HYDROGEN

fuel cell technology in container handling equipment: Industry outlook and technical considerations

A Kalmar white paper

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Contents

EXECUTIVE SUMMARY

Hydrogen-based fuel cell technology is currently generating significant interest across multiple industries, as companies worldwide seek to lower the carbon footprint of their operations in line with internal goals, stakeholder demands and regulatory pressures. So-called green hydrogen is an energy storage that theoretically provides 100% carbon-neutral energy, if the hydrogen (H_2) is produced by electrolysis using renewable power sources. However, the vast majority of hydrogen manufactured today is still dependent on fossil fuels for its generation.

The global hydrogen economy is expected to grow massively over the next decades, but this is contingent on green hydrogen achieving cost-competitiveness with fossil-based alternatives before 2030. At the same time, the H_2 economy will require rebuilding and/or repurposing a massive infrastructure for the production, transport and storage of hydrogen. The development of this critical infrastructure will be shaped not only by the current concentrations of supply and demand around the world – mainly centred around the chemical and petroleum industry – but also by the vastly differing future requirements for importing and exporting H_2 in each country.

Hydrogen-based fuel cells have been used for many years in applications such as light forklift trucks, enabling quick refuelling, local zero emissions indoors and simplified maintenance compared to traditional solutions. For the container handling industry, the key question is whether H_2 fuel cells can scale economically to heavy equipment, and whether H_2-based solutions will offer significant benefits over grid-powered battery electric vehicles (BEVs).

At the time of writing, based on in-house, commissioned and publicly available research, it is Kalmar’s conclusion that in certain highly specific customer scenarios, H_2-based solutions could be an alternative to battery-powered electric systems in the container handling industry. These include situations in which the local electric grid infrastructure is not able to provide enough power, 24/7 operations preclude sufficient recharging times for vehicle batteries, and H_2 is easily and economically available on or near the site, e.g. as a residual from existing process industry.

However, in the vast majority of use cases, when taking into account the unavoidable efficiency losses entailed in converting between energy forms, grid-powered BEVs will offer significantly lower system and energy costs as well as lower total energy usage compared to H_2 fuel cell powered heavy container handling machines. If green electricity is abundantly available for manufacturing H_2 through electrolysis, fuel cell solutions may well be a viable future option.

The new hydrogen economy is expected to have a massive impact on the energy landscape of the next decades, and as ports and terminals are anticipated to become key hubs in the global energy infrastructure, Kalmar and other logistics industry players need to keep H_2 solutions as a focus area. Even if fuel cells will not be able to compete with battery-powered electric vehicles on cost or sustainability in the foreseeable future, future H_2 technologies may bring other opportunities.

1 H_2 and fuel cells: Technical overview

To provide electrical power, a fuel cell requires only hydrogen and air, and generates water as its sole exhaust emission.

HYDROGEN FUEL CELL BASICS

Hydrogen (H) is the lightest element and the most abundant chemical substance in the universe. In standard conditions, it is present as a gas of diatomic molecules consisting of two hydrogen atoms (H_2). Hydrogen is a highly flammable substance that can be used directly as a fuel, or to produce electricity in fuel cells.

A fuel cell is an electrochemical device that produces electrical energy through reduction and oxidation reactions between a fuel such as hydrogen, and an oxidising agent (typically oxygen, O_2). The first fuel cells were developed in the 1830s, with commercial use following a century later. In subsequent decades, fuel cells have seen use as, for example, electrical power sources for space vehicles and satellites.

Hydrogen fuel cells are available in many types. For H_2 fuel cell applications in container handling equipment, the most relevant variety is the proton exchange membrane fuel cell (PEMFC).

As a simplified description, a PEMFC consists of porous anode and cathode plates or membranes that allow fuel (H_2) and air containing oxygen (O_2) to pass through them. Sandwiched between the anode and cathode is a catalytic membrane that splits the incoming H_2 into protons and electrons. The protons permeate through the membrane to the cathode side, while the electrons travel to the cathode via an external load circuit, creating the electrical current output of the fuel cell. On the cathode side, the electrons and protons react with the incoming oxygen, forming water molecules (H_2O) that are vented from the system along with the airflow.

Unlike batteries, fuel cells require a continuous supply of hydrogen and air to generate electricity. Individual fuel cells produce relatively low voltages (typically between 0.5 to 0.9 V), so in real-world applications multiple cells will be connected in series to form so-called fuel cell stacks.

Pros and cons of hydrogen fuel cell technology versus battery-powered technology

Pros	Cons
Clean power with no on-site emissions	Limited worldwide production of green hydrogen
Long operating times compared to battery solutions	Global transport and storage infrastructure required
Lower demand on electrical grid	Higher cost
Smaller on-site infrastructure if H_2 is readily available	Special challenges in handling hydrogen

ATTRACTION AND DEPLOYMENT BARRIERS FOR FUEL CELL VEHICLES

The basic chemical reaction in a fuel cell is also one of its most obvious benefits. To provide electrical power, a fuel cell requires only hydrogen and air, and generates water as the sole exhaust emission. H_2 fuel cells can therefore enable zero on-site emissions for vehicles and have the potential to be a fully carbon-neutral transport solution if the hydrogen fuel is manufactured with renewable energy (see Chapter 2).

Fuel cell powered electric vehicles (FCEVs) also have the potential for longer operating ranges as well as refuelling times that are significantly faster than the charging times for battery-powered electric vehicles (BEVs). With refuelling times comparable to traditional diesel-powered vehicles, this means that long refuelling or recharging breaks do not need to be designed into the daily operating schedules of equipment fleets.

H_2 fuel cells have the potential to be a fully carbon-neutral transport solution if hydrogen fuel is manufactured with renewable energy.

