MAY 2025

SHIELD

Green Hydrogen Use-Cases: **Global realism and Ukrainian relevance**

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Executive Summary

This report analyses potential use-cases for green hydrogen (GH$_2$) in Ukraine to inform the Strategic Hydrogen Integration for Effective Low-Carbon Development (SHIELD) project. This project aims to determine the strategic placement of low-carbon infrastructure for short-term energy security and long-term energy transition in Ukraine, with a focus on hydrogen potential.

GH$_2$ is a crucial energy carrier for decarbonization which may be relevant to Ukraine's reconstruction and EU accession aspirations. It can be used across industrial, transport, power, and residential sectors. However, not every use-case is realistic and feasible everywhere. Here we therefore analyse each potential use case for relevance and realism within Ukraine.

Approach

GH$_2$ use-cases covering fuel and feedstock applications are systematically studied through desktop review of literature and policy. Each is evaluated for global realism and Ukrainian on a five-point scale, visualised from red to green as shown in the table below. The scores for realism and relevance are averaged to give a net importance of including the use-case in SHIELD scenario analysis.

TABLE: Summary of study results on use-case realism, relevance, and importance for further study.

Sector	Type	GH2 Application	Global realism	Ukraine relevance	Further study
Industry	Feedstock	Steel (H2-DRI)			
		Ammonia/Fertilizer			
		E-fuels and petrochemicals			
		Refining processes			
		Others			
	Fuel	Low-temperature heat			
		Medium-temperature heat			
		High-temperature heat			
Transport	Fuel	Cars			
		Trucks			
		Public transport			
		Rail transport			
		Airplanes			
		Ships and maritime sector			
Power	Fuel	Energy shifting and storage			
		Grid balancing and ancillary services			
		Combined heat and power			
		Off-grid and emergency generation			
Residential	Fuel	Residential power & heat supply			
		Heat networks			

Scale:	Very unlikely	Unlikely	Possible	Likely	Very likely

Key findings by sector

1. **Industrial Sector:** GH_2 shows strong potential in high-temperature industrial processes such as steel, glass, and cement production. Ukraine's reconstruction needs and EU accession goals make decarbonizing these industries crucial. Blast furnaces do however dominate Ukrainian steel production, presenting a challenge for GH_2 integration. GH_2-based ammonia and fertilizer production is viable but faces cost barriers. The disruption of fertilizer supply chains due to the conflict highlights the need for domestic production.
2. **Transport Sector:** GH_2 and derivative e-fuels are promising for decarbonization of aviation and shipping. Challenges include infrastructure development to support this and management of chemical properties within vessels and aircraft. EU regulations on sustainable aviation fuels and maritime emissions create a favorable policy environment for Ukraine's adoption. In ground transport, battery electric vehicles currently dominate, but fuel cell electric vehicles show potential for trucking in the medium term. Rail decarbonization is likely to use a mix of hydrogen and electric vehicles across different routes and must be considered given the vital importance of Ukraine's train network.
3. **Power Sector:** GH_2 offers flexibility and resilience for grid management (i.e., balancing and ancillary services) especially with growing renewable energy integration. Electrolysis offers rapid ramp-up and -down, ideal for short-term grid balancing and frequency regulation. Economic viability of this use-case requires value-stacking, combining grid services with hydrogen production for other sectors. GH_2 also enables long-term energy storage to manage seasonal variations in renewable energy supply. It has lower round-trip efficiency compared to batteries which limits viability for short-term storage.
4. **Residential Sector:** GH_2 integration into district heating networks is possible but faces competition from heat pumps. Use of GH_2 in individual home heating has limited practicality due to the higher efficiency of heat pumps for space heating.

Overall assessment

GH_2 holds significant promise for Ukraine, particularly in high-heat industrial processes, fertilizer production, aviation, shipping, and power sector applications. Critical use-cases are identified as fertiliser, direct reduction of iron (DRI) in steelmaking, aviation and maritime fuels, and rail transport. High-temperature heat industrial applications, power applications, and heat networks are also seen as important to study. Other applications, such as e-fuels and petrochemicals, other industrial feedstock applications, trucking, and residential heat could be studied if deemed politically important to the country. Meanwhile, applications in low- and medium-temperature heat, refining, cars, and public transport are unlikely to be feasible in the near future. While cost and infrastructure remain barriers, EU accession goals and the need for energy security and reconstruction present strong drivers for GH_2 adoption.

Recommendations for Further Study

Based on this assessment, GH_2 use-cases are assigned the following priority levels for further study:

- **High:** high-heat industrial applications, steelmaking, fertilizer production, aviation and maritime fuel, rail transport, power applications, heat networks.
- **Medium**: E-fuels and petrochemicals, other industrial feedstocks, trucking, residential heat.
- **Low**: low and medium heat applications in industry, cars, public transport, refining processes.

1 Introduction

This report details potential use cases for green hydrogen (GH_2) and their relevance to Ukraine, given historical context and current geopolitics. This will inform the construction of SHIELD scenarios.

1.1 WHY GREEN HYDROGEN

Hydrogen is seen as an important energy carrier for decarbonisation. It can be used as a feedstock (e.g., in electrochemical conversion or as a reduction agent) or fuel; when used as a fuel, burning it emits only water vapour and not CO_2[1]. However, depending on how it is produced, hydrogen can have vastly different embedded emissions. These production processes are often referred to in shorthand using colours, as listed in Table 1. GH_2 has the lowest emissions of all colours but is currently uncommon due to cost. For instance, at the end of 2021, only 1% of global hydrogen production was GH_2 - the remainder was non-green electrolysis (3%), production with natural gas (i.e., grey/blue, 47%), production with coal (i.e., black, 27%), or as an oil by-product (22%)[2,3].

TABLE 1: **Hydrogen colours and definitions**[4,5,6]

Hydrogen colour	Production process
Green	Electrolysis using renewable energy
Blue	Steam reforming using natural gas *with* carbon capture
Grey	Steam reforming using natural gas *without* carbon capture
Black	Gasification using black coal (bituminous)
Brown	Gasification using brown coal (lignite)
Pink	Electrolysis using nuclear energy (sometimes called purple/red)
Turquoise	Methane pyrolysis with natural gas feedstock
Yellow	Electrolysis using solar power only
White	Natural underground hydrogen deposits created through fracking

Amongst these options, SHIELD focuses on GH_2 for five reasons. First, it has the lowest emissions of all types, which supports Ukraine's decarbonisation targets[7] and its goal of EU accession. Second, it relies on renewable generation, the decentralised nature of which can enhance Ukraine's overall energy security[8]. Third, demand for GH_2 is expected to rise over the coming decades[9] as countries implement regulation to decarbonise their heavy industries. Fourth, the cost of GH_2 production is simultaneously expected to fall[10], bringing it far closer in cost to alternatives. Fifth, the National Climate and Energy Policy of Ukraine foresees electrolysis to be "the main method of hydrogen production".

1.2 GLOBAL OVERVIEW

The anticipated use-cases for GH_2 globally cross industry, transport, power, and residential sectors include applications of hydrogen as a fuel or as a feedstock[11]. Potential applications are taxonomized in Table 2. To derive this categorization, a comprehensive collection of the possible use cases was conducted based on industry literature[12,13,14,15] and then clustered according to sector and application type (i.e., fuel vs. feedstock). Notably, this taxonomy covers all possible uses listed in section 1.1 of Ukraine's draft hydrogen strategy.

TABLE 2: Taxonomy of potential GH2 use-cases by sector and type.

Sector	Type	Application
Industry	Feedstock	Steel (H2-DRI Process)
		Ammonia/Fertilizer
		Low-carbon e-fuels and petrochemicals
		Refining processes
		Others (Chemicals, glass, electronics, pharmaceuticals, food processing)
	Fuel	Low-temp heat (<150C): Space heating, food processing
		Medium-temp heat (150C-400C): Drying and chemical reactors
		High-temp heat (400C-1000+C): Metal, glass, cement, paper, ceramics.
Transport	Fuel	Cars
		Trucks
		Public transport
		Rail transport
		Airplanes
		Ships and maritime sector
Power	Fuel	Energy shifting and storage (seasonal & long-term)
		Grid balancing and ancillary services
		Combined heat and power systems
		Off-grid and emergency power generation
Residential	Fuel	Residential power and heat supply
		Heat networks

Hydrogen is used in many applications today; in the United States, for instance, petroleum refining, metal treatment, fertilizer production, and food processing represent the bulk of hydrogen use[16]. As decarbonisation continues, however, the importance and demand-level for these use-cases may shift and evolve. Globally, ~75 Mt of pure hydrogen are produced per year, and another 20 Mt are produced in gas mixes[17]. By 2050, the projected demand for GH_2 is expected to increase to 100-500Mt/year[18] or 125-585Mt/year [19].

1.3 UKRAINIAN CONTEXT

When considering Ukraine's potential adoption and use of GH_2, it is necessary to place this in the context of conflict and recovery. The KSE Institute estimates that Ukraine has suffered up to $170 billion in direct damage to buildings and infrastructure from the invasion, with the most affected sectors being housing (35%), infrastructure (23%), commerce and industry (9%), energy (9%), and agriculture (6%)[20,21]. It is estimated that Russia's invasion has made 3.5 million Ukrainians homeless and put the homes of 2.4 million more in need of repair[22].

