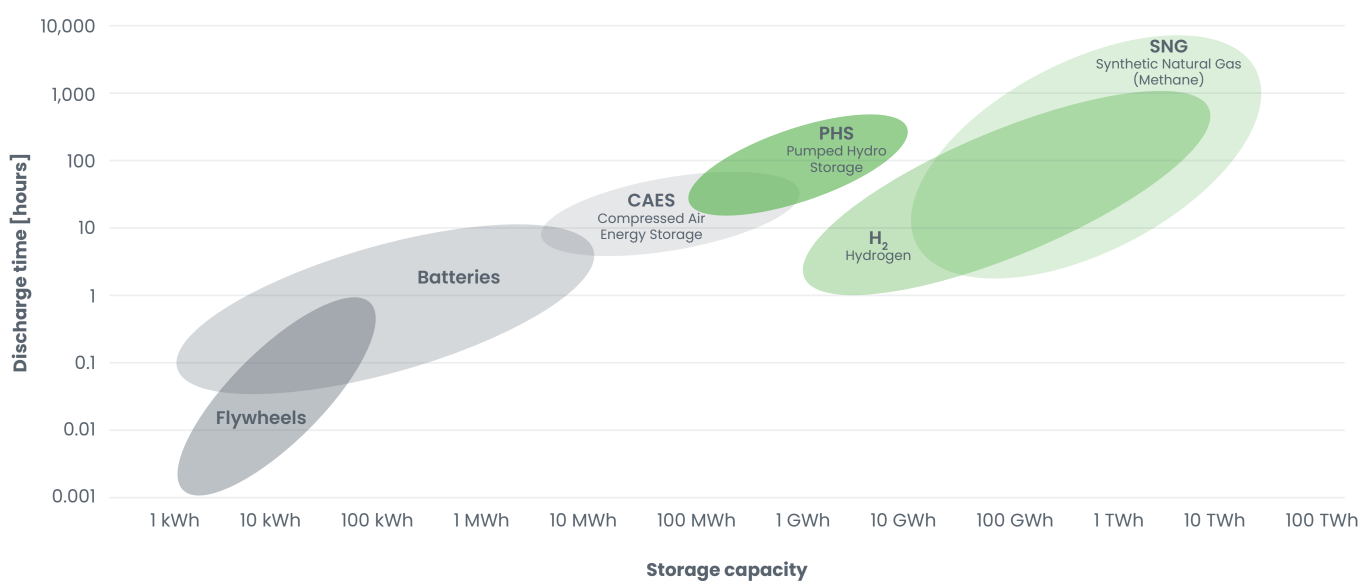

Figure 10: Overview storage capacity of different energy storage systems
Source: Roland Berger (2022)

4.2 Case studies

For a comparative evaluation of the existing net-zero backup solutions, cost-efficiency calculations have been performed comparing five different case studies. These case studies were chosen to cover a diverse spectrum of announced green ammonia projects in terms of geographical location, production capacity, and renewable energy installed capacity. The focus extended to regions where the establishment of green ammonia hubs already have been announced, a selection driven by the high potential for for renewable energy integration (figure 10).

For each case study, namely Chile, Canada, Namibia, Oman, and Australia, hydrogen-based storage and backup systems are compared with battery-electric solutions. The hydrogen engine and the fuel cell as established decentralized energy solutions are compared as re-electrification technologies for hydrogen storage. It is noteworthy that gas turbines operated with 100% hydrogen, although a potential avenue, are excluded from our study due to the absence of commercially available and technologically mature solutions at present. For hydrogen storage, the analysis considers two distinct pressure levels, a high pressure (HP) storage at 400 bar and a low pressure (LP) storage at 150 bar. For battery-electric storage, Li-Ion batteries are considered as an established technology. The following four backup solutions were evaluated in comparison:

