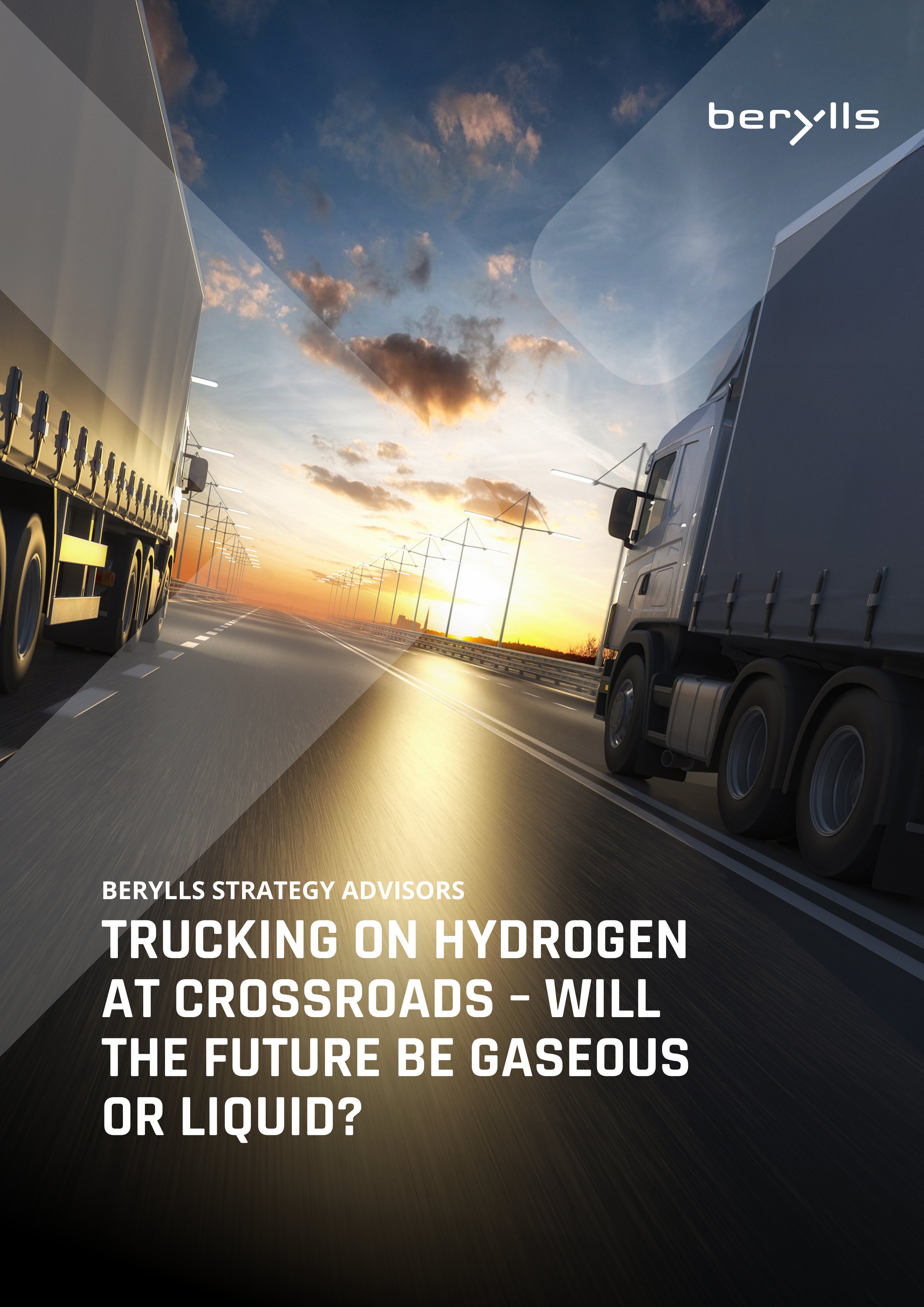


BERYLLS STRATEGY ADVISORS

TRUCKING ON HYDROGEN AT CROSSROADS – WILL THE FUTURE BE GASEOUS OR LIQUID?