Reconstruction will require significant material input. If produced inside Ukraine, this could help the economy and workforce recover from conflict. Analysis by USAID indicates that assuming regular access to electricity, Ukrainian manufacturers could provide 90% of the construction materials needed for reconstruction as of November 2022, which the government has estimated at $62.8 billion[23]. It estimates this could help preserve 100,000 jobs and facilitate $5.6 billion in wages and $4.4 billion in tax revenue.

Importantly, several of the materials that are critical to reconstruction – including steel and cement – are important targets for decarbonisation. This will be critical to support Ukraine's aspirations to accede to the European Union (EU). To fulfil Chapter 27 of the EU acquis, Ukraine will need to comply with 200 major legal environmental acts[24]. As such, decarbonisation is relevant to its global position and security within the EU system.

It is important to note, however, that the conflict currently hinders Ukraine's ability to export materials and goods. Russia's navy has blocked main export routes through the Black Sea[25], albeit with humanitarian exceptions (e.g., for grain export)[26]. Goods which were once shipped by sea may be routed to the EU by train, but due to different train track sizes in Ukraine and neighbouring countries, train transport incurs additional expense (i.e., to unload, store, and reload goods)[27].

1.4 BACKGROUND ON HYDROGEN CONVERSION AND STORAGE

Across all use-cases, GH_2 presents technical complexities in storage and transportation due to its unique properties. Although hydrogen has the highest gravimetric energy density among common fuels, its volumetric energy density is significantly lower, requiring a large storage volume at ambient pressure. To make hydrogen more feasible and economical for storage and transport, various "conversion" techniques have been developed, each suited to different applications and with distinct benefits and limitations[28]. The conversion and storage complexities for the most prevalent hydrogen carriers are detailed below to contextualize use-case discussions. They include compressed gas, liquified hydrogen, Liquid Organic Hydrogen Carriers, ammonia, and methanol.

- One of the most common forms of hydrogen storage is as **compressed gas**. Hydrogen gas is typically stored in high-pressure cylinders, where it is compressed to 200-300 bar for commercial use. For applications like fuel cell vehicles, where maximizing volumetric energy density is critical, hydrogen can be compressed up to 700 bar, reducing tank size requirements and improving energy density[29]. However, compressing hydrogen is energy-intensive: about 13-14% of hydrogen's stored energy is needed to reach 700 bar[30]. As a result, the efficiency of gaseous hydrogen storage depends on the application's specific energy requirements and cost considerations.
- **Liquified hydrogen** provides a higher volumetric energy density compared to gaseous hydrogen, with a density of around 71 kg/m^3, approximately 800 times that of hydrogen gas at ambient pressure. This makes it space-efficient, which is beneficial for applications where volume constraints are critical, such as transport. However, hydrogen's liquefaction process is energy-intensive, as it must be cooled to -252.8°C. This cryogenic process consumes around 28-46% of the total stored energy and incurs further energy losses due to boil-off during storage, with daily losses potentially reaching 3%[31]. While liquified hydrogen offers substantial storage density, the high energy costs and infrastructure required for cryogenic storage make it suitable primarily for large-scale, high-value applications.

- **Liquid Organic Hydrogen Carriers** (LOHCs) offer another method for hydrogen storage. LOHC systems store hydrogen by binding it chemically to a liquid carrier, such as N-ethyl carbazole, a stable and relatively high-density aromatic hydrocarbon. The hydrogen-laden carrier liquid (LOHC+) can be stored and transported safely at ambient temperature and pressure, simplifying handling and reducing infrastructure requirements. When needed, hydrogen can be released through dehydrogenation, a process requiring temperatures above 200°C, which may be catalyzed by materials like platinum. LOHCs offer an energy density of approximately 1.75 kWh/kg when 90% loaded, providing a stable and low-loss storage solution for hydrogen transport[32,33]. However, the loading and unloading processes require significant energy, making LOHCs most advantageous for applications where safe, long-term hydrogen storage is prioritized over rapid deployment.
- **Ammonia** (NH_3) is another promising hydrogen carrier, created by combining hydrogen and nitrogen using the Haber-Bosch process. This process is widely used in agriculture and other industries, meaning ammonia benefits from an established transport, storage, and handling infrastructure. Ammonia's energy density is relatively high, with hydrogen content exceeding that of liquified hydrogen (approximately 105 kg/m^3 compared to 71 kg/m^3). Stored at ambient temperature with moderate pressure (boiling point -33.36 °C, liquid at ~8.6 bar at 20°C), ammonia provides a practical and cost-effective solution for hydrogen distribution. However, ammonia is toxic, which requires stringent safety protocols to prevent leaks, and its energy conversion back to pure hydrogen (via "cracking") is energy-intensive, often involving an additional purification step[34,35].
- **Methanol** (CH_3OH) is another hydrogen-based energy vector, produced by combining hydrogen with CO_2 through a hydrogenation process. Methanol is attractive due to its ease of storage and transport at standard conditions, making it compatible with existing infrastructure. Methanol stores around 4.4 kWh/L, about 50% of gasoline's energy density, but can be used in fuel cells, gas turbines, and combustion engines. Additionally, methanol can serve as a feedstock in petrochemical production or be converted to dimethyl ether (DME), which can replace liquified petroleum gas (LPG) in heating and cooking applications[36,37]. Despite these advantages, methanol production is a complex process involving multiple steps—from hydrogen production to CO_2 capture, storage, and final conversion—each of which adds to the energy and capital costs, potentially impacting profitability[38].

While the above hydrogen carriers are the most popular, there are various other hydrogen-based fuel types (e.g., those listed in Table 3). For each use-case, we focus on whichever hydrogen carrier or hydrogen-based fuel is likely to be most viable given its technical needs.

1.5 ANALYSIS APPROACH

In the following sections, GH_2 use-cases covering fuel and feedstock applications in the industrial, transport, power, and residential sectors are systematically studied through desktop review of literature and policy. Each case is defined in terms of its technical process, and then examined for (1) global realism, and (2) relevance to Ukraine. Each is given a rating on a five-point scale from unlikely to likely, visualised from red to green. These ratings are averaged to give a net importance of inclusion of the use-case in future study (i.e., SHIELD project scenarios).

2 Use-cases by sector

The following sub-sections break down details for each use case listed in Table 2. Industry, transport, power, and residential use-cases are each addressed in turn.

2.1 INDUSTRY

Industrial use-cases for GH_2 include creating heat; producing low-carbon fuels; refining petrochemicals; direct reduction of iron for steelmaking; and use as a feedstock in other industries.

2.1.1 Direct reduction of iron in steelmaking

How it works

Steel can be produced using blast furnaces (BF) or electric arc furnaces (EAFs)[39] (see Box 2). Whereas blast furnaces use coke and limestone to process iron ore, EAFs use electricity to process directly reduced iron (DRI).

Hydrogen can be used in EAF steel production to produce the DRI required as an input. Instead of using natural gas or coal/coke for reduction, hydrogen can be used, bringing significant emissions reductions[40],[41]. If this is combined with EAFs powered by renewable electricity, the entire steel-making process can be reduced to near-zero emissions. Evidence also suggests that steel produced using hydrogen is unlikely to be embrittled[42].

It is important to note that DRI requires a higher grade of iron ore than BF steel production. The grade required is typically at least 67%[43,44].

Box 2: Two ways to make steel.

Steel can be made using a blast furnace or an electric arc furnace.

Blast furnace

Iron ore, coke, and limestone are loaded into the blast furnace, and hot air is blown in. This reacts with the coke to create CO, which acts as a reducing agent to strip oxygen from the iron ore. This reaction takes place at extremely high temperatures (~2,000°C). Molten pig iron (a high-carbon iron) forms at the bottom of the furnace. The limestone removes impurities by forming slag, which floats on top and is removed. The pig iron is then transferred to a basic oxygen furnace, where oxygen is blown into it to reduce the carbon content, producing liquid steel.

Electric arc furnace

Electric arc furnaces can be fed by DRI and/or scrap steel. To produce DRI, iron ore pellets or lumps are exposed to a reducing gas (typically natural gas) in a reactor at temperatures ~800-1,100°C, below the melting point of iron. This strips oxygen from the ore, leaving behind the sponge-like DRI.

Then, DRI and/or scrap steel are loaded into the electric arc furnace. Powerful electric arcs are generated between large electrodes and the metal, reaching temperatures above 1,500°C to melt it. Additional alloying elements can be added to achieve the desired composition. The molten steel is then tapped from the furnace.

Global perceptions and realism

Hydrogen-based steel production, particularly through the Direct Reduced Iron (DRI) and Electric Arc Furnace (EAF) route, is increasingly recognized as a viable pathway for low-emission steel. Unlike the traditional Blast Furnace-Basic Oxygen Furnace (BF-BOF) approach, which relies heavily on coke and emits significant CO_2, the DRI-EAF method offers near-zero emissions when powered by renewable energy. Companies such as SSAB, ArcelorMittal, and Salzgitter are pioneering the shift with projects like Stegra (formerly H2 Green Steel), GrInHy2.0, and HYBRIT, which aim to prove the viability of GH_2 in steel production. However, this technology is still at a pilot stage, and its widespread application is constrained by the availability of low-cost hydrogen and renewable electricity[45,46].

