氢能对能源脱碳的推动作用[1]

综述

在未来的众多“净零”碳排放情景中，氢能都将成为重要的能源载体，因为在某些行业，与电力相比，氢能具有特定优势。然而，氢能的技术路径和最终规模存在许多不确定性，其发展速度取决于诸多因素。

本文将介绍氢能的需求和供给现状，并探究在未来能源体系脱碳进程中，这种能源载体将面临哪些机遇。

- 目前，大部分氢能需求来自工业领域，其基本需求将推动低碳氢能的引入。产业集群让基本需求用户得以与生产基地及其他小容量氢能消费者集中于同一地点。靠近枯竭气田的产业集群是蓝氢生产的有利选址，因为既有利于满足工业氢能需求，又方便利用天然气运输基础设施和枯竭气田来实施碳捕集和封存。

- 在轻型运输领域（包括乘用车和小型卡车），电气化是目前主要的脱碳路线。在重型汽车领域，氢能仍具有潜在的吸引力，其原因包括：续航里程长、有效载荷能力强且无动力损失，并且能快速完成燃料补给。因此，对于长途出行，氢能汽车比电池电动汽车更具明显优势。因此，在此领域，氢能可发挥重要作用，但其潜在需求远低于工业领域。此外，研究人员正在探索将氢能用于一些海洋应用，例如，在区域渡轮上开展试应用。

目前，氢能生产主要依靠化石燃料，因而无法达到低碳标准。“蓝氢”是使用天然气并利用碳捕集技术制取的，是目前成本最低的低碳氢路线，因而

[1] Shell International Limited（伦敦）Mallika Ishwaran（首席经济学家）和 William King（项目协调负责人）

预计到 2030 年，将成为最大的低碳氢来源。然而，在当前开始开发的“绿氢”项目中，氢气是通过使用风力或太阳能发电电力，通过电解而制得的。

本文旨在对氢能的现状和前景进行循证评估，其中包括世界各地氢的新用途、低碳氢生产和氢基础设施开发有关的案例。此外，本文还将基于从这些案例及其他经验中吸取的教训，探究如何鼓励或刺激氢能供给与需求的发展。

氢能对能源脱碳的推动作用

I. 背景

在未来的众多“净零”碳排放情景中，氢能都将成为重要的能源载体，因为与电力相比，氢能具有一系列有利的优势。氢能燃烧燃点高、无污染、相对容易储存，并且能量密度高。因此，在工业和一些无法实施电气化的运输领域，对于一些难以实现减排的应用，氢能成为具有吸引力的脱碳路径。

低碳氢仍需要经过长足发展，以达到商业可行性。这是一个复杂的问题，涉及价值链的各个方面——供给、基础设施和需求（例如，将使用氢能的设备）。然而，至于这种长足发展是否会发生，以及将如何发生，还存在许多不确定性——正因如此，对于氢能在未来各种能源体系情景中的应用规模，人们的预期存在较大差异。

在过去，氢能虽吸引了一波又一波的关注，但每次都未能得到广泛应用。20 世纪 70 年代，石油输出国组织（OPEC）实施石油出口禁令，导致油价暴涨，刺激石油行业开始探寻包括氢能在内的替代燃料。然而，20 世纪 80 年代，当油价跌回 25 美元/桶时（按实际价值计算）时，这一想法被放弃。

21 世纪初，有关将氢能作为低碳能源载体的想法再次浮出水面，但实际部署仅限于非商业试验和试点。本田、日产、福特和通用汽车纷纷推出量产就绪的燃料电池汽车，但未能引起消费者的兴趣。

目前，在全球新一波关注下，氢能有望达到所需规模，从而驱使氢能技术成本下降至商业可行水平。例如，美国《通胀削减法案》规定，对低碳氢生产提供 3 美元/千克的大额补贴。