AGENDA

INTRODUCTION

Governments all over the world have made clear statements: There is no future for Diesel trucks. Batteries have won the race for the future powertrain technology of cars. Yet, the hurdles are much higher for batteries to be used in trucks: Payload is much more critical, range and recharging times strongly impact costs, chargers which could supply enough power for truck charging are not yet developed, and multiple charge cycles per day drastically decrease battery longevity.

Therefore, many industry experts are certain: Hydrogen will be the energy source that trucks of the future will use. Its high energy density, combined with the comparably easy and speedy refueling make it the ideal fuel for heavy long-haul trucks.

After decades of hydrogen truck development and numerous test vehicles on the roads, there is a last decisive question to be solved: Should the hydrogen distributed by truck refueling stations be gaseous or liquid? Standards must be defined, and technologies developed further. Parallel investment in both scenarios must be avoided. The choice depends on user requirements, truck technology, infrastructure build-out, and the sourcing of hydrogen.

TWO MAJOR PATHS

Looking at the volumetric density, liquid hydrogen has clear advantages over the currently available gaseous hydrogen.

It makes the packaging of hydrogen tanks on fuel cell trucks easier and increases their range, it simplifies the distribution with ships, railcars, and trucks and reduces the space required for the storage at refueling stations. However, liquification increases the energy demand of hydrogen production by approximately one third. And it requires storage at - 253°C, causing continuous losses due to the so-called boil off effect.

If we imagine a true hydrogen society – as outlined in several policy statements launched by governments worldwide – hydrogen will be a major energy carrier of the future. It will provide large-scale storage for the fluctuating renewable power generated by wind and sun at close to zero marginal cost. It will fuel a variety of industries like chemistry and steel (sector coupling). And it will be distributed by a ubiquitous pipeline network, just like natural gas today. In such a world, a parallel supply chain for liquified hydrogen makes little sense.

MULTIPLE OPTIONS ON THE TABLE: GAS IN DIFFERENT PRESSURE LEVELS, CRYO-COMPRESSED, LIQUID

Hydrogen at ambient conditions has a very low density and is 15 times more lightweight than air.

It is therefore necessary to increase the density of hydrogen so that sufficient amounts of energy fit into the truck tank. This can be either achieved by compressing the hydrogen or cooling it down until it liquefies.

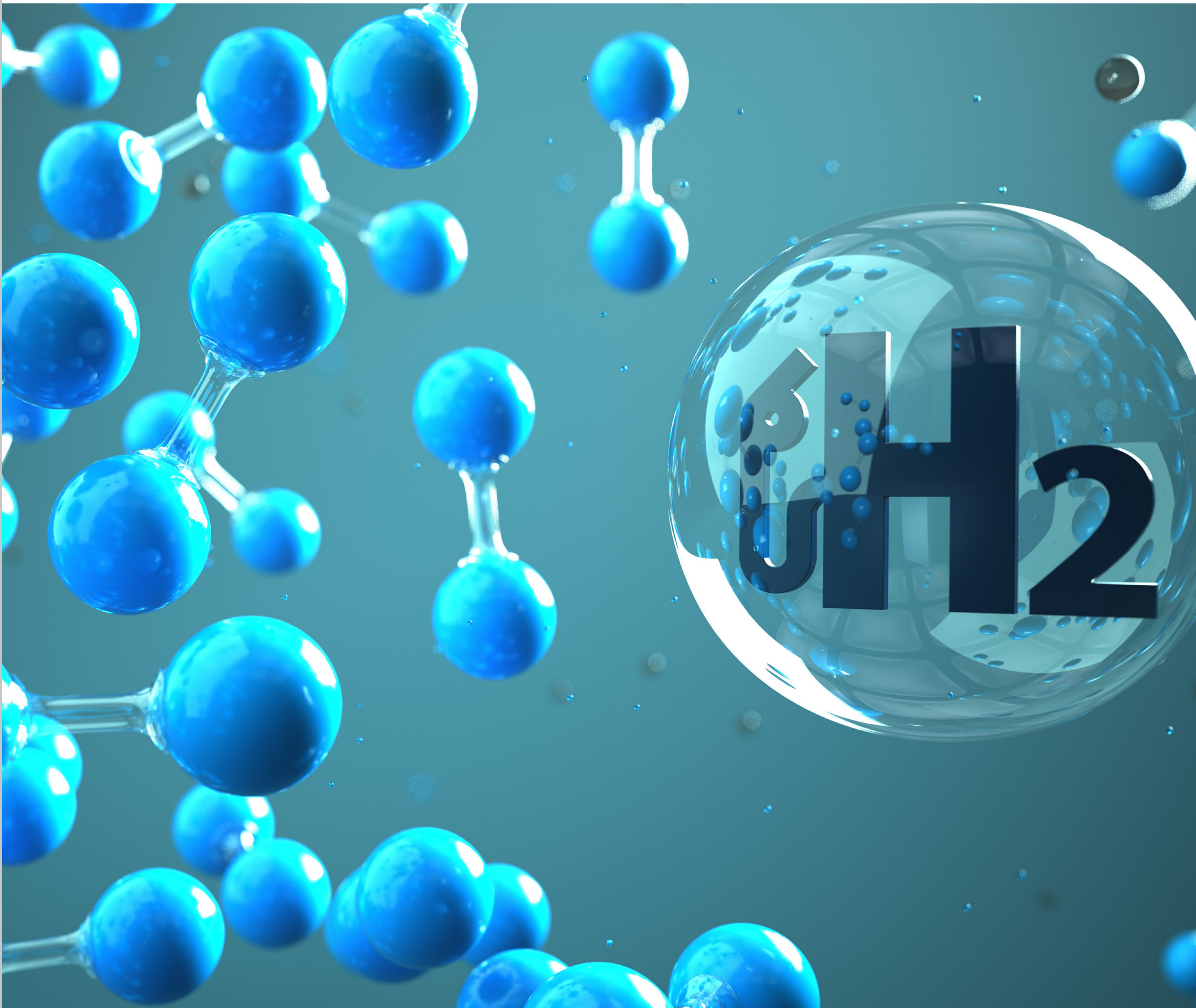
So far there are four forms which could be used in vehicles: Gaseous hydrogen at pressure levels of 350 bar and 700 bar, liquid hydrogen, and the so-called cryo-compressed form, which can be seen as both pressurized and cooled to temperatures close to liquefaction.