While promising, hydrogen-based steel production currently comes with a significant "green premium" due to higher costs for green hydrogen compared to fossil fuels. Estimates place this premium between 20% and over 100%, translating to an additional $100-$300 per ton, depending on the region and scale of production[47,48,49,50,51]. The automotive sector has emerged as a key driver for green steel, with companies like BMW and Volvo committing to its use as part of their supply chain decarbonization strategies[52,53]. This demand signals optimism that the premium could be absorbed in certain industries willing to pay for low-emission materials. Additionally, regulatory measures such as the EU's Carbon Border Adjustment Mechanism (CBAM) are expected to further incentivize low-carbon steel adoption, thus supporting market conditions for hydrogen-based DRI[54].

In parallel, hydrogen injection into existing BF-BOF systems is being explored as a partial decarbonization measure. For example, Tata Steel is investing in the injection of hydrogen into blast furnace processes to reduce emissions of existing plants[55]. Full transition to GH_2-based DRI-EAF is still favoured for deeper decarbonization, as it can achieve near-zero emissions when renewable-powered[56].

Looking forward, the hydrogen DRI route, including both integrated production and transportable Hot Briquetted Iron (HBI), is widely seen as one of the most realistic near-term decarbonization options for the steel industry. As this technology matures, industry projections indicate that the green premium associated with hydrogen steel will likely decrease due to enhanced electrolyser efficiency and the scaling up of renewable power, leading to lower hydrogen production costs[57].

This cost decline makes the H_2-DRI and HBI pathways particularly attractive, as they allow the steel sector to decouple from high-carbon sources and capitalize on the willingness of downstream industries—especially automotive and construction—to absorb the green premium. These sectors have strong sustainability commitments, creating demand for low-carbon materials and positioning hydrogen-based steel as a viable, scalable solution for immediate and future emissions reductions.

Ukrainian context and relevance

Steel has historically been an important industry in Ukraine. Before 2014, its nominal steel production capacity was 42Mt[58]. This had dropped to 27Mt of capacity by 2021[59], of which 21.4Mt was crude steel[60].

Steel production has dropped dramatically throughout the war. In 2022, 6.3Mt was produced, representing a 71% year-on-year reduction[61]. Production remained roughly stable in 2023 at 6.2Mt from six plants, and 7Mt of total production is expected in 2024[62]. Nominal production capacity has now dropped to 17.8Mt[63]. Steel plants report operating at their maximum possible capacity due to electricity, workforce, and supply chain constraints[64]. Post-war reconstruction in Ukraine will require vast amounts of steel[65]., and it has been estimated that a full recovery of Ukraine's steel sector will take $62b over 20 years[66.]

The locations of steel plants in Ukraine's southern and eastern industrial heartland make them vulnerable to shelling[67]. For instance, ArcelorMittal Kryvyi Rih is around 80km from the front lines - Russian missiles can cover this distance in two minutes. Metinvest, Ukraine's largest steel producer, lost two huge plants in Mariupol in 2022, and around 65% of its business[68].

Ukraine's steel industry has historically been among the world's dirtiest, accounting for 15% of its total pre-war CO_2 emissions[69]. It will be difficult to decarbonise due to the high prevalence of blast furnaces. Most current Ukrainian steel production is BF based, with April 2024 reports showing five BFs and two EAFs operational[70]. Furthermore, Ukraine is also using outdated open-hearth furnaces at the Zapirizhzhya steel plant. The owner, Metinvest, was going to replace it with BF-BOF, but the plans were delayed multiple times. The use of outdated and higher-emitting steel production methods in Ukraine affects both its EU accession process, and its export prospects within the EU as CBAM comes into full force[71].

Nevertheless, the National Energy and Climate policy projects a 51% reduction in energy intensity in the metallurgy sector by 2050 due to "gas consumption decreasing due to hydrogen substitution"[72]. It outlines expenditures on DRI production with hydrogen presumably for its existing and planned EAF steel plants. It is important to caveat, however, that Ukraine's iron ore reserves at the quality required for DRI are limited[73], which may limit EAF uptake.

2.1.2 Ammonia and fertilizer

How it works

Ammonia is a critical feedstock in the production of mineral fertilizers and requires hydrogen as a feedstock for its own production. By producing ammonia via a green process (i.e., renewable electricity, hydrogen electrolysis, and Haber-Bosch) instead of by using fossil fuels, the emissions of fertilizer production can be cut significantly[74]. Meanwhile, the end-product fertilizer is the same, making this a drop-in switch.

Global perceptions and realism

Fertiliser producers are reticent to pay more to go green[75]. Most fertiliser production operates "on thin profit margins"[76], which make any reduction in profits difficult to swallow. The firms producing green ammonia and fertilizers today are generally small in scale[77]. Nevertheless, there is demand for green fertilisers; for instance, the Indian government increased their purchase of green-hydrogen-based ammonia from 550,000 to 750,000 tonnes in 2024, based on increased demand[78]. Analysis indicates that by using green fertilisers, the overall emissions of food productions can be reduced significantly while adding a "relatively low share" to full food production cost[79].

Ukrainian context and relevance

Before the war, agriculture contributed 10% to Ukraine's GDP, employed 14% of the labour force, and accounted for 41% of total exports. However, following the start of the full-scale invasion, its grain and oilseed production fell 30% year-on-year to 73Mt in 2022[80].

While Ukraine is endowed with highly fertile land, it still requires ammonia, phosphorus, and potassium fertilizers to restore depleted soil[81]. However, fertilizer application decreased 27.7% year-on-year in 2022 to 20.8Mt, and most farmers could only access half of the fertilizer they need for the 2024 harvest season[82].

Pre-war, Ukraine produced enough nitrogenous fertilizer to meet over 70% of domestic demand; by 2022, domestic production had fallen by 78.3%[83]. Meanwhile, whereas it previously imported much of its potash[84], urea[85], and complex fertilizers[86] from Belarus, following the full-scale invasion, it had to rely on other trade partners instead.

The invasion's impacts on fertilizer access have impacts beyond Ukraine as well. Russia and Belarus are among world's largest suppliers of chemical fertilizers[87]. There have been sanctions exemptions to allow them to continue to supply these for food security reasons globally, but their exports have still been reduced by other mechanisms intended to isolate their economies[88]. This led to a jump in fertilizer prices globally following the invasion[89].

2.1.3 Low-carbon e-fuels and petrochemicals

How it works

Hydrogen can be used to produce low-carbon e-fuels via Fischer-Tropsch (FT) synthesis, hydrogenation, power-to-liquid (PtL) synthesis, or methanol-to-gasoline (MTG) synthesis. These fuel types are listed in Table 3. Both hydrogen and e-fuels can be used in transport or in power systems. Some of these compounds (e.g., ammonia, methanol) can also be used in turn as feedstocks to other chemical processes.

Alongside hydrogen, production of most of these fuels requires CO_2. This CO_2 can come from biogenic processes and carbon capture. However, this can lead to potentially unsustainable competition for finite biomass and land resources. Alternatively, direct air carbon capture (DACC) could be explored to capture CO_2 straight from the atmosphere. However, this is far more expensive than capture from a concentrated source.

TABLE 3: **Hydrogen-based e-fuels and their applications**

Fuel	Production	Applications
E-Methane (Synthetic natural gas)	Reacting H_2 with CO_2	• Injection into natural gas grids for residential and industrial heating. • Compressed natural gas vehicles • LNG ships. • Gas turbines for electricity
E-Diesel	FT synthesis	• Diesel engines vehicles • Diesel-powered ships (e.g., cargo, ferries) • Construction, mining, agriculture machinery.
E-Methanol	Hydrogenation of CO_2	• Fuel for methanol-powered ships. • Feedstock for chemicals and plastics. • Methanol fuel cells for smaller-scale power generation or transportation. • Can be used in specially designed vehicles or as a fuel additive.
E-Gasoline	FT or MTG synthesis	• Drop-in fuel for existing gasoline-powered cars and motorcycles.
E-Kerosene (Synthetic jet fuel)	PtL including FT synthesis	• Drop-in fuel for conventional aircraft

H_2	Green, Blue, Grey, etc.	• Fuel cell electric vehicles • Gas turbines or fuel cells for electricity • Use in steel production and refining, or in H_2-based furnaces. • Hydrocracking and hydrotreating. • Building-block for all e-fuels listed.
NH_3	Haber-Bosch process	• Ammonia-powered ships. • Gas turbines or fuel cells for electricity • Store and transport renewable energy • Carrier for H_2, "crack" at the destination • Traditional use in the fertilizer industry

Global perceptions and realism

As fossil fuel reserves become depleted, new sources of these fuels will be needed[90]. However, the incumbent fuels that each e-fuel aims to displace are still currently cheaper[91]. In specific markets and sectors, there are incentives to take up different e-fuels (e.g., the ReFuelEU aviation and FuelEU maritime regulations).