	H2-Engine	H2-FC	Redox flow	Li-Ion
Storage system	Compressed hydrogen (400 bar)	Compressed hydrogen (400 bar)	Redox flow	Lithium-Ion storage
Re-electrification	-	PEM fuel cell	Power electronics	Power electronics
Total round trip efficiency	25%	28%	72%	90%
CAPEX storage (€/kWh)	1.2	1.2	36	45
CAPEX re-electrification (€/kW)		3,800	35	35
Calendar lifetime storage (a)	30	30	25	13
Calendar lifetime re-electrification (a)	25	10	50	50

Table 3: Backup solutions for comparative evaluation- techno-economic data (NREL, 2022)

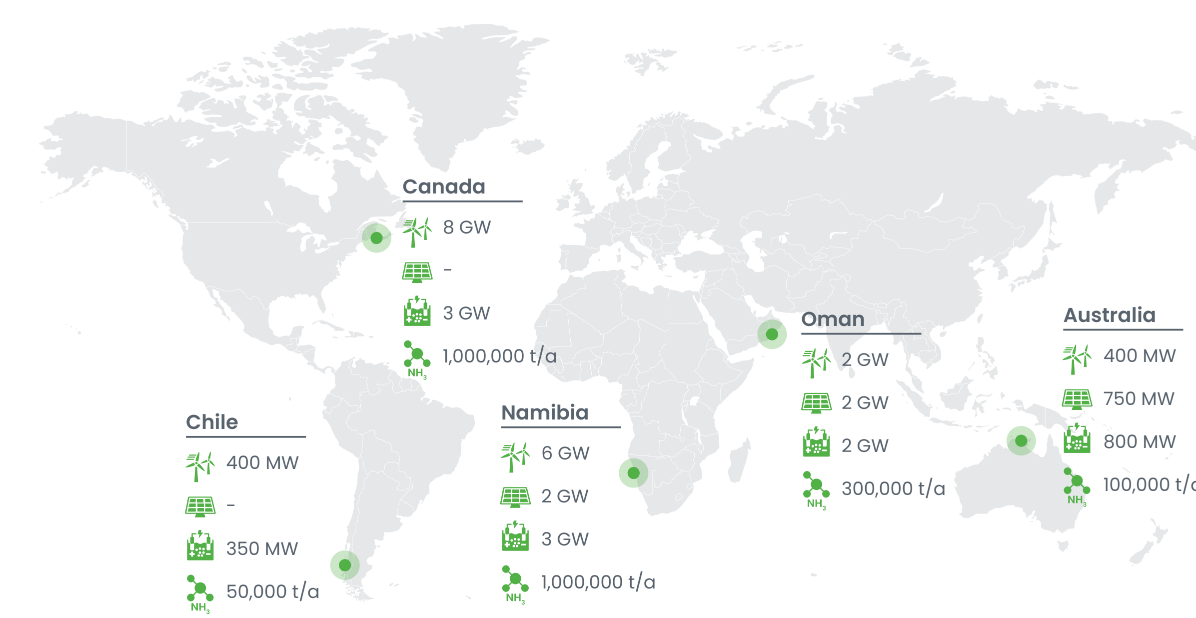

Figure 11: Locations for the economic case studies

4.3 Levelized cost of electricity for relevant scenarios (sensitivity analysis)

This study presents a power dispatching balance calculation of the proposed green ammonia hub systems for components (equipment) design and related cost estimation. A constant energy consumption has been assumed for the Haber Bosch process as well as for the corresponding periphery (air separation, desalination, compression, ammonia cooling) according to the most up to dates references. Such an energy consumption is seen under the power flow dispatch as a demand to be supplied. In the specific case study, the Haber Bosch process is fed primarily by the green electrons produced through the renewable energy systems (namely solar PVs and wind turbines), while the electrolyzer is operated according to the remaining availability of green electricity. Surplus electricity is used to fill up the hydrogen storage tanks, similar to what happens with BESS. The hydrogen then is available both for conversion to ammonia and for backup power generation during periods of undersupply.

Furthermore, it has been assumed the facility is operated in an islanded (off-grid) mode, and consequently it must ensure self-sufficiency since no grid backup exists. In the case study, the focus was to provide a robust sensitivity analysis, therefore the optimization of the demand side through an Energy Management System (EMS) was not considered.