Other potential benefits of FCEVs include a potentially smaller on-site infrastructure footprint (assuming that a H_2 supply is available) as well as significantly reduced demand on local electricity grids compared with a BEV solution.

However, despite the potential gains, hydrogen-based fuel cell vehicles still face many serious obstacles to widespread deployment and adoption. Most significantly, the capacity for the worldwide production of green hydrogen is still extremely limited. At the same time, the transition to the projected global hydrogen economy will require a massive buildup of production, storage and distribution infrastructure for H_2 (see Chapter 3).

For the foreseeable future, FCEVs will have higher capital and operating costs compared to traditional internal combustion engine vehicles and BEVs, though against internal combustion engines this may eventually change as a result of regulatory efforts towards decarbonisation.

Fuel cell based vehicle solutions are also highly complex systems that require a sophisticated array of control, cooling and auxiliary equipment around the actual fuel cell. Fuel cells cannot therefore be simply ”slotted into” existing battery-powered vehicles. Much of the technology is still far from mass-market adoption, so the maturity, reliability and performance of each component needs to be evaluated with particular care for mobile container handling machines. Finally, comprehensive industry standardisation in areas such as H_2 vehicle refuelling is still in development.

ENVIRONMENTAL LIMITATIONS

H_2 fuel cell systems have some specific requirements for environmental conditions. As the cathode and anode exhaust gases from the fuel cells consist of humid gases, exhaust pipes will need heating to prevent icing in sub-zero temperatures. Cold conditions may require additional pre-heating and flushing procedures upon startup and shutdown to avoid blockages and mechanical damage caused by water freezing inside the fuel cell.

A PEM fuel cell intermittently releases some hydrogen as an anode exhaust. This may be an issue in confined spaces or hazardous environments. If hydrogen release cannot be tolerated, a catalytic burner can be installed on the equipment.

Currently, 98% of global hydrogen production is still based on fossil fuels.

Fuel cells depend on a steady supply of air, and the intake dust filter is a key maintenance component that needs to be replaced regularly. Certain airborne pollutants such as sulphur, nitrogen oxides and ammonia may have an impact on the lifetime of the fuel cell. Fuel cells in mobile equipment also need to be adequately protected from vibration and shocks that might compromise the physical durability of the unit.

SAFETY CONSIDERATIONS

The main safety consideration when operating H_2 fuel cell equipment is ensuring the safe handling of hydrogen, which is a highly flammable gas with a wide flammability range and very low ignition energy. However, hydrogen released into open air dilutes rapidly without causing danger, if it is present as a non-flammable mixture (under 4% of hydrogen in air).

As the lightest element, hydrogen also has the smallest molecule of any substance, which causes some special issues. Hydrogen will leak from minuscule openings faster than other fuels, and can permeate through polymer tanks. Long exposures to hydrogen can cause embrittlement of metals including high-strength steels, aluminium and magnesium alloys, and titanium.

Existing industry standards for the safety of hydrogen systems outline some general steps for limiting the consequences of a possible H_2 incident. These include minimising the quantity of H_2 onboard the vehicle; isolating H_2 from oxidizers, hazardous materials and dangerous equipment; eliminating potential ignition sources; and ensuring adequate ventilation of the fuel cell system from the top of the vehicle.

2 H_2 production methods

FOSSIL FUELS VS. ELECTROLYSIS

Hydrogen can be produced by many different methods that have widely differing carbon footprints. These range from coal gasification and steam methane reforming to the electrolysis of water. Currently, some 98% of global hydrogen production is still based on fossil fuels. Of this production, 76% is from natural gas, 23% is from coal and 1% is from oil products.

This means that at the time of writing (late 2022), H_2 is still far from being a sustainable, carbon-neutral energy form. However, it is also important to remember that currently the vast majority of hydrogen is produced for use as a feedstock for other industrial processes. To become a fully sustainable energy source, hydrogen will need to be produced with renewable green energy. In the meantime, its main immediate potential for the transportation sector may be as an alternative form of distributing and storing energy through gas storage.

THE HYDROGEN COLOUR SPECTRUM

Hydrogen production methods are popularly assigned colours to differentiate their manufacturing methods and carbon footprints. For the context of this paper, the most relevant are so-called ”green”, ”grey” and ”blue” hydrogen.

The hydrogen colour spectrum

GREEN	Manufactured by the electrolysis of water using electricity generated from renewable sources.
GREY	Produced from natural gas or methane using steam methane reforming.
BLUE	Produced by steam methane reforming, or coal gasification, with CO_2 captured and sequestered using carbon capture and storage.
PINK	Produced by electrolysis generated by nuclear power.
YELLOW	Produced by electrolysis using grid electricity.
TURQUOISE/ CYAN	Produced through methane gas pyrolysis.
BROWN/ BLACK	Produced through gasification of black coal or lignite.

Green hydrogen is manufactured by the electrolysis of water using electricity generated from renewable sources. The electrolysis breaks down water (H_2O) into hydrogen (H_2) and oxygen (O_2). A theoretical 100% efficient electrolyser would require 39 kWh of electricity to manufacture 1 kg of H_2. In practice, 50–55 kWh is required for each kilogram of hydrogen. The carbon footprint and emissions of green hydrogen therefore depend on the power source used, but it is the only form of H_2 production that can theoretically be fully sustainable.

Grey hydrogen accounts for nearly all of the hydrogen produced worldwide today. The term refers to H_2 that is produced from natural gas or methane using steam methane reforming. In the process, methane (CH_4) and water (H_2O) react to release carbon monoxide (CO) and hydrogen (H_2). Steam methane reforming produces significant carbon emissions, but it is by far the most advanced, cheapest and most scalable H_2 mass production method that is currently available.