目前的氢能总需求相对较小。氢能主要被用于工业中的氨和甲醇生产

（超过总需求的 50%），以及为炼油厂提供化学原料（超过总需求的 40%）。

随着相关投资、政策战略和氢能项目规模的迅速发展，许多国家（经合组织国家等及其他国家）宣布了氢能战略路线图，对扩大氢能应用规模给予了政策支持。

本报告中使用了一些与氢能相关的常见术语，相应解释分别如下：

- 灰氢、黑氢和棕氢是指使用化石燃料（分别为天然气、煤炭和褐煤），通过热化学过程制取的氢气。

蓝氢、绿氢和粉氢属于低碳氢。绿氢和粉氢是指使用可再生电力（绿氢）或核能（粉氢），通过电解制取的氢气，它们是零碳氢。蓝氢是指使用化石燃料，通过碳捕集、利用与封存技术（CCUS）制取的氢气。捕集的碳量取决于项目设计和技术。

- 电解是一种利用电力，将水分解为其组成元素（氢和氧）的电化学过程。
- FCEV 和 FCH 是指燃料电池电动汽车（FCEV）和氢燃料电池（FCH）。它们分别被用于氢动力运输和氢动力重型机械。

II. 氢能需求

目前的氢气总需求为 9500 万吨。氢气主要被用作工业原料。目前，超过 40%的氢气被用作炼油厂的化学原料。约 30%的氢气被用于生产农用产品制造中所需的氨，其余大部分被用于生产化学品制造中所需的甲醇。氢气的其他用途（例如玻璃制造、电子产品生产和运输）不到总需求的 5%。过去 40 年来，氢气需求一直在增长。

在运输业，氢气被直接用作燃料，其需求量目前可忽略不计。随着能源转型的推进，氢气的应用案例将日益增多，尤其是低碳氢——已成为脱碳途

径的一部分。

a. 工业

随着一系列新的应用领域对低碳氢的需求开始增长，我们也开始面临一项挑战，即确保供给、需求及所需基础设施共同发展。没有供给就没有需求；反过来，假如需求难以迅速形成，那么新的生产设施和基础设施的建设将面临资金困境。

目前，由于大量使用氢气，工业对氢气的需求自然构成了一项基本需求。该需求最初可通过“灰氢”来解决，这种氢气是使用未经碳捕集的天然气制取的，碳排放量较高。预计在得到恰当碳价格或其他赋能因素的支持后，才能成功地以低碳氢来取代灰氢。这一基本需求有助于带头刺激低碳氢的供给，进而促使其供应范围扩展至新出现的应用领域。

低碳氢之应用面临的主要障碍在于，面对液态化石燃料需求的不断下降，以及蓝氢造成的成本增加（相对于灰氢），炼油厂和化工厂的投资预算不足。尤其是对于贸易活跃、本地和国际竞争激烈的工业部门，政府需要出台有利的政策并做出协调。

首批低碳氢生产项目可能采用大规模*集中化*生产，例如，鹿特丹-安特卫普走廊和杰罗姆港（Port Jerome）化工产业园这两个产业集群中的蓝氢项目。此外，这类产业集群日后还可能开发直接还原铁（DRI）、工业供热和合成“电力多元转换”（PtX）燃料等应用。

对于蓝氢生产项目，沿海产业集群是理想的选址，因为其中的炼油厂和化工厂的氢消耗量非常大，而且靠近并可利用近乎枯竭的海上气田（以实施CCUS）及交通基础设施（一旦附近油田枯竭，这些交通基础设施往往面临被搁浅的风险）。

产业集群让工业部门能够与渡轮、卡车、工业供热、水泥和钢铁生产商等附属消费者共址并对接。空间距离的邻近有利于新商业模式的创建和资源共享，从而为需求增长提供基础。

案例研究：鹿特丹 H-Vision 蓝氢项目

这是鹿特丹产业集群中的 16 家公司（包括壳牌）共同实施的一个合作项目。

H-Vision 项目旨在响应荷兰政府提出的在 2050 年前实现气候中立的倡议。2018 年 2 月，为遵守《巴黎协定》，荷兰政府和商界发起了一场关于 CO2 减排目标的讨论。2019 年 6 月，《气候协定》确定了 CO2 减排 49%的目标，并呼吁行业到 2030 年实现减排 1430 万吨，而鹿特丹/穆尔代克产业集群单独就实现了减排 1000 万吨。