Accordingly, a concurrent option of multi-energy storage was not presented for clearly showing the effect of each storage technology on the LCOS.

The calculations are based on regionally specific load profiles for offshore wind and PV electricity in hourly resolution. The robustness of the model is ensured by the fact that the yearly data of the RES are related to the well-established meteorological database of the NASA, MERRA Reanalysis, and a satellite-based climatology of the solar surface irradiance from CM-SAF's SARAH dataset. For the case study in Namibia, the green electricity generation and the proportionate consumption for the green ammonia production over the year are shown in figure 12.

In the production of green ammonia, the flexible electrolysis for hydrogen production accounts for most of the electricity demand.

Depending on the regional conditions, concurrent options of having wind and PV electricity combinations can significantly reduce supply gaps, as shown for the Namibia case (figure 13 (left)). Conversely, regions reliant on a singular source of renewable energy for electricity supply such as the Canada

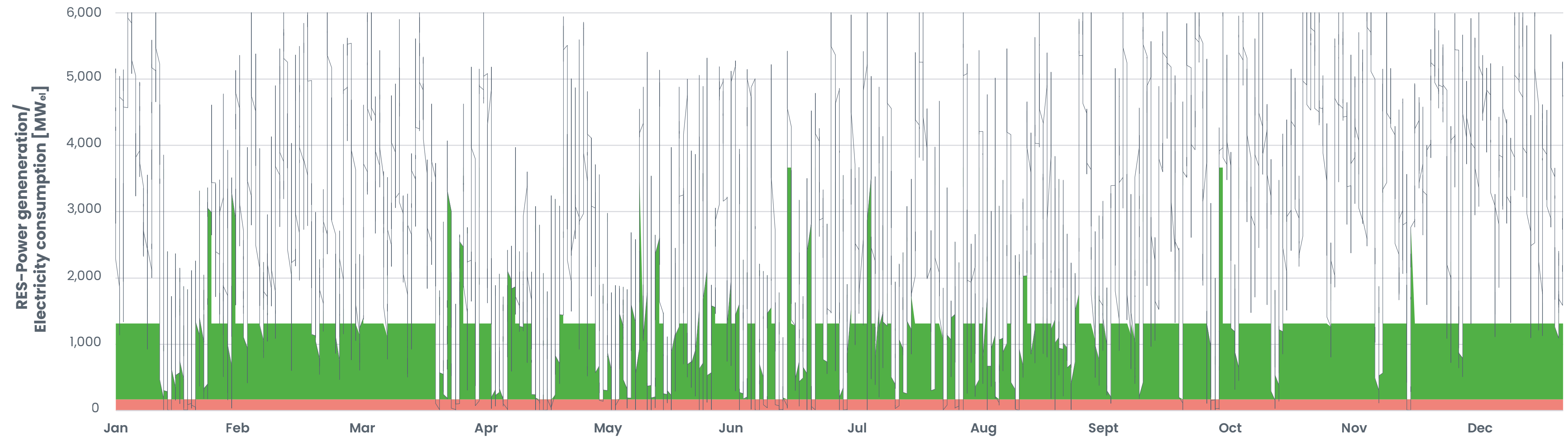

Figure 12: Electricity consumption for H_2 production and Haber Bosch process (including air separation, compression, reactor and ammonia cooling) – case study Namibia