Blue hydrogen is a process in which H_2 is produced from steam methane reforming or coal gasification, but with the produced carbon captured and sequestered instead of releasing it into the atmosphere. The carbon footprint of blue hydrogen therefore depends on the efficiency of the carbon capture technology used, with maximum CO_2 capture rates typically cited at 70% to 95%. Blue hydrogen production does not yet exist at scale; however, it is expected to play an important interim role during the projected ramp-up of global green H_2 production over the next decades (see following chapter).

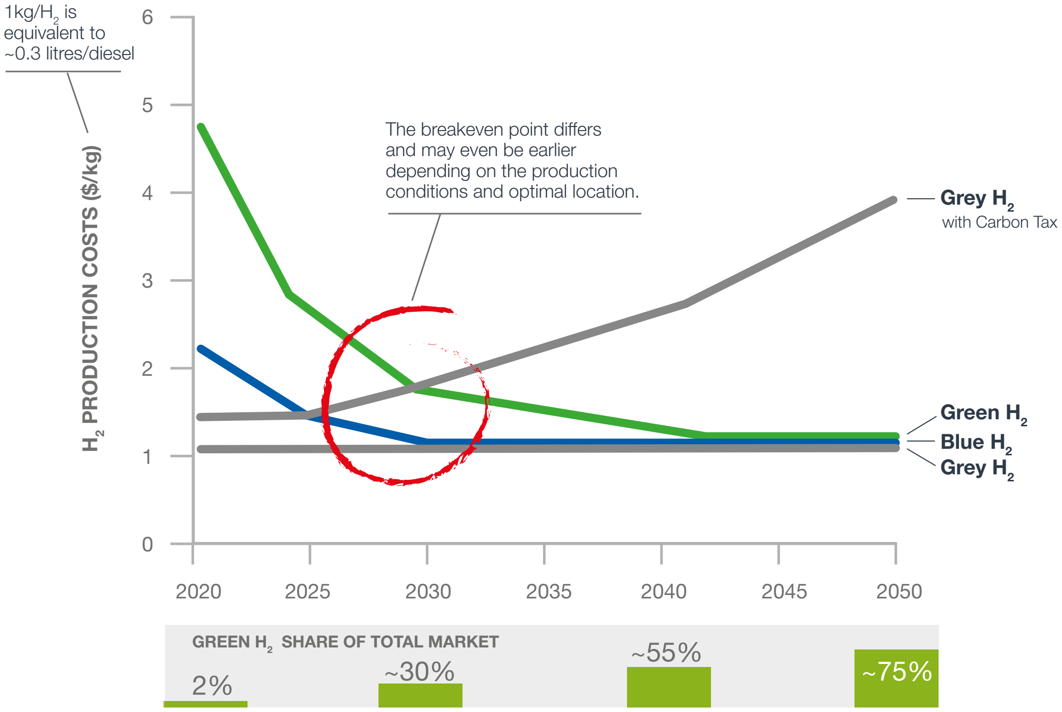
Several other colour codes have also been designated for hydrogen production, with ”pink” and ”yellow” hydrogen denoting electrolysis powered by nuclear or electrical grid power, respectively. ”Brown” or ”black” hydrogen refer to H_2 manufactured from coal gasification, a process with extremely high CO_2 emissions that is the polar opposite of green hydrogen.

3

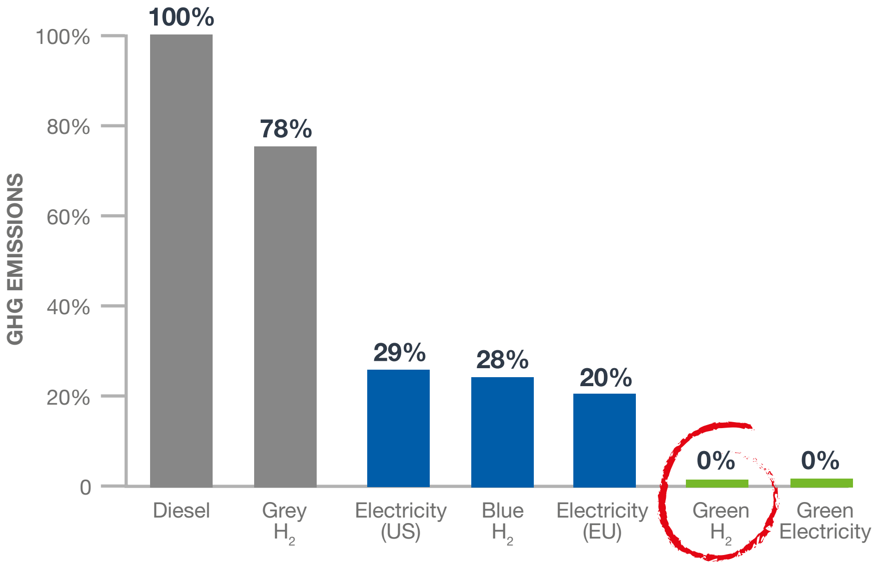
Market drivers for green H_2 supply and demand

CO_2 EMISSIONS VS. PRODUCTION COSTS

On the global scale, a shift towards green hydrogen will be driven on one hand by its potential for decarbonising industry and transport, and on the other hand by increasing cost-competitiveness. The key question is when will green H_2 achieve the cost breakeven point with grey H_2 when taking into account both the gradual decrease in green H_2 production costs and increased CO_2 taxation. Depending on the research source quoted, it is expected that this breakeven might be reached around 2030, or possibly even earlier at some locations.



Paradoxically, the most significant future competitor to green H_2 may not be grey hydrogen, but green grid power itself. Green H_2 will eventually be able to compete on cost with grey H_2, but it will always be more expensive than the green electricity that is needed to generate the hydrogen via electrolysis. Furthermore, using H_2 in fuel cell based electrical mobility applications entails a three-step conversion from electrical energy to hydrogen and back to electricity, resulting in a total energy efficiency of around 25–35% compared with charging an electric vehicle directly from the grid (see next chapter for details).