H-Vision 该项目的大部分投资来自私营部门，但仍需要获得补贴或其他形式的政策支持。该项目每年可减少 540 万吨 CO2 排放，相当于荷兰工业总排放量的 10%左右。

b. 运输业

目前，在轻型运输领域（包括乘用车和小型货车），电气化是主要的脱碳路径。电动汽车越来越先进、高效，并且其成本逐渐与内燃机汽车趋同。

在重型汽车（HDV）领域，氢能可在远距离运输较重负载方面发挥作用。然而，与工业使用情景相比，此领域对氢能的总需求可能要低得多。对于重型汽车，氢能是一种具有吸引力的燃料，其原因包括：续航里程长、载荷能力强且无动力损失，并且能快速完成燃料补给。2023 年，多家公司推出了续航里程超过 1000 公里的卡车，因此，在远距离出行中，这些卡车相比电池电动汽车更具优势。此外，FCEV 区域配送卡车的燃料补给仅需 3-8 分钟，而配备 600 千瓦充电器的纯电动汽车需要 60 分钟才能完成充电。然而，由于运行成本较高，并且电池技术不断改进，在许多地区，FCEV 卡车的优势已不再明显。

此外，公交车也在氢能应用试验的范围之内。与卡车一样，氢燃料电池公交车的燃料补给速度比电池电动公交车更快，续航里程更长。

与此同时，还有一些小规模运输领域也给氢能提供了应用机遇。

- 对于在大型露天矿场运输矿石的大型运输卡车，效率高、排放低的氢燃料成为具有吸引力的选择。例如，英美资源集团（Anglo American）矿业公司正在南非的 Mogalakwena 矿场，试运行 40 辆氢燃料电池矿车。每辆矿车最多可运载 315 吨矿石，每年以绿氢（使用太阳能制取）取代约 100 万升化石燃料。

- 区域渡轮特别适合以氢燃料为动力。由于这些渡轮每天完成多次航行，周转时间短，因此，燃料补给耗时短是关键，这使得氢动力渡轮具有相对于纯电动渡轮的实质性优势。在公共采购的支持下，一些可获得丰富可再生能源发电电力的地区已开始对渡轮开展氢能应用试验。例如，“MF Hydra”是一艘在挪威运营的液氢动力渡轮，最多可容纳300名乘客和80辆汽车。同时，在该国运营的还有混合动力渡轮和纯电动渡轮，因此，随着时间的推移，这些不同的动力系统的相对优势将得到有效的比较。

- 目前，由于所需劳动力少、维护成本低，投资运营氢燃料电池（FCH）叉车是有利可图的。停机时间少、燃料补给耗时短、无动力损失、维护要求低——这些优势让 FCH 叉车得以在北美和欧洲市场，与普通电动叉车展开竞争（包括生产力和总成本方面）。从规模经济的角度来看，只有大型仓库运营商才有能力运营 FCH 叉车车队并保证盈利（相比于目前更具成本效益的 LPG 叉车）。例如，亚马逊（规模最大的 FCH 叉车车队运营商之一）于2022年签署了一份协议，即明确从2025年开始，每年采购1万吨以上绿氢。这些绿氢可为 30000 台叉车或 800 辆长途运输用重型卡车提供一年所需的动

力）。

c. 隔离地区所需能源

氢能的另一个潜在用途是为隔离地区提供能源，例如，岛屿或偏远社区。这些地区可使用可再生能源，在本地生产氢能并通过短距离运输，为当地交通提供动力，并为住宅和商业建筑供暖。例如，英国奥克尼群岛近十年来一直利用可再生能源发电来获得其所需的全部电力。然而，由于电网容量存在局限，所生产的可再生能源可能发生损耗或浪费，因此，该地区正在开发新的项目——将多余的电力用于制氢，然后将氢能用于多种应用或予以储存。在此基础上，该地区还开发了一些探索性项目，例如，在当地一艘商业渡轮上，开展氢燃料/柴油双燃料转换系统试用试验，以及对一架中程小型客机开展 250 英里的零排放氢动力试飞试验。