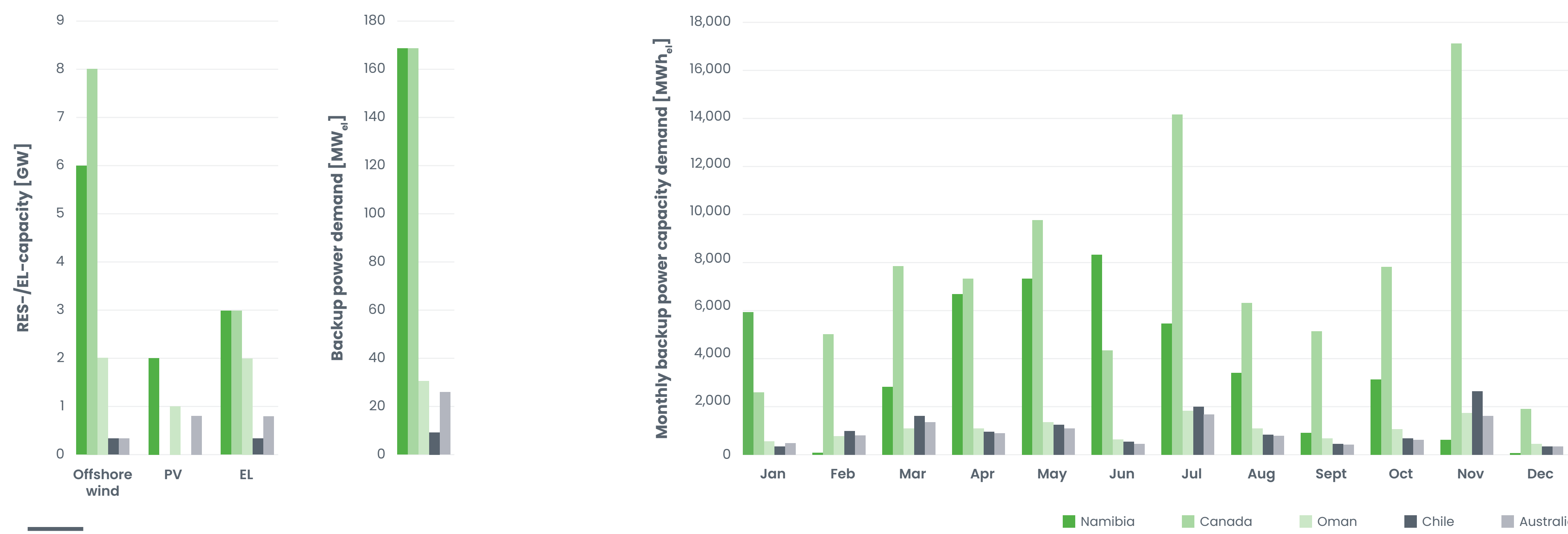

Figure 13: Available RES/EL-Capacity (left), required peak backup power (middle) and monthly demand for backup power (right)

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case experience prolonged periods of substantial undersupply, requiring relevant compensation taken from the backup systems (figure 13 (right)).

Nevertheless, phases in which no electricity is produced at all cannot be avoided throughout the year, which is why the backup demand shown in figure 13 corresponds to the constant electricity demand in the respective cases.

Examining figure 13 (left), it becomes evident that the largest announced projects worldwide with a production capacity of 1 million tons of ammonia per year require backup systems in the order of 150 MWel, an amount that still can be met by decentralized energy solutions.

The monthly breakdown of the required backup capacities presented in figure 13 (right) illustrates the strong seasonal fluctuations in all the regions and RES constellations considered. Bridging these seasonal fluctuations requires high storage capacities across all technologies.

Despite the implementation of a hydrogen-based backup system resulting in a modest 5% increase in annual hydrogen demand (figure 14), the need to address seasonal demand peaks drives a more significant surge of approximately 25% in the need for additional storage capacity (figure 15). The marginally lower surplus capacities required for the fuel cell-based backup system stem from the slightly enhanced efficiency of the fuel cell technology.

For the economic feasibility studies, these additional storage capacities are added to the backup system and taken into account in the final calculation of the levelized costs of storage (LCOS). The required storage capacities for a battery-electric backup solution are shown in figure 16.