The viability of H_2 fuel cell based transport solutions will depend greatly on infrastructure, logistical factors and business scenarios that will be unique to each region, market and company. As renewable energy production and decarbonisation gain ground over the years to come, in many cases the most efficient solution will likely be to power electric vehicles directly from the grid.

The global hydrogen economy of the future will be shaped by a complex interplay of regulatory pressures, market dynamics and stakeholder expectations.

PUSH AND PULL INDUSTRY DRIVERS

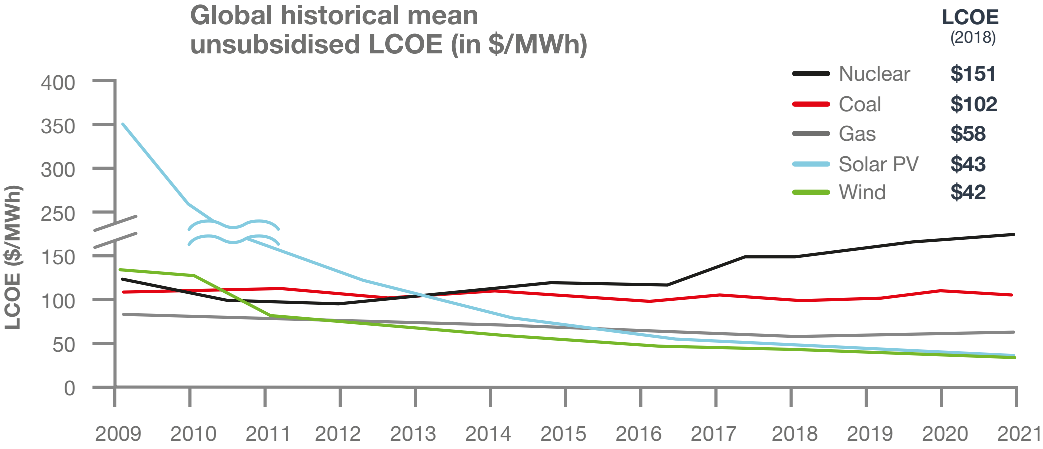
The global hydrogen economy of the future will be shaped by a complex interplay of regulatory pressures, market dynamics and stakeholder expectations at all levels from national governments to individual companies. Regulatory bodies and capital markets are aggressively pushing investments towards ”green” assets, and support for green hydrogen is gaining ground around the world. Over 30 countries have already developed or are developing national hydrogen strategies, and CO_2 is being priced through taxation or emission trading systems.

At the same time, global drives to reduce CO_2 emissions are impacting all sectors of industry. Energy-intensive businesses such as the steel and chemical industries face a strong pull towards decarbonisation and are actively looking at green hydrogen as a tool to meet their targets.

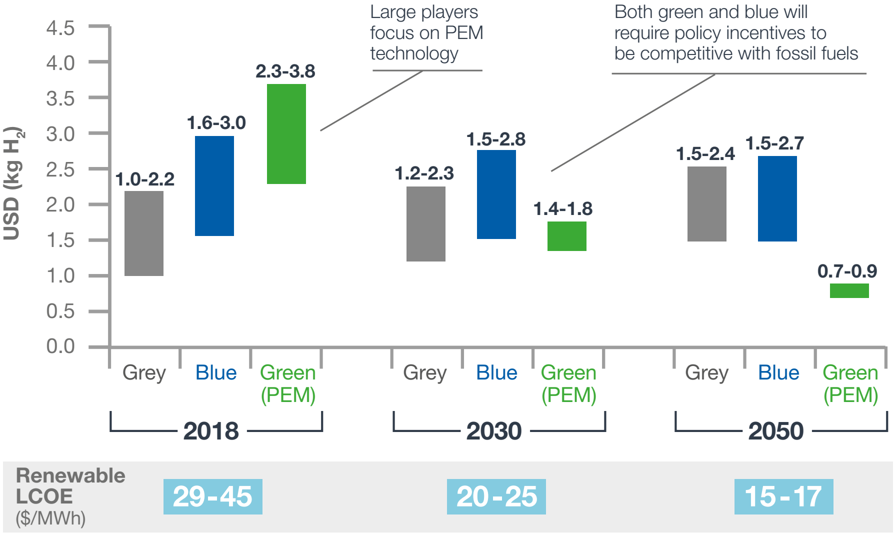
Levelised cost of energy (LCOE) calculations show that the costs of renewable energy have been falling steadily over the last years, with the price of renewable power falling towards or even under 20 €/MWh. This is a major driver in decreasing the cost of green H_2, which depends on renewable power for its production.

Finally, the COVID-19 pandemic has led to a somewhat unexpected boost for the hydrogen economy, as both the EU and the US have announced massive stimulus packages for COVID recovery, including significant earmarked funding for hydrogen.

Global historical mean unsubsidised LCOE (in $/MWh)



Price competitiveness comparison with alternatives



PEM = proton exchange membrane fuel cell

GROWTH FORECASTS 2022–2050

Global H_2 demand is forecasted to grow approximately tenfold by 2050

Predictions for the structure of the future hydrogen economy vary somewhat between analysts and scenarios. However, a general consensus is that global H_2 demand is forecasted to grow approximately tenfold by 2050, with Europe and the US accounting for 20% of H_2 usage and China alone approximately 30%.