Ukrainian context and relevance

As Ukraine continues to pursue EU accession, it will become subject to EU regulations and targets on the use of green fuels. The production and use of these fuels are therefore likely to become politically important to Ukraine. It is also important to note that the conflict's overall increase in conventional fuel prices may drive increased investment and innovation in e-fuel alternatives.

2.1.4 Refining processes

How it works

Hydrogen is used in the refining industry to purify fuels and increase yield through processes like hydrocracking, catalytic reforming, and hydrotreating[92]. Hydrocracking uses hydrogen under high pressure and temperature in the presence of a catalyst to break down heavy, long-chain hydrocarbons into lighter, more valuable products (e.g., gasoline, jet fuel, diesel). In catalytic reforming, low-octane hydrocarbons are transformed into higher-octane compounds to improve gasoline quality. Hydrogen is both a product and sometimes a reactant in this process. Reforming creates aromatic hydrocarbons and hydrogen as by-products; the hydrogen can be recycled within the refinery for other processes. In hydrotreating, hydrogen is used to remove contaminants like sulphur (i.e., desulphurisation), N_2, and metals from crude oil fractions. The oil fractions are combined with hydrogen in the presence of a catalyst, resulting in cleaner-burning fuels and reduced pollutants that could damage refining equipment and affect fuel performance.

Global perceptions and realism

Over 65% of the hydrogen needed for traditional refining is produced as a by-product from catalytic reformers and ethylene crackers[93]. This hydrogen is therefore unlikely to be replaced with green hydrogen in traditional refineries. The remaining proportion of hydrogen required could be green, although viability will depend on cost as compared to grey and blue alternatives. Beyond traditional refining, however, there is discussion around the potential use of GH2 in biorefineries[94], and some projects have emerged on this (e.g., by Air Liquide[95]).

Ukrainian context and relevance

While Ukraine has a refining capacity four times larger than its market (i.e., 50.4Mt per year in seven refineries), this capacity is largely unused, as the infrastructure is aging and damaged. Ukraine only had one operational refinery in 2017 (Kremenchug) alongside one gas processing plant (Shebelinsky)[96]. Both have been hit by Russian missiles multiple times within the first months of the invasion, casting doubt on whether they will resume operation in the future.

2.1.5 Other feedstocks

How it works

Hydrogen is used as a feedstock in numerous other industries, including electronics, pharmaceuticals, food processing, and plastic production. Several examples follow below to illustrate.

In food processing, hydrogen is used in the process of hydrogenation. This involves adding hydrogen to unsaturated fats and oils to convert them into saturated fats. Hydrogenation is commonly used to produce margarine, shortening, and various cooking oils. By hydrogenating these oils, manufacturers can improve the texture, stability, and shelf life of food products[97]. However, the trans fats formed during partial hydrogenation are detrimental to health, contributing to both clogged arteries and heart attacks[98].

Hydrogen can also be utilized in food packaging to create an inert atmosphere that helps preserve food quality and extend shelf life[99,100]. When used in modified atmosphere packaging, hydrogen can be combined with other gases (such as N_2 and CO_2) to displace oxygen inside the packaging. This reduces the growth of aerobic bacteria and slows down oxidative processes, thus helping to maintain the freshness and quality of perishable food products.

For plastic production, while the production of plastics typically requires fossil fuels as a feedstock, the usage of hydrogen-based e-fuels (e.g., e-methanol) is being investigated as an option for decarbonisation.

Global perceptions and realism

While these industries will continue to require hydrogen as a feedstock, they are not frequently discussed as key elements to the uptake of GH_2. They will also come with the same cost issues as other industries which may limit GH_2 uptake. For instance, plastics produced using e-fuels can currently be up to four times more expensive than conventional options[101].

Ukrainian context and relevance

As one of the world's largest producers of wheat, barley, and corn, food processing is an important part of Ukraine's economy. Specifically, the crushing of oilseeds and primary processing of agricultural commodities plays a significant role[102]. The products are diverse, however, including meat, fish, oils, fats, dairy, flours, and breads, among others[103]. Both the hydrogenation and packaging applications may therefore be relevant to Ukraine's food industry as the sector evolves.

2.1.6 Low and medium heat

How it works

Hydrogen could be used to produce heat for low (i.e., <150°C) and medium (i.e., 150-400° C) heat for industrial applications. These include space heating, papermaking, food processing, drying, and chemical reactors. For instance, in papermaking, wood chips must be heated alongside chemicals in a digester to ~150-170°C to produce wood-pulp; later, heated cylinders at ~85-100°C must be used to evaporate excess moisture. Hydrogen could, in theory, be used as a fuel to generate the required heat in these processes.

Global perceptions and realism

While these uses of hydrogen are theoretically possible, they are seen as unlikely to materialise. Electricity and heat pumps can provide decarbonised heat more efficiently than hydrogen[104] due to the thermodynamics of the respective processes. Thus, hydrogen is more likely to find application in high-heat applications, where electricity-based heating is difficult to achieve.

Ukrainian context and relevance

As this use-case is unlikely to materialise anywhere globally, it is also unlikely to materialise in Ukraine. Ukraine's industrial sectors and reconstruction primarily require materials produced in high-heat processes, including glass, cement, and steel.

2.1.7 High heat

How it works

Hydrogen can be used to produce high heat (400-1,000°C+) for metal, glass, cement, and ceramics production. In glassmaking, hydrogen could be burned to produce the extremely high temperatures (i.e., up to 1,700° C [105,106]) needed to melt raw materials (i.e., silica sand, soda ash, limestone) into molten glass. Hydrogen can similarly be used to heat raw materials needed to form clinker for cement production (i.e., limestone and clay[107]). Ceramics production requires high-heat kiln-firing in two stages: the biscuit/low-fire stage (~600-900°C), and the high-fire stage (~1,200-1,450°C) for full vitrification, which could similarly be accomplished with hydrogen.

Currently, these industries use fossil-fuels for heat. Natural gas is typically used to generate heat for glassmaking[108], while coal, petcoke, or natural gas is used for cement and ceramics. GH_2 can be burned in place of fossil fuels to reduce emissions from these processes.

Global perceptions and realism

While these uses of hydrogen are being piloted and tested, they are not yet deployed commercially at scale and may require existing equipment to be adapted. For instance, the use of 100% hydrogen has been successful for glassmaking in laboratory conditions[109]. However, partial injection is more feasible than 100% replacement when using existing equipment. Similarly, cement kilns may need to be adapted to handle the combustion characteristics of hydrogen, particularly if 100% hydrogen is targeted[110].

Furthermore, burning hydrogen will not fully decarbonise some of these industries. The chemical processes involved sometimes inherently release CO_2, making other decarbonisation measures like carbon capture and storage (CCS) necessary. This is particularly salient with regards to cement, as described in Box 1.

Box 1: Decarbonising cement: Hydrogen, Bioenergy, or CCS?

In cement production, while hydrogen can eliminate emissions from fuel combustion, it does not address emissions from the calcination process (i.e., the chemical reaction in which limestone decomposes into lime and CO_2)[111], which accounts for 65% of the total CO_2 emitted[112]. Thus, two parallel decarbonization strategies are widely discussed in the literature: (1) decarbonizing the fuel source by using alternative heating vectors, (e.g., biofuels, biomass, hydrogen, electricity), and (2) capturing process-related emission through carbon capture and storage (CCS)[113,114].

To achieve net zero cement, CCS will be necessary, as global demands are projected to stay high and the emissions from this chemical reaction cannot be avoided another way[115]. Thus, CCS is often the focus for decarbonisation.

CCS may be used with or without integrating hydrogen or other low-emissions fuels[116]. However, to quickly reduce the overall emissions of existing cement plants, decrease the dependency on fossil fuels and potentially even create net negative emissions, hydrogen or other low-emission fuels are still relevant[117,118].

The IEA projects that, by 2035, energy for cement production will come from bioenergy (~25%), with or without carbon capture, utilization, and storage (CCUS), alongside fossil fuels and non-renewable waste with CCUS (22%), a small amount of hydrogen (3%), and no electricity (0%). By 2050, these figures are anticipated to rise to 8% for bioenergy, 31% for fossil fuels with CCUS, 9% for hydrogen, and 8% for electricity.

Therefore, to decarbonize cement production, CCS alongside bioenergy utilization looks most promising in the near term. While other low-emission heat technologies are expected to play a more prominent role by 2050, GH2's direct use in cement may be limited in the near term due to its high costs as a combustion fuel. This bolsters the case for alternative decarbonization strategies that align more closely with industry and regulatory goals in the short- to medium-term[119].

Ukrainian context and relevance

Glass is an important material for reconstruction. Windows can break due to distant explosions, and people are reticent to move back into buildings with smashed windows. Despite having ample raw materials for glass production, Ukraine has no ongoing production and is facing major glass shortages[120]. Some non-profits (e.g., Insulate Ukraine[121]) are working to replace glass windows with more durable alternatives to protect vulnerable households from cold exposure.