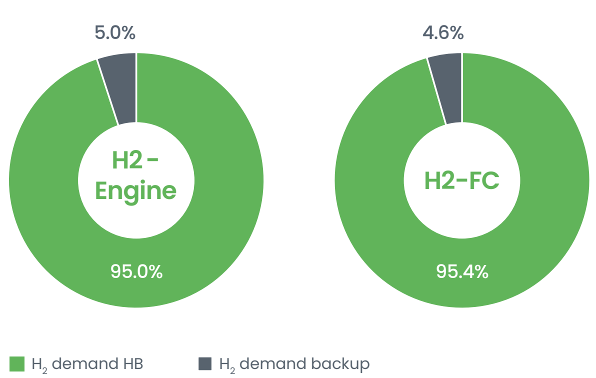

Figure 14: H_2 demand for backup power – case study Namibia

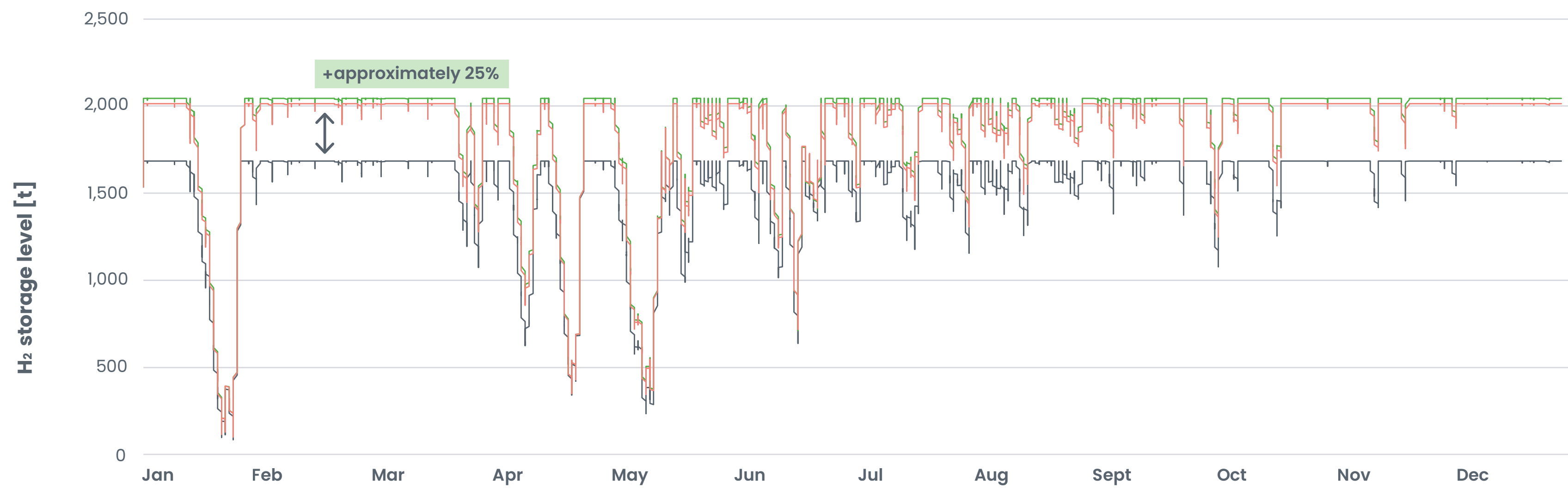

Figure 15: Required additional H_2 storage capacities for H_2-based backup power systems – case study Namibia