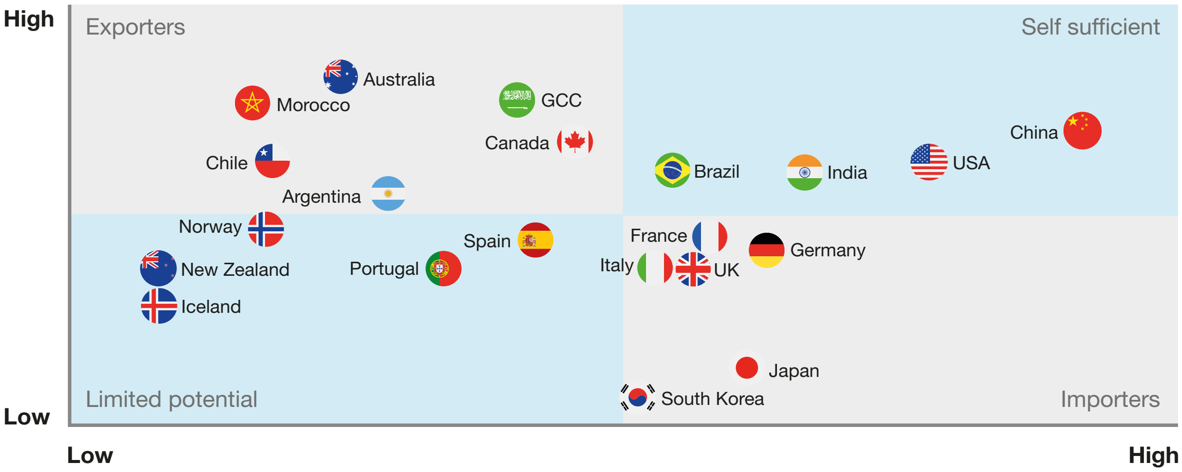
The roles of H_2 import and export will depend on each country's individual production and consumption potential. Europe is expected to see less overall demand than the US or China, even though the largest share of current H_2 pilots and projects is concentrated in Europe. Overall, the existing use of H_2 across Europe, the US and China will continue to focus on refining, chemical and other industrial uses. However, the expectation of H_2 market growth is based on the assumption that H_2 production can transition to low-carbon processes – first to blue H_2 via carbon capture and storage, and then to green H_2 via electrolysis. For example, Europe sees the share of green and blue H_2 reaching up to 75% and 15%, respectively, by 2050.

The share of renewables in hydrogen production is still very small, but the widely shared assumption is that in order for the global hydrogen economy to truly take off, green H_2 will need to achieve cost-competitiveness over the next decade. This will, in turn, unlock an exponential growth potential driven by new application areas. The volume of hydrogen used as an industrial process feedstock is expected to remain relatively constant over the upcoming decades. Instead, the most significant growth is likely to come from new H_2-based solutions in e.g. transportation, heating and power generation.

GLOBAL IMPORT & EXPORT SCENARIOS

The H_2 economy will rely on a global production network that will depend principally on the ready availability of renewable power sources, usually wind or solar photovoltaic generation. In addition to solar farms and onshore wind turbine installations, offshore ocean wind farms are an interesting new concept that is currently being piloted by multiple energy companies around the world.

The long-term roles of H_2 import and export will differ widely between countries once the market matures. Europe has limited green H_2 production potential but is expected to be a major importer of hydrogen. Conversely, countries such as



Australia and Morocco have very high production potential due to the ready availability of photovoltaic and/or onshore wind power, but will see relatively little H_2 consumption. The United States and China are expected to be at the forefront of both hydrogen production and consumption.

Green H_2 will become more economical over time, and as regions reach the point of breakeven costs for production, they are likely to become exporters. Without a price on carbon emissions, grey hydrogen is currently inexpensive at €1 to €2 per kilogram. By contrast, green H_2 is significantly more expensive, currently costing €3 to €8/kg in Europe, and €3 to €5/kg in regions with abundant, low-cost renewable resources (e.g. the Middle East, Africa, the US and Australia).

The key factor that underpins all of these long-term predictions is that for the H_2 economy to take off, green H_2 needs to become cost competitive within this next decade.

Hydrogen production costs are expected to decrease by around 50% through 2030, and then continue to fall steadily at a slightly slower rate until 2050. By 2050, green H_2 production costs in the Middle East, Africa, China, the US and Australia are predicted to be in the range of €1 to €1.5/kg. Over the same time period, production costs in regions with limited renewable resources, such as large parts of Europe, Japan or Korea, will be approximately €2/kg, making these markets likely importers of green hydrogen from elsewhere.

The key factor that underpins all of these long-term productions is that for the H_2 economy to take off, green H_2 needs to become cost-competitive within this next decade. The cost structure of green hydrogen is driven mainly by local electricity prices for the electrolyzers used to produce it. By the 2050s, large-scale, centralised electrolysis is expected to supply the majority of green hydrogen.

Blue hydrogen (manufactured from natural gas with carbon capture and sequestration) can kick-start the transition by supplying low-carbon H_2 to companies that do not want to wait for green hydrogen costs to come down. Blue hydrogen currently bears additional costs of $55-80 USD per ton of CO_2. Despite the steady decrease of the levelised cost of energy (LCOE) of renewables over the last several years, it is clear that both green and blue hydrogen will require decisive policy incentives in order to become competitive with fossil fuels.

4 Green H_2 efficiency from source to battery

There are two key factors that have a significant effect on the carbon footprint and total energy consumption of green hydrogen based transportation solutions. Firstly, green H_2 requires green energy for its generation by electrolysis. In other words, it is only as sustainable as the electricity used for its production.

Secondly, the conversions from electricity to hydrogen in the electrolyzer and back to electricity in the fuel cell will always involve energy losses. These losses are important when comparing the overall energy consumption and sustainability of H_2-based mobility solutions to alternatives based on grid electricity.

STORAGE AND TRANSPORTATION CONSIDERATIONS

One of the major benefits of H_2 is that since it is a gas, it can be used as a form of long-term energy storage, or as an energy carrier that can be transported with relative ease e.g. by ship, tanker or pipeline. However, H_2 does not exist naturally so it always needs to be produced or converted from other feedstock substances or energy forms.