III. 氢能的供应及基础设施

目前，氢能生产主要依靠化石燃料，相对而言，全球零碳绿氢的供应量可忽略不计，全球蓝氢供应量仅占总供应量的 1%。

“蓝氢”是使用天然气并利用碳捕集技术制取的，是目前成本最低的低碳氢路线，因而预计到 2030 年，将成为最大的低碳氢来源。在一些国家，由于本土化石燃料供给受限，或者 CO_2 封存空间有限，蓝氢的发展机会也受到限制。由于无法充分获得低成本的本土天然气资源，导致蓝氢的成本上涨。然而，在这些限制（例如，本土化石燃料供给方面的限制）中，一部分可通过进口来解决。例如，尽管韩国本土化石燃料资源极少，但该国已成为世界第五大氢能市场。

虽然与蓝氢相比，绿氢尚不具有成本竞争力，但其成本预计会下降，并且在 2030 年后，绿氢可能长期占据主导地位，尤其是在西欧，以及其他缺

乏充足本土化石燃料资源的区域。

一些拥有丰富的可再生资源和充足的化石燃料储备的国家正在让市场力量来决定低碳氢的发展路径。挪威和美国仍在继续投资于低碳氢关键技术的研发，这些技术包括 CCS、电解槽、CHP 燃料电池，以及以氢作为潜在燃料的模块化天然气工厂。

目前，随着碳价格的不断上涨，蓝氢即将显现成本竞争力，因此，在未来碳价格上涨预期下，围绕蓝氢和绿氢产能的投资受到激励。然而，由于投资回收期长，而且项目、技术和市场方面存在风险，这些投资仍需要获得政府的支持。例如：

- 加拿大最大的蓝氢生产设施之一 Quest 获得了 8.5 亿美元的补贴，并通过提高石油采收率而获益。

- Air Liquide 公司通过将 CCUS 机组与现有的蒸汽甲烷重整（SMR）制氢厂对接，减少了 55%的 CO_2 排放。该公司将这些氢气出售给附近的炼油厂，并将处理后的 CO_2 出售给食品和饮料行业。总体而言，该项目获得的补贴金额接近总资本成本的四分之一。

- 沙特阿拉伯的 Neom 大型开发项目计划开发一座生产绿氢和绿氨的工厂。建成后，该工厂的绿氨产能达到 120 万吨/年。这个耗资达 50 亿美元的项目是沙特公共投资基金支持的重大项目之一，旨在使该国经济多样化，摆脱对石油的依赖。

- NortH2 项目是多家企业共同开展的一个大规模绿氢生产合作项目。该项目将利用海上风力发电电力来生产绿氢，然后将其储存并交付给荷兰及其他地区的工业和重型运输业客户。该项目需要政府的大力支持才能进入最终投资决定（FID）阶段，预计将使用 10GW 的海上风电为电解槽供电，并

计划于 2027 年开始生产绿氢。

各国纷纷开始关注氢能的部署和推广所需的基础设施建设。例如，荷兰认为，自身处于有利的地理位置，可作为向西北欧供应氢能的能源门户，并成为整个欧洲的重要低碳能源中心。为此，该国已开始建设一个总跨度达 1200 公里的氢能输送网络。该网络的前 30 公里预计将于 2025 年投入运营，但整个网络最终将跨越 1200 公里，主要由重新利用的现有天然气管道组成。该网络旨在将大型制氢厂、海港的进口码头，以及荷兰和国外在低碳转型中改用氢能的公司相对接。

IV. 推动氢能发展的因素

有一些政策方面的因素可以帮助推动氢的使用、供应和基础设施的发展。

- 制定具有明确长期目标和中短期里程碑的氢战略。例如，欧盟委员会于 2020 年 7 月发布的欧盟氢战略，以及荷兰的 Klimaat Akkoord（国家气候法案）；
- 制定脱碳氢气生产路径的标准，以及计算生命周期温室气体排放和相关认证的方法。例如，欧盟可持续活动分类法；
- 刺激重型运输和工业等关键部门对脱碳氢气需求的政策，包括结合目标的碳定价。例如，加拿大提出了清洁燃料标准法规，以推动其清洁燃料行业的投资和增长；欧盟委员会提出了欧盟工业的约束性目标，作为 "适合 55 "提案的一部分，即部分转向可再生氢；
- 支持鼓励脱碳氢气项目的机制，减少脱碳氢气与传统生产的氢气之间的成本差异。这些机制包括碳差价合约、增加对项目的公共资助、对脱碳的氢气提供支持性的税收安排、激励可再生能源电力的生产、为研发提供资金支持；