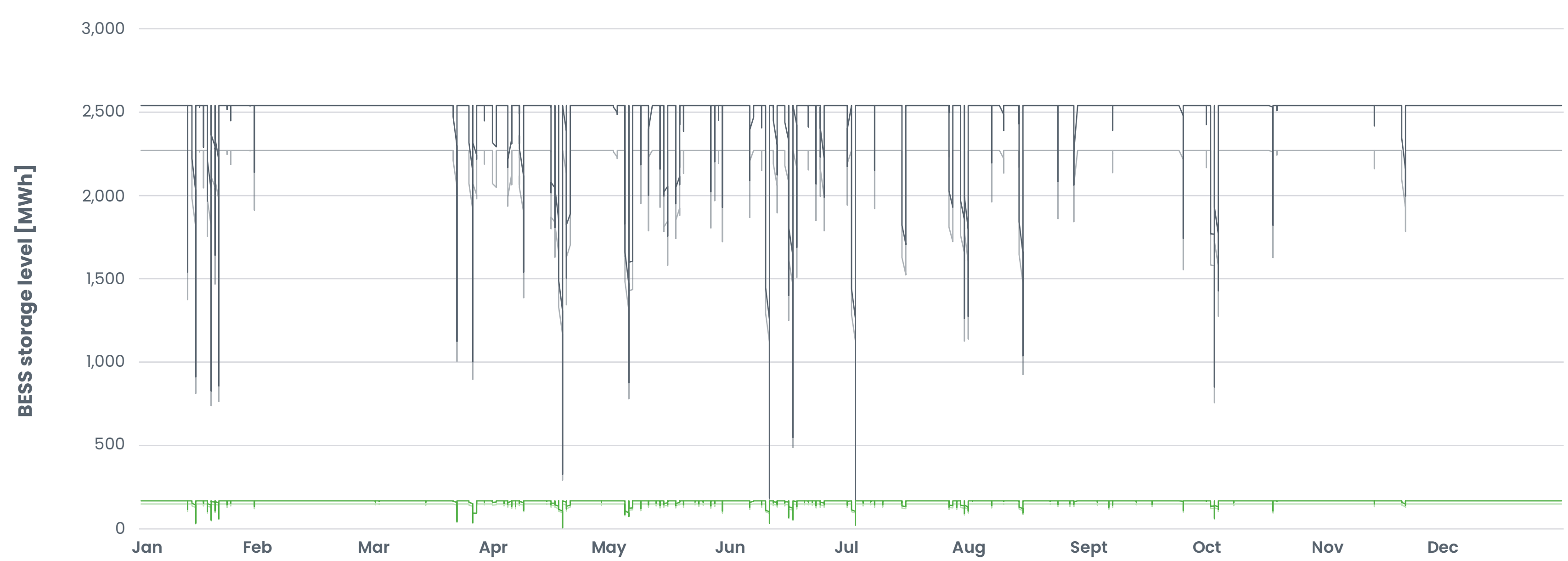

Figure 16: Required storage capacity for BESS-backup solution – case study Namibia

The magnitude of green ammonia projects is exposed in the Namibia case study, where the imperative for battery storage systems is underscored by a substantial demand, approximating 2.5 GWh (fig. 16). This storage size is approximately 60% above the capacity of the current largest storage system globally. In terms of technical feasibility, particularly with regards to space requirements, BESS should, therefore, be considered in projects as large as the one described in the Chile case study. Notably, redox flow battery systems, owing to their lower turnaround efficiency, require larger storage capacities when compared with similar Li-Ion-based BESS competitors. These significant additional storage capacity requirements come at the economic expense of storage solutions with high capacity-specific storage costs. This represents a notable drawback for battery-electric storage systems, where the predominant factor influencing the total cost of ownership (TCO) throughout a project term of 20 years is the overarching storage costs.

The cost-effectiveness of hydrogen-based systems is notably shaped by the diminished specific costs linked to high-pressure storage systems, resulting in a significant reduction in capital expenditures (CAPEX) and total cost of ownership (TCO) (figure 18). In contrast, the substantially elevated TCO observed for fuel cell-based systems primarily result from the necessary replacement of fuel cell stacks throughout the life cycle of the system.

Cost effectiveness of the different backup solutions is shown in figure 19 (as measured by the levelized cost of storage or LCOS). The LCOS clearly shows that a hydrogen engine-based backup system is an economically competitive and promising solution for fulfilling backup power requirements in green ammonia hubs.

Relative to BESS, competitiveness of the H2-Engine can be mainly attributed to the substantially reduced capacity- specific storage costs. When compared to fuel cells, H2-Engines clearly shows an advantage due to power- specific backup costs. These LCOS cost advantages persist in all five scenarios ranging between 17% for the Namibia and 66% for the Canada case. The abundant surplus of RES throughout the year coupled with the significant H2-Engine cost advantage more than offset relatively low H2-Engine round trip efficiency. In green ammonia projects where PV dominates the power supply, as in the Australia case, the advantages of battery-electric backup systems for balancing out power fluctuations during the day come into play.