Cement will also be needed to rebuild homes and infrastructure. Current cement production capacity is much greater than its demand (i.e., 2.7x the size of demand in 2023, compared to 1.4x in 2021[122]). During reconstruction, however, it is projected that cement demand will surpass current production capacity. Analysis from USAID indicates that Ukraine will need 15-16Mt of cement per year over three years for reconstruction, which is ~2-3Mt more per year than it can currently produce[123]. The Ukrecement chairman dismisses these findings, saying that less cement will be needed[124]. Ukraine currently has either 9[125] or 10[126] cement plants, one of which is in occupied land, and four of which are within 300km of frontlines. In 2021, Ukraine consumed 10.6 Mt of cement. This decreased to 4.6Mt in 2022 and recovered slightly to 5.4Mt in 2023[127].

It is important to note that before the war, the cement market in Ukraine was highly concentrated. Ukrecement members held 95% of the domestic market, and four companies effectively controlled the sector[128]. This led to market slippage[129] and increasing prices (i.e., prices rose 35-50% over three years until 2021[130],[131]). The only competitors to these players were Turkish exporters from across the Black Sea[132]. A recent major deal between two cement producers, CRH and Dyckerhoff, intensifies this market concentration. The $108 million deal, in which CRH would essentially acquire Dyckerhoff's production in Ukraine, reduces the number of major cement players in the country from four to three[133].

2.2 TRANSPORT

GH_2 could be used in various transport modalities. These include cars, trucking, public transit, aviation, and shipping. Different modalities have different factors and constraints, as discussed in the sub-sections below.

2.2.1 Cars, Trucks, and Public Transit

How it works

Fuel cells (see Box 3) enable hydrogen to react with O_2 to produce electricity, water, and a small amount of heat[134]. Hydrogen powered vehicles have hydrogen tanks and fuel cells. As opposed to battery electric vehicles (BEVs) which store energy in charged batteries, these fuel-cell electric vehicles (FCEVs) store energy as hydrogen which is used in the fuel cell to generate electricity and power the motor[135]. FCEVs produce no CO_2 emissions, are more efficient, quieter, and require less frequent refuelling than vehicles with internal combustion engines.

Box 3: What are fuel cells?

Fuel cells generate electricity through an electrochemical reaction rather than combustion. This process combines H2 with O2 to produce electricity, water, and heat, without emitting pollutants or carbon dioxide. The main types of fuel cells are[136]:

- Proton Exchange Membrane (PEM): Often used for smaller-scale applications like backup power or transport but also used in some larger power systems.
- Solid Oxide Fuel Cells (SOFC): Better suited for stationary power generation, especially at larger scales.
- Direct-Methanol Fuel Cells (DMFC): Similar to PEM but without need of fuel reforming. They are of interest for powering portable electronic devices.
- Alkaline Fuel Cells: Cheapest to manufacture. Used originally in space missions but now applied more broadly for portable power.
- Phosphoric Acid Fuel Cells: Used in medium-to-large stationary applications.
- Molten Carbonate Fuel Cells: Used in stationary large generation[137].

Global perceptions and realism

With regards to cars, BEVs dominate over FCEVs in the global market due to lower costs, the difficulties in transporting hydrogen, and the pre-existing electric network which enables BEV uptake[138]. For instance, in the United States, there are only 17,000 FCEVs on the roads (notably all in California, the only state with a fuelling network) compared to millions of BEVs[139]. Indeed, sales of FCEVs are so low that it is difficult to project their future role in the market[140].

The future of FCEVs in trucking shows some promise in the medium term. Projections show that while BEVs are more likely to be used for pre-2030 trucking decarbonisation, cost parity between

FCEVs and diesel vehicles will follow closer to 2040[141], after which FCEV trucking might experience broader uptake.

Ukrainian context and relevance

The draft Hydrogen Strategy of Ukraine indicates that a detailed plan for the use of hydrogen in transport will be produced by 2026. It then stipulates that a network of hydrogen filling stations for road transport will be implemented by 2035[142]. Ukraine's transport law lays out a gradual transition to low-carbon public transit in urban areas, allowing for this to be fulfilled by "electric buses and/or buses running exclusively on methane (compressed or liquefied) or biogas, and/or buses with a hydrogen fuel cell"[143]. This grants greater flexibility than the previous target on filling stations.

Ukraine's transport sector is critical to reconstruction. Transport infrastructure critical to the supply chains needed to ship important reconstruction materials, and it has been heavily damaged. The EIB has invested 60m EUR into transport infrastructure reconstruction alongside new buses and public transport options[144], while UNOPS and the World Bank have supplied $15.4m in new modular bridges[145]. However, the focus of these reconstruction efforts is on ensuring continuous passage of people and goods, not on the decarbonisation of the transport sector in the near-term.

2.2.2 Rail transport

How it works

Hydrogen can similarly be used to power rail transport via fuel cells. The hydrogen is stored in high-pressure tanks aboard the train and can be refuelled relatively quickly. These trains can offer an emissions-free alternative to diesel locomotives, making them particularly valuable on non-electrified rail lines where overhead electric cables are costly or impractical to install.

Global perceptions and realism

While electric trains are more technologically mature than hydrogen trains, the infrastructure required to support them (e.g., wires, substations, battery swap stations) can be expensive, particularly in areas where construction is challenging (e.g., mountainous regions)[146]. However, there are still concerns about hydrogen safety and storage on-board. Nevertheless, depending on the technical parameters of specific routes, it seems that decarbonisation of rail transport may involve electric trains, hydrogen trains, or some combination of the two[147].

There are a small number of hydrogen trains already in commercial operation. The first hydrogen powered train was implemented in Germany in 2018[148]. Since then, further hydrogen train pilot projects and implementations have sprung up countries such as Canada[149], Korea[150], Italy[151], and China[152]. France is set to start use of its first hydrogen regional trains in 2025[153].

Ukrainian context and relevance

Ukraine has Europe's third largest rail network with a total track length of 24,000 km[154]. As air travel is impossible in the country right now, the railway, which has always been a source of national pride, is playing a critical role in the transport of refugees, visitors, and political officials throughout the country. For instance, the railway was used to evacuate 61,000 people from front-line settlements in 2023[155]. There are also specially equipped medical trains operated by MSF[156].

The gauge of Ukraine's current train tracks is different than neighbouring European countries. This makes it difficult to export goods to Europe by train without incurring additional expenses (e.g., to unload and reload at the border). Construction of tracks with a matching gauge is underway[157].

2.2.3 Aviation

How it works

The aviation industry is looking to decarbonize through development of planes which use sustainable aviation fuels (SAF). These planes are expected to either blend 10-50% SAF with conventional fuels[158], or to use modified gas turbine engines and/or fuel cells (i.e., for use of pure hydrogen)[159].

Using hydrogen directly in aviation presents technical challenges. First, the use of hydrogen as a fuel would add more weight to planes than conventional alternatives. This would dramatically cut flight range, likely limiting the use of hydrogen to short-haul flights[160]. Second, airports currently lack infrastructure for hydrogen supply. Major infrastructure investment would therefore be required to bring hydrogen planes into common commercial use.

Global perceptions and realism

In the near term, SAFs derived from bioenergy are expected to play a significant role, potentially accounting for up to 10% of aviation energy use by 2030 and up to 33% by 2050[161]. However, the scalability of biofuels is limited by feedstock availability and land-use considerations. Consequently, hydrogen-based synthetic fuels, produced using renewable energy, are gaining attention as a more sustainable long-term solution.

However, they are not the only viable SAF contenders. There is also, for instance, the possibility to use lignocellulosic biomass from residues for SAF production[162],[163]. This could be lower-cost than e-fuels while still avoiding resource and land constraints. The balance between different SAF production types is ultimately yet to be determined as the sector evolves.

Nevertheless, hydrogen and its derivatives are increasingly recognized as pivotal in decarbonizing aviation. The IEA projects that by 2050, hydrogen-based fuels could constitute approximately 37% of the aviation industry's energy consumption. However, hydrogen's adoption is still in its early stages, facing challenges related to fuel storage, infrastructure, and the redesign of aircraft to accommodate its unique properties. Thus, hydrogen-based fuels are forecasted to only meet ~1% of the final energy consumption by 2030[164].

Major commercial players are accelerating hydrogen innovation for aviation. Airbus, for instance, aims to introduce the first hydrogen-powered commercial aircraft by 2035[165]. Other companies are advancing hydrogen technologies, particularly for smaller aircraft. ZeroAvia continues to test its 600 kW fuel cell propulsion system, which first flew in 2023, targeting commercial flights with up to 19 passengers by 2025[166]. The company is also developing a 2-5 MW system for aircraft carrying up to 80 passengers, anticipated by 2027. Additionally, H2FLY achieved the first piloted flight using liquefied hydrogen in September 2023, doubling the range compared to gaseous hydrogen[167]. Several other advancements are underway. At the close of 2023, Airbus conducted ground tests on a 1.2 MW fuel cell system, with in-flight tests scheduled on an A380 by 2026. In November 2023, Airbus also tested a small hydrogen engine in a glider to study hydrogen contrails during a 30-minute flight. Japan's NEDO announced a significant grant in April 2024 for IHI to develop a 4 MW fuel cell using liquefied hydrogen, targeting a three-hour flight for an aircraft with at least 40 seats by 2029[168].