	Gas 350 bar	Gas 700 bar (cGH2)	Liquid (LH2)	Cryo-compressed
Pressure in bar	350	700	4	300
Temperature	ambient	ambient	- 253°C	- 235°C
Density in kg/m³	24	40	70	80
Compression and cooling energy in kWh/kg	2	3…5	10	3
Tank requirements	Carbon fiber pressure tanks	Carbon fiber pressure tanks	Stainless steel tanks	Stainless steel tanks
Technological maturity for trucks	High	Medium	Medium	Low
Application examples	Hyundai Xcient heavy duty truck, buses, trains	Nikola Tre, cars like Toyota Mirai, Hyundai Nexo	Daimler GenH2 Truck	BMW Hydrogen 7

Most importantly, the forms differ in the space required to store a defined amount of hydrogen and in the energy required to produce them. Essentially, there is a trade-off between energy density on one side, and energy costs for compression and cooling on the other.

As a technological decision for one of the technologies is required soon and first vehicles are slated for series production by 2023, the current level of technological maturity of in-vehicle and refueling equipment plays a crucial role.

The most mature technology as of today is 350 bar cGH2. It is in commercial operation in several Hyundai Xcient trucks, mostly operated in Switzerland. Yet the latest OEM proposals for hydrogen trucks bet on other technologies.



THE RACE IS DOWN TO LH2 AND 700 BAR cGH2

Although 350-bar-technology is the most mature, its rather low density disqualifies it for the most important future applications.

Design studies from OEMs show that the necessary amount of hydrogen for a useful range of at least 800 km required for long-haul cannot be fitted in current designs. Even worse for the technology, the medium-haul segments where these trucks are currently running, are expected to go battery electric in the long-term as battery vehicles are just the cheaper option for this less range and payload-sensitive application. Therefore, there is no future for today's 350-bar-technology.

Instead, energy forms with densities of at least 40 kg/m^3 must be looked at for the future fuel cell trucks. Among all forms, cryo-compressed hydrogen has the highest density. Its handling, however, is delicate. Cryo-compressed hydrogen is neither gaseous nor liquid, a state called supercritical, and requires new technologies for refueling and storage. Therefore, cryo-compressed hydrogen is not expected to be in commercial truck operation in the near future.