- 支持基础设施规划和投资，为氢能市场发展创造条件。例如，氢能和燃料电池经济国际合作组织 (IPHE) 的法规、规范、标准和安全 (RCSS) 工作组正在推动国际合作，促进基础设施和运输方面的规范和标准的统一。

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The role of Hydrogen as an enabler for energy decarbonisation[1]

Executive Summary

Hydrogen is an important future energy carrier in many 'Net Zero' carbon emission scenarios because in some sectors it has specific advantages compared with electricity. However, the pathway and ultimate scale of hydrogen has many uncertainties, and its pace of development depends on many factors.

This paper looks at the status of both hydrogen demand and hydrogen supply and considers where the future opportunities for this energy carrier may be as the energy system decarbonises.

- Industrial segments currently account for most hydrogen demand and provide the base demand which will help the introduction of low carbon hydrogen. Industrial clusters enable co-location of the base demand users with production facilities and additional smaller volume consumers of hydrogen. Industrial clusters close to near-depleted gas fields are appealing locations for blue hydrogen production due to both the existing industrial consumption of hydrogen and to the potential access to the gas transportation infrastructure and depleted fields for carbon capture and storage.
- In the light duty transport segment (which includes passenger cars and small vans), electrification is now the dominant decarbonisation route. In the heavy-duty vehicle segment, hydrogen is potentially still attractive for several reasons including longer range, high payload capability without loss of power, and fast refuelling. This gives hydrogen a distinct advantage over battery-electric options for long-distance journeys and hydrogen could play a substantial role but with much lower potential demand than for industry. Hydrogen is also being explored for some marine applications and there are, for example, trials with regional ferries.

Hydrogen production is today dominated by fossil fuels and is not low carbon. 'Blue hydrogen', which is produced from gas with carbon capture, is currently the lowest cost route to low carbon hydrogen and hence expected to be the largest source of low carbon hydrogen to 2030. Projects are however starting to be developed for 'green hydrogen' in which the hydrogen is produced by electrolysis using electricity from wind or solar power.

This paper aims to be an evidence-based assessment of the status and outlook for

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hydrogen and includes examples of activities from around the world relating to new hydrogen uses, low carbon hydrogen production, and hydrogen infrastructure development. Based on the learnings from these and other experiences, also included are ways in which the development of both hydrogen supply and hydrogen demand could be encouraged or stimulated.

The role of Hydrogen as an enabler for energy decarbonisation

I. Background

Hydrogen features as an important future energy carrier in many 'Net Zero' carbon emission scenarios because it has some useful advantages over electricity. Hydrogen burns cleanly and at a high temperature, it is relatively easily stored, and it has a high energy density. This makes it attractive to decarbonise several hard-to-abate applications in industry and parts of transport where electrification is not practical.

Low carbon hydrogen still needs considerable development before it is commercially viable. This is a complex issue involving all elements of the value chain - supply, infrastructure, and demand (i.e., the equipment which will use hydrogen). There is a lot of uncertainty about whether and how this development will occur, and this partly explains why, when looking across the various energy system scenarios, there are large differences in the expected future scale of hydrogen.

Hydrogen has attracted waves of interest in the past, but each time wider adoption has failed to take-off. The 1970s oil price shock because of OPEC's oil export embargo led the industry to explore alternative fuels including hydrogen. Aspirations were, however, scrapped when oil prices reduced back to around $25/bbl (in real terms) in the 1980s.

Interest in hydrogen as a low carbon energy carrier resurfaced again at the beginning of the 2000s but deployment did not move beyond non-commercial trials and pilots. Road-ready fuel-cell vehicles were introduced by Honda, Nissan, Ford and GM but failed to gain consumer's interest.

The current new wave of global interest may provide the scale needed to be able to drive hydrogen technology costs down to commercially viable levels. For example, the US Inflation Reduction Act provides a significant $3/kg subsidy for low carbon hydrogen production.