These initiatives highlight a promising trajectory for hydrogen in aviation, with increasing government and industry support accelerating research, testing, and prototype development to make hydrogen-powered commercial flights a reality by the mid-2030s.

Ukrainian context and relevance

Ukraine's accession to the EU would require it to abide by EU directives on aviation. This includes ReFuelEU Aviation directive, part of the EU's Fit for 55 package which aims for SAF to reach 70% penetration across EU airports by 2050[169].

2.2.4 Shipping and maritime

How it works

Ammonia, hydrogen, and methanol are being explored as alternative fuel candidates for the decarbonisation of shipping. Among these options, ammonia is seen as preferable[170]., and there is a growing consensus that, because of its properties, green ammonia will be the most suitable zero-carbon marine fuel for long distance shipping. However, the technology-readiness-level of ammonia in the shipping industry is still low. Ammonia's toxicity and flammability requires careful ship design[171], and while pilot designs are being tested and shipyards are building ammonia-fuelled vessels[172],[173] they are not available yet for deployment at scale. The shipping industry faces similar challenges to aviation in terms of hydrogen use, notably better suitability in short-sea routes[174], and design challenges to accommodate the fuel on-board.

Global perceptions and realism

Hydrogen-based fuels are showing considerable potential for decarbonizing shipping, with projections indicating that hydrogen, methanol, and ammonia could contribute up to 65% of the sector's energy needs by 2050[175]. However, due to the logistical complexities of storing and transporting hydrogen and handling ammonia, their adoption as shipping fuels remains in the early stages.

Short-haul and smaller vessels are expected to decarbonize primarily through battery-electric engines, which provide efficient, zero-emission propulsion suitable for shorter routes. In contrast, long-haul maritime shipping, which requires high energy density over extended periods, will likely depend on fuel-based solutions rather than direct electrification[176,177].

Indeed, hydrogen and hydrogen-based derivatives are emerging as critical fuels for decarbonizing the maritime industry, particularly for heavy-duty carriers such as bunkers, chemical tankers, container ships, and large cargo vessels. These vessels, responsible for transporting vast amounts of tonnage, require high-energy-density fuels, which hydrogen and ammonia can provide while enabling substantial emissions reductions[178]. Regulatory frameworks, including the EU's FuelEU Maritime initiative and the IMO's updated greenhouse gas strategy, are driving a shift toward renewable fuels of non-biological origin (RFNBOs)—fuels produced from renewable electricity rather than fossil sources. RFNBOs, including green hydrogen and ammonia, are favoured in these regulations as they align with net-zero goals, supporting both compliance and climate action[179]. Prototypes of hydrogen and ammonia-powered vessels are already operational, indicating a promising demand trajectory as these technologies advance[180].

While waiting for these technologies to mature, in the near term, liquefied natural gas (LNG) has become a prominent transitional fuel, already powering 6% of the global fleet[181]. LNG offers notable emissions reductions, including near elimination of sulphur oxides (SOx) and nitrogen oxides (NOx), positioning it as a practical solution until green hydrogen and ammonia technologies mature. While LNG combustion emissions are much lower than those of heavy fuel oil (HFO), LNG (methane) leaks have a very large detrimental effect (the Global Warming Potential of methane over 20 years is 84-

87[182]). Additionally, methanol is emerging as a decarbonization option in the short- to medium-term[183] despite the fact that it is also toxic. Methanol has similar combustion characteristics to existing marine fuels, making it easier to integrate with current engines and infrastructure.

With ongoing policy support and technological validation, hydrogen derivatives are expected to become mainstream in maritime decarbonization, especially in segments where other zero-emission options remain challenging. In the long term, hydrogen and ammonia are expected to become the primary decarbonization fuels for the heavy-duty maritime sector, with continued infrastructure investment and safety developments likely supporting this shift. These fuels offer the promise of zero emissions, which aligns with international shipping's 2050 net-zero targets set by the International Maritime Organization[184].

Ukrainian context and relevance

While there are currently no global regulations for hydrogen use in ships - the International Maritime Organization (IMO) intends to release such regulations in 2025[185] - there are relevant regulations within the EU, which would apply to Ukraine if it acceded. The FuelEU Maritime Directive sets limits on emissions in shipping and is intended to promote the use of low-carbon fuels in the EU[186].

2.3 POWER

GH_2 could fulfil numerous roles in the power sector. It could do long-term energy shifting and storage, or short-term shifting to enable grid balancing and ancillary services. Alternatively, it could be used to fuel combined heat and power systems, or for emergency off-grid generation. These applications are explained in detail below.

2.3.1 Energy shifting and storage

How it works

Hydrogen can be used for energy storage. Excess electricity can be used to produce hydrogen via electrolysis, which can then be stored and later converted back to electricity. It can be used to shift energy in time (i.e., via in-place storage) or in space (i.e., via electrolysis, shipping via pipeline or truck, and reconversion to electricity). Any stored hydrogen which is not needed could also be used in other fuel applications, creating a power-to-gas pathway.

To generate power later when it is needed, hydrogen can be blended with natural gas to fuel gas turbines in power plants[187]. Blending hydrogen into these systems reduces CO_2 emissions while leveraging existing infrastructure, although this infrastructure may require significant modification (e.g., to manage increased flammability[188], different compression needs and volumes, and embrittlement risk[189]). Indeed, even blending as little as 5% H2 into natural gas infrastructure can require retrofitting to the tune of millions of euros[190].

Global perceptions and realism

It is unlikely that hydrogen will displace storage options such as batteries directly for short-term energy storage. Its low volumetric energy density[191] and lower round-trip efficiency than lithium-ion batteries[192] make it difficult to use for this purpose. However, it could be a useful vector for longer-term seasonal energy shifting, where the discharge rates of batteries limit their usage. For grid-scale hydrogen storage, underground salt caverns are seen as a promising option[193]

Ukrainian context and relevance

Much of Ukraine's power grid has been damaged or destroyed since Russia's invasion. Its generation capacity has been reduced to about one third of pre-war levels[194] is under constant attack. While the United Nations see these attacks as likely violations of international humanitarian law[195], there is no sign of them stopping. The damaged generation facilities can take months to rebuild, and worse, there are shortages of the required parts for rep. To make up the shortfall, Ukraine has relied heavily on interconnections with the EU. These previously had 1.7 GW of capacity; based on concerns of inadequate capacity throughout the winter[196], this has been to 2.2 MW plus 150 MW emergency support, totalling 2.35 GW. Given the lack of existing infrastructure to support hydrogen, however, it will be difficult for hydrogen generation and storage to cover these gaps in the near-term.

The draft Energy Strategy of Ukraine foresees 17% of hydrogen produced in the country being used in gas-fuelled power plants[197]. However, in terms of energy security, this is no improvement over the status quo – large-centralised gas-fuelled plants and hydrogen storage make it easier to do substantial damage with few attacks.

Ukraine has salt deposits which could be leveraged for underground hydrogen storage[198]. However, the placement of these with regards to conflict zones should be studied, and their above ground operations could still be a target. It has been argued that decentralised renewables may instead play the same decarbonising role while being harder to attack due to their disperse nature.

2.3.2 Grid balancing and ancillary services

How it works

> Hydrogen technologies, particularly electrolysers and fuel cells, are increasingly considered for grid balancing and ancillary services. Electrolysers can absorb excess electricity during periods of high renewable energy generation by producing hydrogen, which can be stored and later converted back to electricity through fuel cells or turbines when demand peaks. This provides immediate power, acting as a "spinning reserve" for rapid response. Additionally, hydrogen systems can support "black start" capabilities, enabling the restart of grid components after major outages, which is especially valuable in grids with high renewable energy penetration where conventional black start resources may be limited[199].
>
> Electrolysers offer rapid ramp-up and ramp-down capabilities, making them ideal for short-term grid balancing and frequency regulation. By adjusting their power consumption instantly, electrolysers can absorb excess electricity, stabilizing the grid during periods of high renewable energy generation or low demand. Strategically placing electrolysers near renewable generation sites or grid congestion points can maximize their efficiency and support grid stability [200].

Global perceptions and realism

Globally, the integration of hydrogen technologies into grid balancing is gaining traction, particularly in regions with significant renewable energy deployment. In Europe, countries with high volatile renewable energy deployment, like Germany, Denmark or Spain, are exploring the use of electrolysers for grid services [201]. France's "HyBalance" project demonstrated the combined operation of a PEM electrolyser providing both grid balancing services and hydrogen for industry and transport[202]. Similarly, the "Demo4Grid" project in Greece focused on a 4 MW pressurized alkaline electrolyser for grid balancing under market conditions[203].

However, the economic viability of deploying electrolysers solely for grid services is currently limited due to high capital and operational costs. Revenue from ancillary services alone may not justify the investment. Therefore, a value-stacking approach is often considered, where electrolysers provide multiple services—such as hydrogen production for industrial use and participation in grid services—to improve the overall business case[204].