So the race is down to 700 bar cGH2 versus LH2. Both forms can be expected to reach technological maturity within the next years and both forms offer a sufficiently high energy density for long haul-trucks. Among the two, LH2 can be transported more easily and requires less space. 700 bar cGH2 requires less energy for production and can be efficiently transported in pipelines, which additionally allow for seasonal storage capacity.

„700 bar cGH2 offers a higher energy density than 350 bar, but in the long term, even that will not be sufficient"

Head of R&D, Truck OEM

ENERGY EFFICIENCY IS KEY

The most crucial factor for fuel cell trucks to reach large-scale market adoption is the cost of hydrogen.

Experts agree that hydrogen in trucking can only work if the costs at the pump are at or below 5 €/kg. These costs are directly determined by the choice for LH2 or 700 bar cGH2 technologies. If supply chains are not aligned for one of the two forms, hydrogen can become prohibitively expensive. Consider a scenario where hydrogen is only available in gaseous form, but trucks require LH2: Liquefaction at the refueling station with network electricity at 0.20 €/kWh would amount to 2 €/kg only for the reforming. These incremental costs alone make fuel cell trucks uneconomic.

CUSTOMER REQUIREMENTS

Refueling will inevitably change in the initial age of green trucking.

Whether it is recharging or hydrogen refueling, future route planning will need to consider a less dense network than today, and longer refueling times. With an expected network of around 300 hydrogen refueling stations in Europe by 2030, detours will often be inevitable. In addition, refueling of hydrogen currently takes up to 30 minutes, however, improvements can be expected.

Both detours and refueling times are cost factors for fleet operators. Refueling times favor cGH2. With current technology, an advantage of 10 minutes can be expected over LH2. Converting the added costs, the advantage for cGH2 is in the range of 0.10 €/kg hydrogen.

Contrarily, LH2 allows for significantly higher ranges, therefore decreasing the cost for detours, as they occur less often. Based on data provided by the German Federal Motor Vehicle Office (Kraftfahrtbundesamt), we assume that liquid hydrogen eliminates the need to refuel on the route in 20% of the relevant cases. The operational cost advantage for LH2 sums up to 0.22 €/kg hydrogen. ❯

„The race will be won by the technology which is the easiest to operate for the customer"

CEO, Logistics Consultancy

Furthermore, the increased range gives operators an additional margin in case of higher-than-expected fuel consumption or longer routes and is a factor which should not be underestimated.

Overall, fleet operators would obviously prefer the increased flexibility of liquid hydrogen, unless the additional cost for liquefaction overcompensate the operational benefits. Regarding the pros and cons of each technology, OEMs are expected to preempt future customer needs.

WHERE WILL THE FUTURE HYDROGEN COME FROM?

The shift to green energy offers the unique opportunity to become independent from foreign energy exports by producing renewable fuel in Germany.

The amount of additional renewable energy required is, however, enormous. With most recent projections, the hydrogen demand would take up more than all renewable power currently installed. It is more than questionable whether sufficient solar and wind power capacity can be built. Therefore, and despite

some studies arguing for the cost competitiveness of locally produced hydrogen, most experts consider hydrogen imports as the main source.

The costs for hydrogen production in certain foreign countries will be significantly lower than in Germany. One factor is that many regions have more sun and wind than Germany, so that the same wind turbine or solar panel produces more electricity, bringing down levelized cost of energy (LCOE). Secondly, electrolyzers are expensive and need maximum operating hours to be cost-efficient. This is not possible in Germany, where onshore wind and solar achieve load factors of 25% and 12%, respectively.

Many countries come into question as a source for hydrogen. Northern Europe has ample wind and hydropower, while e.g., northern Africa and the Middle East are suitable for solar power. Whatever the source of the energy, it is likely that imports will come as LH2 by ship as for most of those regions, it is infeasible to have hydrogen pipelines installed.

Strategically, countries will prefer to source liquid hydrogen as a global commodity from multiple regions in parallel to keep the supply risk low.

THE ENTIRE SUPPLY CHAIN NEEDS TO BE CONSIDERED

The production site of the hydrogen has a major impact on the technological choice.