An optimized backup storage system certainly would involve a synergistic combination of H_2-based and battery-electric storage systems, in which the storage robustness and long-term storage capacities address seasonal surpluses are supplied by the on-site hydrogen infrastructure, while batteries serve as a supplementary component to offset daily fluctuations.

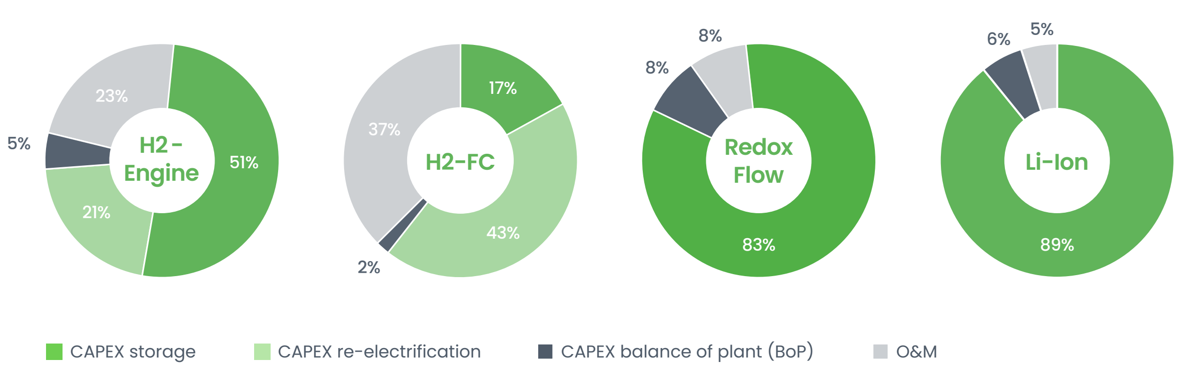

Figure 17: Composition of the cost items for the total costs of ownership (TCO) over the project term - case study Namibia