Hydrogen has an energy content that is three times higher than that of gasoline for one kilogram of substance. However, 1 kg of hydrogen takes up a much larger volume than gasoline – approximately 12,000 standard litres at atmospheric pressure, or 40 litres at a pressure of 300 bar. Hydrogen also has a very low critical temperature, i.e. the highest temperature at which a substance can be liquified. For H_2, the critical temperature is 33.1° K (-240° C) with a pressure of 1.3 MPa (13 bar). This means that liquifying hydrogen is an extremely energy-intensive process that will consume up to a third of the energy content of the gas.

The majority of H_2 production currently takes place at locations that are connected to existing refining and chemical industry operations. Many of these industrial hubs are near ports, which are expected to play a major role in the future hydrogen economy, whether through ship refuelling with H_2-based fuels, or managing the import, export or production of green H_2.

There are several ways to transport hydrogen from production to the end consumer, with the ideal method depending on the volume and distance. Pipelines are particularly cost-effective when transporting large volumes of hydrogen, and are thus ideally suited for delivering hydrogen to clusters of large industrial users.

KEY INSIGHTS **Applied in near term**

Transportation costs of hydrogen are primarily driven by volumes and by distance, with different transport modes being the most cost-effective for different combinations of these drivers:

Transport by pipeline **In local hubs**

Particularly cost-effective when transporting large volumes of hydrogen, and is thus ideally suited for delivering hydrogen to clusters of large industrial users.

Transport by ship **On selective routes**

The only way to move hydrogen over distanaces when pipelines are no longer cost-effective.

Transport via truck **For pilot projects**

Particularly cost-effective when transporting small volumes and when the end user is not located near pipelines.

Hydrogen transportation options

Both in Europe and the US, the continent-wide hydrogen pipeline network is expected to expand rapidly from early-stage hydrogen supply and demand hubs. In Europe, the total hydrogen backbone in 2040 could have a total length of 22,900 km, consisting of approximately 75% retrofitted existing gas infrastructure and 25% of new hydrogen pipelines. At that point, the network would be able to meet the projected 1130 TWh of annual hydrogen demand in Europe.

In the US and China, extensive existing natural gas pipeline networks could potentially be used for distributing hydrogen. Green H_2 can be blended with natural gas in concentrations of 5 to 30% by volume, helping significantly reduce emissions if the H_2 can be utilised to decarbonise multiple end user sectors.

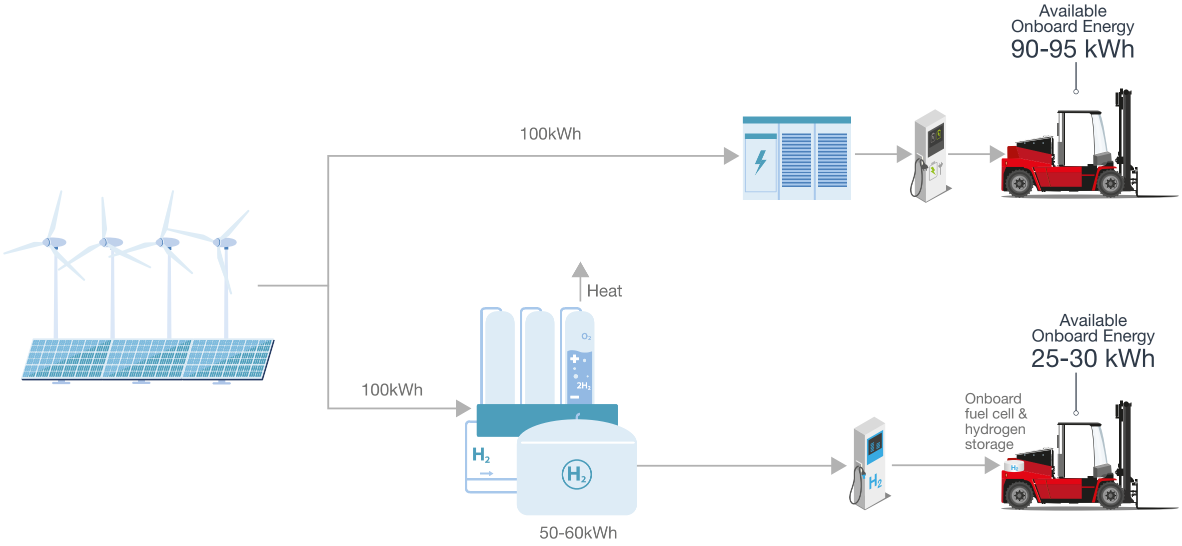
For long-distance transportation of H_2 on routes where pipelines are no longer cost-effective, transport by ship is the only option. This can be accomplished via liquefaction of the H_2 or by converting it to an intermediate substance such as ammonia or a liquid hydrogen organic carrier (LOHC), an organic compound that can absorb or release hydrogen via chemical reactions.

Finally, transportation via truck is a viable option for transporting small volumes of H_2, or when the end user is not located near a pipeline. Similar considerations to ship transport apply; however, in both cases, conversions should be avoided whenever possible.

ENERGY LOSSES IN CONVERSION

As a rough example, we can consider two scenarios in which green electricity is used to power a container handling machine or vehicle with a fully electric driveline. For a battery-powered electric vehicle, 100 kWh of electricity from the grid will result in approximately 90 kWh that is usable by the vehicle, after losses from the charging system.

By contrast, if 100 kWh of electricity is used to produce H_2 by electrolysis, some 40-50 kWh of energy will be lost as heat in the electrolysis process. In the fuel cell on the vehicle, the hydrogen will be converted back to electricity, incurring additional losses. As a result, of the 100 kWh originally drawn from the grid, only 25-30 kWh will remain as usable onboard electric energy for the vehicle.