Ukrainian context and relevance

Recent regulatory changes in Ukraine are positioning the balancing market as a new business opportunity for storage and other responsive technologies. The Ukrainian National Energy and Utilities Regulatory Commission has adopted regulations to support ancillary services, including frequency containment reserves (FCR) and automatic frequency restoration reserves (aFRR), through special auctions that are designed to incentivize energy storage and flexibility resources[205].

Battery Energy Storage Systems (BESS) are expected to play a primary role in Ukraine's short-term balancing strategy due to their established performance in rapid-response applications. However, the projected demand for balancing services creates potential opportunities for hydrogen-based solutions, such as electrolysis, which could complement BESS by providing additional capacity for longer-duration storage and flexible power ramping[206].

With companies like DTEK pioneering investments in aFRR and advocating for storage and flexibility as essential to grid stability, hydrogen electrolysis could be strategically placed at grid congestion points or near renewable energy hubs to absorb excess generation[207]. This setup would not only bolster grid resilience but also support Ukraine's transition to decentralized energy solutions in the face of ongoing infrastructure challenges. Hydrogen's potential to serve as a "black start" resource further strengthens its role, especially in a grid heavily reliant on variable renewables and vulnerable to disruptions.

2.3.3 Combined heat and power systems

How it works

Hydrogen-based combined heat and power (CHP) systems function by using hydrogen as a primary fuel to generate both electricity and thermal energy, thus achieving high energy efficiency and significantly reducing carbon emissions compared to conventional fossil-fuel-based CHP systems. These systems can leverage various technologies, including hydrogen-fuelled gas turbines, internal combustion engines, and fuel cells, each offering different efficiencies and operational advantages. Notably, fuel cell-based CHP systems can reach up to 90% efficiency, as they convert hydrogen's chemical energy directly into electricity while capturing waste heat for heating applications, making them ideal for distributed energy resources and localized energy generation[208].

Global perceptions and realism

While hydrogen-based CHP has potential as a long-term decarbonization solution, it faces significant cost barriers today, particularly in large-scale applications where fuel costs and infrastructure requirements make it less economically feasible compared to other low-carbon technologies. Hydrogen combustion in gas turbines and internal combustion engines, while technically feasible, is costly and currently less efficient than other decarbonization pathways, making hydrogen CHP an option best suited for future deployment when GH2 costs are expected to decrease. At present, high costs, alongside infrastructure requirements for transport and storage, limit its competitiveness[209].

Some countries are deploying pilot projects to test hydrogen's role in large-scale CHP for industrial settings. For instance, Germany's National Hydrogen Strategy includes pilot CHP projects designed to assess the feasibility of hydrogen in district heating and industrial applications[210]. Similarly, the Netherlands and Austria are exploring hydrogen as a fuel for large-scale CHP in demonstration projects that aim to decarbonize industrial heat and power production in heavy industry[211]. However, these projects remain in testing phases, with commercial viability still to be demonstrated over the longer term.

Ukrainian context and relevance

Eighteen large CHP plants alongside 800 boiler-houses have been damaged or destroyed in Ukraine since 2022[212]. Ukraine's winter season can last up to six months, including three months which average –4.8°C to 2°C[213]. Rebuilding and reinforcing Ukraine's heating infrastructure is therefore critically important[214].

In the immediate future, fast and dependable technologies must be prioritized to ensure security of supply for both electricity and heating. Given the current lack of large-scale hydrogen availability and the high costs associated with hydrogen infrastructure, hydrogen-based CHP solutions remain impractical in the short term.

Instead, Ukraine could focus on quickly rebuilding with flexible gas turbines and other CHP systems that can operate on conventional fuels today but might be hydrogen-compatible for potential future transition. This would allow Ukraine to meet its immediate energy security needs while reducing the risk of locking into fossil fuel technologies. By selecting adaptable systems, the country can respond to current demands while preparing for a sustainable energy transition, supporting both energy resilience and long-term decarbonization as hydrogen infrastructure develops and becomes more economically viable in the future.

2.3.4 Off-grid and emergency power generation

How it works

> Hydrogen fuel cells generate power by converting hydrogen's chemical energy directly into electricity, with only water vapor as a by-product, making them an efficient and clean solution for power generation. Fuel cells are especially suited for distributed power generation, remote areas, and backup power for industries and critical infrastructure due to their scalability, low emissions, and ability to operate independently from the central grid. Hydrogen fuel cells can be deployed in various configurations, including stationary installations for continuous power supply and portable units for flexible, on-demand power[215].

Global perceptions and realism

Globally, hydrogen fuel cells are increasingly recognized as a viable solution for decentralized energy generation and resilience in off-grid applications. In Japan for example, the government funds hydrogen fuel cells for backup power in hospitals and other critical infrastructure, underscoring the technology's importance in emergency preparedness[216]. Moreover, hydrogen fuel cells are being deployed for backup power in critical infrastructure, such as data centres and military bases, focusing on resilience and energy security[217,218]. Furthermore, hydrogen is being used in microgrids to support rural communities and ensure uninterrupted power during natural disasters, especially in areas prone to grid instability[219].

While hydrogen fuel cells offer significant benefits, high costs and infrastructure requirements remain challenges. The cost of hydrogen production, transportation, and storage is substantial, and fuel cells are currently more expensive than many conventional power solutions. This limits hydrogen fuel cells' short-term competitiveness, particularly in rapid-deployment contexts. For countries prioritizing immediate emissions reductions or energy security, more readily available and cost-effective options, such as fossil fuel-based backup systems or rapidly deployable renewable energy sources (e.g., solar and battery storage), might be more feasible solutions in the near term. As technology advances and hydrogen production costs fall, hydrogen fuel cells are expected to become more competitive for distributed and backup power applications[220,221].

Ukrainian context and relevance

In Ukraine, the need for decentralized and resilient energy solutions has become urgent as conflict continues to damage and destroy centralized energy infrastructure[222]. Hydrogen fuel cells could play a vital role in bridging energy gaps, particularly in remote or isolated regions where grid repairs are challenging. They offer a decentralized, clean, and resilient power source that can provide backup power for critical infrastructure, such as hospitals, industrial sites, and emergency response facilities, especially in areas with unreliable grid access.

However, given the high costs and relatively slow deployment speed of hydrogen fuel cells, more immediate solutions—such as fossil fuel-based backup systems or rapidly deployable renewable energy sources—may be more practical to ensure immediate security of supply for electricity and heating. Focusing on flexible and adaptable energy systems now, including those capable of later transitioning to hydrogen when it becomes more accessible and affordable, would enable Ukraine to address immediate needs while positioning itself for a future transition to cleaner energy sources.

2.4 RESIDENTIAL

GH2 could be used for residential power and heat or could serve as input to heat networks as described with regards to CHP above. These applications mirror some of those in the previous section. However, there are specific considerations related to the interface with residential homes to consider.

2.4.1 Residential power and heat supply

How it works

Hydrogen could be burned in purpose-built or “hydrogen-ready” boilers to heat homes and buildings. Proponents of this idea argue that this could enable existing natural gas infrastructure to be repurposed with a lower emissions fuel.

Global perceptions and realism

Many do not see this as a likely use for hydrogen. Heat pumps can provide the same decarbonisation benefits several times more efficiently[223] due to the thermodynamics of the respective processes. IEA analyses foresee hydrogen playing a “negligible” role in space heating[224]. A recent meta-review similarly concluded that the role of hydrogen in heating is likely to be only in niche applications or minimal complementary operation alongside heat-pumps[225].

Ukrainian context and relevance

40% of Ukraine’s population uses centralised district heating powered largely by natural gas[226]. Specifically, it is the main source of heat for multi-family buildings[227]. However, its district heating systems are outdated and inefficient. Furthermore, the invasion had caused an estimated $2.1 billion to district heating systems as of December 2023[228].

The draft Hydrogen Strategy of Ukraine indicates that a detailed plan for the use of hydrogen in heating will be produced by 2026[229]. However, hydrogen-based district heating would have the same vulnerabilities as conventional CHP and be more expensive. Nevertheless, the National Energy and Climate Plan outlines expenditures on both fuel cell CHP and hydrogen boilers over coming years[230].

2.4.2 Heat networks

How it works

As previously discussed, hydrogen can be used to generate heat which feeds into district heating networks. Some are also considering the use of electrolysis waste heat in these networks[231].

Global perceptions and realism

Regarding the use of electrolysis waste heat, some studies show that this could successfully be integrated in district heating, even if it is likely to provide a small proportion of heat needs[232]. Of course, this would require a separate off taker for the produced hydrogen.

Ukrainian context and relevance

As previously discussed, while heat networks are critical to urban Ukrainian residents in multi-family buildings, this infrastructure is ageing and damaged by war. Further, the same caveats apply here as in the previous section; direct use of renewable electricity and heat pumps is likely to be a more efficient and cost-effective option than hydrogen-fuelled heat networks.

3 Synthesis and next steps

To synthesise the information from the previous sections, we use a five-point scale from red (unlikely) to green (likely). Each use-case is given a rating on both global realism and Ukrainian relevance. These ratings are then averaged for each use case to give an indication of whether the use-case merits further study. The results are shown in Table 3.

Table 3: Synthesis of the presented use-cases, their global realism, and their relevance to Ukraine. The five-point colour scale is presented under the table.