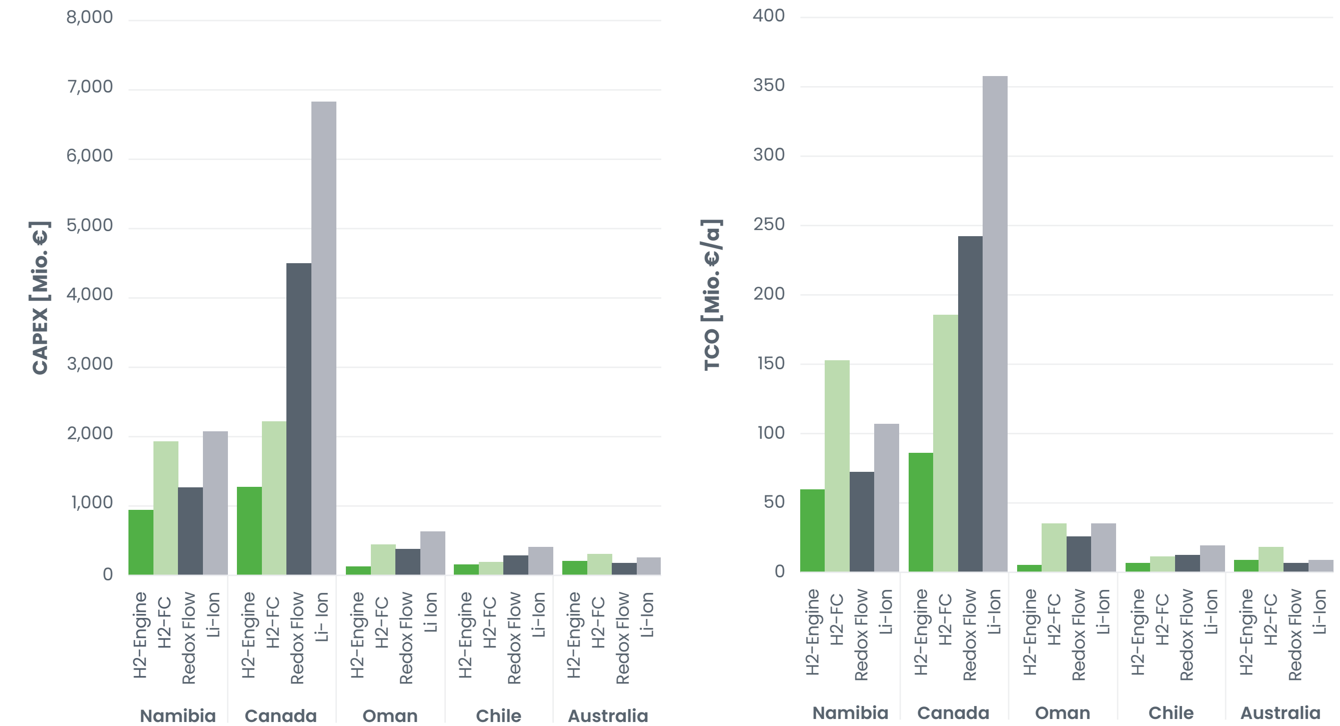

Figure 18: Capital expenditures (CAPEX) and total cost ofownership (TCO) for the different backup solutions

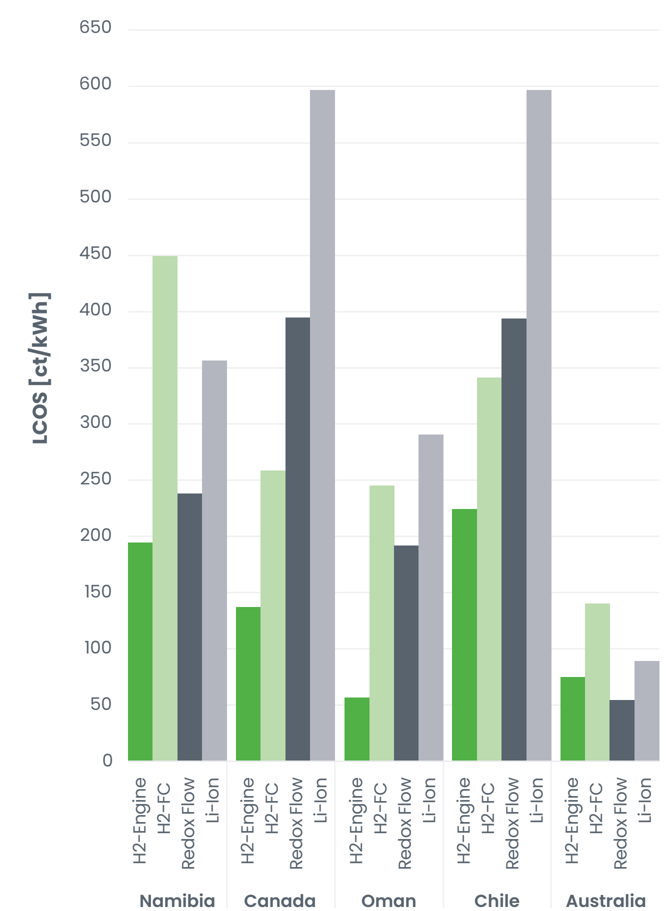

Figure 19: Levelized costs of storage (LCOS) for the different backup solutions

LITERATURE

LITERATURE

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INNIO Group is a leading energy solution and service provider that empowers industries and communities to make sustainable energy work today. With its product brands Jenbacher and Waukesha and its digital platform myPlant, INNIO offers innovative solutions for the power generation and compression segments that help industries and communities generate and manage energy sustainably while navigating the fast-changing landscape of traditional and green energy sources. INNIO is individual in scope, but global in scale. With its flexible, scalable, and resilient energy solutions and services, INNIO enables its customers to manage the energy transition along the energy value chain wherever they are in their transition journey.

INNIO is headquartered in Jenbach (Austria), with other primary operations in Waukesha (Wisconsin, U.S.) and Welland (Ontario, Canada). A team of more than 4,000 experts provides life-cycle support to INNIO's more than 55,000 delivered engines globally through a service network in more than 100 countries.

In March 2023, INNIO's ESG rating ranked first out of more than 500 companies worldwide in the machinery industry assessed by Sustainalytics.

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