As a general rule, it can be stated that in container handling applications, electricity is the most usable and purest energy form and should be used without conversions as much as possible. However, if green electricity is abundantly available, conversion into H_2 for storing energy could be a good option.

5 Potential of H_2 in container handling applications

COST CALCULATIONS AND COMPARISONS

In the examples below, we will walk through dimensioning, cost estimate and energy usage calculations for a complete fuel cell based solution to replace an onboard battery-powered electric system. The calculations are done for three different types of machine: a terminal tractor, medium forklift truck and reachstacker. The dimensioning calculations are simplified for the purpose of illustration but are representative of the general scenario. In addition to fuel cell electric vehicles (FCEV) and battery electric vehicles (BEV), energy costs for a traditional diesel-powered solution are included as a reference.

The equipment cost calculations are based on expected manufacturing runs of approximately 100 units per year. It is important to note that these volumes are significantly smaller than those for battery-powered cars or trucks, where yearly manufacturing volumes could easily be in the range of 100,000 to 1,000,000 vehicles. The component and system prices used in the estimates below are indicative OEM purchase prices, not end customer buying prices. Furthermore, no development costs are included in the calculations.

Definitions

P_{avg} = Average used power of the electric vehicle [kW]
P_{peak} = Peak power of the electric vehicle [kW]
P_{FC} = Rated (max) power of the fuel cell pack [kW]
$P_{cooling}$ = Required cooling power of the fuel cell pack [kW]
t_{op} = Operation time without refuelling/recharging [h]
E_{FCbat} = Available battery capacity in the fuel cell system [kWh]
E_{H2} = Available hydrogen capacity [kg]
E_{op} = Energy used during operation
E_{BEV} = Available battery capacity in the battery electric vehicle [kWh]
C = Battery charge/discharge factor

High level simple dimensioning proposal

$P_{FC} = 2 \times P_{avg}$ [kW] (for efficiency & lifetime of the fuel cell)
$P_{cooling} = P_{FC} / 2$ [kW] (50% efficiency of the fuel cell)
$E_{op} = P_{avg} \times t_{op}$ [kWh]
$E_{H2} = E_{op} \times 0.0599$ [kg]
$E_{FCbat} = P_{FC} \times 1$ (h) [kWh] (proposal)
$C = P_{peak} / E_{FCbat}$ [1/h] (C>2 requires power battery)
$E_{BEV} = E_{op}$ [kWh]

Estimates & comparison 1: Terminal tractor FCEV vs. BEV

Input and assumptions

P_{avg} = **15 kW**

P_{peak} = **125 kW**

t_{op} = **8 h**

Fuel cell pack price: **750 €/kW @ volumes below 100**

H_2 tank price: **1,000 €/kg**

Battery price: **Energy type 250 €/kWh**
Power type 750 €/kWh

Fuel cell cooling system: **100 €/kW**

Installation and auxiliaries: **10,000 €**

Diesel price in 2025: **1.9 €/litre**

Green H_2 price in 2025: **8 €/kg**

Green electricity price in 2025: **0.13 €/kWh**

High level simple dimensioning proposal

$P_{FC} = 2 \times P_{avg}$ = **30 kW**

$P_{cooling} = P_{FC} / 2$ = **15 kW**

$E_{op} = P_{avg} \times t_{op}$ = **120 kWh**

$E_{H2} = E_{op} \times 0.0599$ = **7.2 kg (minimum 8 kg tank)**

$E_{FCbat} = P_{FC} \times 1$ (h) = **30 kWh**

$C = P_{peak} / E_{FCbat}$ = **125/30 = 4.2** => Power battery needed

$E_{BEV} = E_{op}$ = **120 kWh (150 kWh capacity)**

OUTCOMES	
FCEV system cost	**64.5 k€**
BEV system cost	**37.5 k€**
Energy cost diesel vehicle	**8.37 €/h**
Energy cost H_2 FCEV	**5.39 €/h**
Energy cost BEV	**1.46 €/h**

Estimates & comparison 2: Medium forklift truck FCEV vs. BEV

Input and assumptions

P_{avg} = **25 kW**

P_{peak} = **170 kW**

t_{op} = **8 h**

Fuel cell pack price: **750 €/kW @ volumes below 100**

H_2 tank price: **1,000 €/kg**

Battery price: **Energy type 250 €/kWh**
Power type 750 €/kWh

Fuel cell cooling system: **100 €/kW**

Installation and auxiliaries: **10,000 €**

Diesel price in 2025: **1.9 €/litre**

Green H_2 price in 2025: **8 €/kg**

Green electricity price in 2025: **0.13 €/kWh**

High level simple dimensioning proposal

$P_{FC} = 2 \times P_{avg}$ = **50 kW**

$P_{cooling} = P_{FC} / 2$ = **25 kW**

$E_{op} = P_{avg} \times t_{op}$ = **200 kWh**

$E_{H2} = E_{op} \times 0.0599$ = **12.0 kg (minimum 13.3 kg tank)**

$E_{FCbat} = P_{FC} \times 1$ (h) = **50 kWh**

$C = P_{peak} / E_{FCbat}$ = **170/50 = 3.4** => Power battery needed

$E_{BEV} = E_{op}$ = **200 kWh (250 kWh capacity)**

OUTCOMES	
FCEV system cost	**100.8 k€**
BEV system cost	**62.5 k€**
Energy cost diesel vehicle	**13.96 €/h**
Energy cost H_2 FCEV	**8.99 €/h**
Energy cost BEV	**2.44 €/h**