If hydrogen is produced locally and transported via pipelines, there is no need for the energy-intensive liquefaction and the cost impact of truck distribution is minor.

Contrarily, hydrogen arriving by ship from overseas will rather be liquid and could remain liquid through the entire transport chain. Energy-intense liquefaction can happen at the hydrogen production sites with low-cost green energy.

A mixing of the two alternatives is not economic: warming and compression of the LH2 from ships for a pipeline transport, with expansion and liquefaction for the last-mile transport is prohibitively inefficient and expensive.

The technological decision for either cGH2 or LH2 therefore largely depends on the future sources of hydrogen.

HOW DOES THE HYDROGEN REACH THE TRUCK?

Despite ample discussions about repurposing natural gas pipelines or building new ones, the completion of a reliable network of hydrogen pipelines cannot be expected soon.

In addition, it is not economically viable to connect every refueling station to a pipeline. Therefore, hydrogen will be transported with trucks at least on the last mile.

This is where a decision for either cGH2 or LH2 comes into play: Fuel supply trucks can carry either 1,000 kg of cGH2, or 4,000 kg of LH2. This constitutes a substantial transport cost advantage for LH2. For an average transport distance of 300 km to the closest distribution hub, LH2 has an advantage of 0.54 €/kg over cGH2.

In the end, this means that, as long as there is no comprehensive pipeline network, the impact of transport costs strongly speaks for using LH2.

At refueling stations, the higher density of LH2 is an advantage again, as there is less space required to store the fuel. Furthermore, compressors and pumps are simpler in the case of LH2. The overall cost advantage of refueling stations running on LH2 rather than cGH2 is approximately 0.42 €/kg.

OUTLOOK: WHAT DOES THAT MEAN FOR SELECTING A TECHNOLOGY?

An efficient future hydrogen supply chain can work in two different ways:

A supply chain for gaseous hydrogen would rely on locally produced hydrogen, transported to major hubs through pipelines. In this case, energy-intense liquefaction is avoided entirely, and transport costs are kept low by using trucks only for the last mile.

A liquid hydrogen supply chain entails global sourcing of hydrogen, including liquefaction and transport by ship and truck. In this case the energy-intense liquefaction happens at the location with cheap and ample energy, and transport costs are kept low as the liquid hydrogen is comparably dense.

Ultimately, total cost of operation (TCO) will decide which form of hydrogen will prevail in the future. Strategic, technical, and operational aspects are clearly in favor of liquid hydrogen. So, in a case where the costs through both supply chains described above are on a similar level, the higher range and flexibility of LH2 trucks can become the decisive factor.

By the way: Almost 60% of the respondents of our expert survey "Trucking 2030" supported the view that liquid hydrogen will be the best option for refueling trucks in the future. The challenge is now to prove not only the technical feasibility, but also the economic viability of that technology path.

NEED FOR ACTION

In a nutshell, a joint effort along the entire hydrogen value chain is required.

And OEMs and their suppliers are the main actors. They need to align with their partners to ensure that hydrogen supply and distribution is ready when needed so that fuel cell electric trucks can be launched successfully.

A quick roll-out of pilots to qualify technologies is needed. Safety and viability need to be proven so that we are ready for a firm decision on large-scale ramp-up before 2025. Along the value chain, all players need to have their products ready. **These especially include:**

- **Scalable and efficient new truck architectures by OEMs,**
- **Affordable and modular fuel cells, tanks, and refueling equipment from the supplier side,**
- **Accessible refueling infrastructure at strategically important sites for the roll-out, ready to serve as a backbone for a growing network,**
- **Hydrogen carrying trailers**
- **A logistics network for an efficient supply of refueling stations.**

The shift away from a former core business and towards hydrogen technology, pushing the technological boundaries, is not an easy one. New business models, new competencies and new partnerships are required. Prepare for the future of trucking on hydrogen: Define your strategic target picture, adjust your business model and value proposition, transform your organization and thoroughly plan a successful go-to-market.

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BERYLLS STRATEGY ADVISORS

YOUR CONTACT PERSONS

T +49-89-710 410 40-0

info@berylls.com

Steffen Stumpp
steffen.stumpp@berylls.com
T +49 152 27 27 83 27

Florian Müller
florian.mueller@berylls.com
T +49 151 22 35 48 10