Sector	Type	GH2 Application	Global realism	Ukraine relevance	Further study
Industry	Feedstock	Steel (H2-DRI)			
		Ammonia/Fertilizer			
		E-fuels and petrochemicals			
		Refining processes			
		Others			
	Fuel	Low-temperature heat			
		Medium-temperature heat			
		High-temperature heat			
Transport	Fuel	Cars			
		Trucks			
		Public transport			
		Rail transport			
		Airplanes			
		Ships and maritime sector			
Power	Fuel	Energy shifting and storage			
		Grid balancing and ancillary services			
		Combined heat and power			
		Off-grid and emergency generation			
Residential	Fuel	Residential power & heat supply			
		Heat networks			

3.1 CLASSIFICATION OF USE-CASES

From Table 3, use-cases unlikely to be prioritised for further study include low and medium heat, cars, public transport, and as a feedstock in refining. Low- and medium-heat can be produced more cheaply via direct use of electricity/heat pumps than via GH2. Cars and public transport are more likely to be decarbonised via BEVs than FCEVs worldwide, even though Ukraine policy highlights hydrogen as a possible mechanism to decarbonise public transport. While GH2 may find use in refining globally (where H2 cannot be sourced from other refining processes on-site), Ukraine's refining capacity is aging and largely unused, making this unlikely to be a key focus area.

Use-cases which could possibly be relevant to specific future scenarios include e-fuels and petrochemicals, other industrial feedstock uses, trucking, and residential power and heat. While traditional fuels are still much cheaper than e-fuels, Ukraine's EU accession will push it towards fuel decarbonisation. Other uses of GH2 as a feedstock have the same trade-off, increasing the final price of the product but supporting decarbonisation targets. As cost parity between FCEVs and diesel vehicles for trucking is projected close to 2040, this transport application is more likely than cars or public transport. While use of GH2 in residential heating has been featured in hydrogen policy documents in Ukraine, and is technically possible, heat-pumps or direct use of renewable energy is more efficient in individual homes.

Finally, use-cases which should almost certainly be considered include high-heat industrial applications, fertiliser production, direct reduction of iron in steelmaking, airplane and maritime fuel, rail transport, all power applications, and heat networks. High heat is required in the production of many materials required for reconstruction (e.g., cement, glass, steel), and these will also be bound by EU decarbonisation targets as accession proceeds. Given the importance of agriculture to Ukraine's economy, and the disruption of fertilizer supplies from Russia, increased in-country green fertiliser production would be advantageous. Steelmaking is historically a significant industry in Ukraine, and despite the dominance of BF-BOF production, Ukraine has iron ore deposits of high enough quality to instead use decarbonised DRI and EAF. Reconstructing the steel industry to use this green approach would align with EU green steel targets. Similarly, aircraft and maritime fuel in Ukraine will be bound by EU fuel policies if accession proceeds, and those applications are seeing strong technological advances worldwide. Rail transport using hydrogen is also already commercialised in various countries, including EU countries such as Germany, and Ukraine's strong and important rail network make this an important case to consider. The power system of Ukraine is going to need significant reconstruction following the invasion due to repeated Russian attacks on infrastructure, and hydrogen can play a role in this system, for instance in long-term energy storage and grid services to enable higher integration of renewables. Heating networks similarly require reconstruction, and hydrogen-based CHPs could be useful here to meet the needs of Ukraine's urban buildings that currently rely on district heat.

3.2 ALIGNMENT WITH DRAFT HYDROGEN STRATEGY

The draft Ukrainian hydrogen strategy does not denote specific consumption levels of hydrogen targeted by specific sectors. Stage I of its implementation plan plans to assess potential uses of hydrogen by 2026; specific targets are more likely to be available by this time. Nevertheless, the text of the strategy does clarify the country's position and priorities within different industries.

EU accession

The focus on European hydrogen market integration as part of accession is a stated priority in the draft strategy. The European Commission and Ukraine have signed a memorandum of understanding to cooperate on hydrogen certification, licensing, markets, and other institutional requirements to develop the sector.

Industrial use

The draft hydrogen strategy and the draft energy strategy of Ukraine prioritise the development of hydrogen for industrial use in metallurgy and chemical industry. The section of the draft on industrial usage highlights metallurgy, cement, glass, and fertilizers as the most important hydrogen users. These largely align with this report's findings.

In metallurgy, it speaks specifically about the iron and steel industry, and how decarbonisation will be important despite the current prevalence of BF-BOF production. This aligns with this report's evaluation of the industry and the importance of green steel given EU targets.

Regarding cement, the draft highlights that over the past 15 years, natural gas in cement production has been replaced by coal, given the high costs fo natural gas. This casts doubt on any replacement of either natural gas or coal with hydrogen. Nevertheless, it highlights that in post-war recovery, demand for cement in construction will grow rapidly.

The draft highlights the production of ammonia as a significant part of Ukraine's chemical industry and discusses how Ukraine is among the top 10 producers of these compounds worldwide. Low-carbon ammonia production is highlighted as important under CBAM. This agrees with this report's evaluation of ammonia production as an important use-case.

Use of hydrogen to produce methanol is also highlighted due to (a) its importance in the natural gas industry, and (b) Ukraine's former reliance on Russia for methanol.

Power and residential heating

The draft strategy recognises the use of GH2 as economically impractical where batteries or hydro storage could be used instead, due to the efficiencies of each technology, agreeing with this report. It highlights the possibility of underground storage of hydrogen in former natural gas reservoirs, salt mines, and coal mines, with a focus on seasonal energy storage for balancing. It highlights the importance of storage specifically to overcome energy shortage periods. This makes sense, given the blackouts caused by frequent Russian attacks on energy infrastructure throughout the invasion. Careful mapping of underground storage options would be needed to verify their security.

On residential heating, the draft flags that 90% of district heating needs are currently met by gas and coal. It highlights concerns on the economic feasibility of hydrogen use for heating as compared with heat pumps, renewable energy sources, and biomass. This echoes the same concerns expressed in this report.

The strategy has no clear plan on hydrogen mixing in current infrastructure (e.g., generators and pipelines), saying that it requires detailed study. As this can require very expensive retrofitting, it will be key to assess during implementation stage I.

As Ukraine has 45 different gas distribution system operators, it may be worth considering how and whether all will be brought on-side to plans for hydrogen mixing. Use of existing ammonia pipeline infrastructure may be a more promising option where available.

There is some confusion in the draft as to whether GH2 will form an integrated part of the power system or whether it will leverage stand-alone generation facilities. The draft cites that the draft energy strategy's envisioned increase of the proportion of renewable energy in the electricity mix (i.e., up to 50% in 2050) can be used for GH2 production. However, it is not clear whether this capacity is already airmarked for other uses. Indeed, it states directly thereafter that new renewable energy facilities for hydrogen production are "envisaged separately". This needs to be clarified to understand whether the integrated system plans include capacity for on-grid hydrogen production.

There is similar confusion around nuclear energy. The draft cites that this could be used for hydrogen production without making it clear whether the draft energy strategy has accounted for this in the projected size of nuclear generation. These points need to be clarified to design hydrogen plants appropriately.

Transportation

The draft includes the potential use of hydrogen in water and air transportation but does not provide much detail on Ukrainian aspirations in these areas, rather stating that further study is required to handle technical, economic, and infrastructural challenges. Given the importance of these fuels in EU accession, as highlighted in this report, this should be a focus during implementation stage 1.

The potential use of hydrogen in public transport features in Ukrainian policy despite the lower cost of BEVs, perhaps to keep in line with EU directives. Ukrainian road transport policy specifies that for all cities exceeding 250,000 people, the number of buses which are either electric or burning defined clean fuels (including hydrogen) must be 25% by 2030, 50% by 2033, and 100% by 2036. The inclusion of hydrogen here may be surprising, as the draft hydrogen strategy indicates that electric vehicles are the likely decarbonisation approach for passenger vehicles. At the same time, the draft notes that the EU Hydrogen strategy includes a focus on buses and trucks. Perhaps this motivates the inclusion of hydrogen as an option for public transit. The draft also cites recent EU directives on the implementation of hydrogen filling stations in all urban centres and at every 200 km along the Trans-European transport corridor. More in line with this report, the strategy indicates that hydrogen may be important for long-distance freight transportation by truck given the limited range of electric vehicles. It also puts a focus on meeting EU objectives for refuelling stations.

3.3 LOOKING AHEAD

These results will be considered during scenario development for the SHIELD project. They will complement parallel policy analysis, which is being undertaken to better understand Ukraine's stated priorities, context, and potential futures. The results of this report will serve as a technical reality check for the scenarios developed and the use-cases they contain.

Acknowledgements

The authors receive funding from the Foreign, Commonwealth and Development Office of the UK Government via the Strategic Hydrogen Integration for Effective Low-Carbon Development programme. However, the views expressed herein do not necessarily reflect the UK government's official policies.

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ACKNOWLEDGEMENTS

The authors receive funding from the Foreign, Commonwealth and Development Office of the UK Government via the Strategic Hydrogen Integration for Effective Low-Carbon Development programme. However, the views expressed herein do not necessarily reflect the UK government's official policies.

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