Estimates & comparison 3: Reachstacker and Straddle Carrier FCEV vs. BEV

Input and assumptions

P_{avg} = **60 kW**

P_{peak} = **270 kW**

t_{op} = **8 h**

Fuel cell pack price: **750 €/kW @ volumes below 100**

H_2 tank price: **1,000 €/kg**

Battery price: **Energy type 250 €/kWh**
Power type 750 €/kWh

Fuel cell cooling system: **100 €/kW**

Installation and auxiliaries: **10,000 €**

Diesel price in 2025: **1.9 €/litre**

Green H_2 price in 2025: **8 €/kg**

Green electricity price in 2025: **0.13 €/kWh**

High level simple dimensioning proposal

$P_{FC} = 2 \times P_{avg}$ = **120 kW**

$P_{cooling} = P_{FC} / 2$ = **60 kW**

$E_{op} = P_{avg} \times t_{op}$ = **480 kWh**

$E_{H2} = E_{op} \times 0.0599$ = **28.8 kg (minimum 32 kg tank)**

$E_{FCbat} = P_{FC} \times 1$ (h) = **120 kWh**

$C = P_{peak} / E_{FCbat}$ = **270/120** = **2.2** => Power battery needed

$E_{BEV} = E_{op}$ = **480 kWh (600 kWh capacity)**

OUTCOMES	
FCEV system cost	**228.0 k€**
BEV system cost	**150.0 k€**
Energy cost diesel vehicle	**33.49 €/h**
Energy cost H_2 FCEV	**21.56 €/h**
Energy cost BEV	**5.85 €/h**

To summarize, in the vast majority of use cases, when taking into account the unavoidable efficiency losses entailed in converting between energy forms, grid-powered BEVs will offer significantly lower system and energy costs as well as lower total energy usage compared to H_2 fuel cell powered heavy container handling machines. If green electricity is abundantly available for manufacturing H_2 through electrolysis, fuel cell solutions may well be a viable future option.

In certain highly specific customer scenarios, H_2-based solutions could be an alternative to battery-powered electric systems in the container handling industry. These include situations in which the local electric grid infrastructure is not able to provide enough power, 24/7 operations preclude sufficient recharging times for vehicle batteries, and H_2 is easily and economically available on or near the site, e.g. as a residual from existing process industry.

6 Future roadmap

LONG-TERM OUTLOOK ON MARKET ACTIVITIES 2022/2025/2030–

The new hydrogen economy is likely to have a massive impact on the energy landscape of the next decades...

The full benefits of H_2 and fuel cell technologies will play out when deployed at scale and across multiple applications. As the immediate next steps (2022–2023), we will see markets setting clear ambitions for a H_2 future, continuing to implement early pilots, and announcing further R&D investments. The nascent growth of the hydrogen economy will be accelerated by the applications that are already furthest in H_2 utilization, such as material handling.

Over the next few years, early scale-up will follow in the form of the first large-scale industrial deployments that will lay the groundwork for the further growth of green H_2. Electrolyzers in the 50 to 100 MW power range, along with developing carbon capture and sequestration solutions, will bring down production costs and enable new applications. Expanding H_2 pipeline networks and delivery systems in industry clusters will provide feedstock for e.g. refineries, the steel industry and ports. Along with the next generation of fuel cell electric vehicles, we will see the introduction of hydrogen fuelling stations for heavy-duty vehicles.

In the latter half of the decade (2026–2030), the market will begin to diversify beyond the early adopter geographies and segments. The ammonia, steel and refining industries will begin to transition to low-carbon and green H_2, while hydrogen will start to be blended into the existing natural gas infrastructure for heating. The H_2 infrastructure and electrolytic production will continue to scale up. Along with the first H_2 transmission pipelines, we can expect to see the first H_2-based fuels for shipping and aviation.

In the longer term (2030–), a broader rollout will take place as cost-competitive green H_2 enables utilization across regions and industries. The relevant infrastructure will continue to be built at an accelerating pace, as distribution pipelines, fuelling networks and storage locations take shape across the globe.

Looking towards the future, the direction is clear: The new hydrogen economy is likely to have a massive impact on the energy landscape of the next decades, and as ports and terminals are expected to become key hubs in the global H_2 infrastructure, Kalmar and other logistics industry players need to keep H_2 solutions as a focus area. Even if fuel cells do not yet bring immediate or widespread benefits to powering heavy container handling equipment, future H_2 technologies may well do so.

AUTHORS

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Per-Erik has more than 39 years of experience in R&D for Kalmar's mobile equipment and has for the past five years worked with electrification of the company's heavy machines, addressing the issues and concerns that come with providing a zero emission solution for customers. "The electrification journey for our customers includes so many challenges and concerns that need to be resolved, and that is what makes it so exciting! If I can contribute to making the world a better place for my grandchildren, it's my duty to do so and I'm actually enjoying it very much."

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Mikko works as Product Manager for Kalmar's horizontal transportation solutions. His areas of interest are hybrid and electric power trains for mobile working machines, including charging solutions. In his work, Mikko has focused especially on batteries and other energy storage systems, electric drives and motors. Mikko has more than 20 years of experience in hybrid and electric power line applied research, as well as development of mobile applications. He has participated in the electrification of Kalmar's horizontal transportation equipment from the beginning.

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Mette has worked at Kalmar for six years, focusing on a broad scope of development initiatives for counterbalanced container handlers, including digitalisation, electrification and automation. She has 25 years of experience in product and business development and is now responsible for facilitating Kalmar's reduction of its value chain emissions by 50% before 2030 by decarbonising the supply chain and reducing use phase emissions from cargo handling equipment.

ABOUT THE COMPANY

Kalmar, part of Cargotec, offers the widest range of cargo handling solutions and services to ports, terminals, distribution centres and to heavy industry. Kalmar is the industry forerunner in terminal automation and in energy efficient container handling, with one in four container movements around the globe being handled by a Kalmar solution. Through its extensive product portfolio, global service network and ability to enable a seamless integration of different terminal processes, Kalmar improves the efficiency of every move.

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