Currently the total demand for hydrogen is relatively small. It is used primarily in industry for ammonia and methanol production (more than 50% of overall demand) and in refineries as chemicals feedstock (more than 40% of overall demand).

The number of investments, policy strategies, and real-world hydrogen projects has been growing rapidly, with many countries (in the OECD and beyond) announcing strategic hydrogen roadmaps and signalling policy support for greater adoption of hydrogen.

There are a number of common terms relating to hydrogen which are used in this report, and these are explained below:

- Grey, black, and brown hydrogen refers to hydrogen produced from the fossil fuels (gas, coal, lignite, respectively) using thermochemical processes. Blue, green and pink hydrogen are low-carbon hydrogen. Green and pink hydrogen are produced via electrolysis with renewable power (green) or nuclear power (pink). Blue hydrogen is produced from fossil-fuels with the carbon capture, utilisation and storage technology (CCUS) installed. The amount of carbon captured depends on the project design and technology.
- Electrolysis is an electrochemical process which uses electricity to split water into its constituent elements (hydrogen and oxygen).
- FCEV and FCH are fuel-cell electric vehicle (FCEV) and hydrogen-fed fuel-cell hydrogen (FCH). They are used to refer to hydrogen powered transport and hydrogen enabled heavy machinery, respectively.

II. Hydrogen Demand

Total hydrogen demand is currently 95 million tonnes. Hydrogen is primarily a feedstock for industry. More than 40% of hydrogen today is used in refineries as a chemical feedstock. About 30% of hydrogen is used for ammonia production for products used in agriculture and most of the remainder is used to produce methanol for use in chemicals manufacture. Other uses of hydrogen, for example, for glassmaking, electronics production and transport are less than 5% of demand. Demand for hydrogen has been growing for the last 40 years.

In the transport sector, the direct use of hydrogen as a fuel is currently negligible.

As the energy transition progresses, there are going to be more use cases, specifically for low carbon hydrogen, as part of the pathway to decarbonisation.

a. Industry

As the demand for low carbon hydrogen starts to grow for new uses, it can be a challenge to ensure supply, demand and the needed infrastructure develop together. There can't be demand without supply, and if demand takes time to develop the economic case is difficult for building new production facilities and infrastructure. Industry creates a natural base demand due to its large existing usage. This can initially be fulfilled by high carbon emissions 'grey' hydrogen which is produced from gas without carbon capture. Successful substitution with low-carbon hydrogen can happen later when the economic case is supported by an adequate carbon price or other enablers. This base demand helps support the initial business case for low carbon hydrogen supply which can then also supply new applications as they emerge.

Key barriers for the adoption of low carbon hydrogen are constrained investment budgets in the refining and chemicals sector given decreasing demand for fossil liquids, and the additional cost of blue hydrogen over grey. Particularly in industry segments where products are highly traded and there is strong local and international competition, enabling policy and co-ordination is required.

The first low carbon hydrogen production is likely to be large scale *centralised* production, for example, blue hydrogen projects in the industrial clusters of Rotterdam-Antwerp corridor and Port Jerome chemical complex. Additional applications such as Direct Reduced Iron (or DRI) steel, industrial heat and synthetic 'Power-to-x' (PtX) fuels can later be developed in such clusters.

Coastal industrial clusters are appealing locations for blue hydrogen production due to the large existing consumption of hydrogen in the refining and chemical sectors, and potential access to the near-depleted offshore gas fields (for CCUS) and transportation infrastructure which is often at risk of being stranded once the nearby fields are depleted.

Industrial clusters enable sector coupling and co-location with the ancillary consumers of hydrogen – ferries, trucks, industrial heat, cement and steel producers. Close spatial proximity is conducive to the creation of new business models and resource sharing – providing a base from which demand could grow.

Case Study: Rotterdam H-Vision Blue Hydrogen Project

This is a collaboration between 16 companies that are present in the Rotterdam Industrial Cluster, including Shell.

H-Vision is a response to the government's initiative to attain climate neutrality by 2050. In February 2018, the Netherlands government and business community launched a discussion on CO_2 *reduction goals to bring the country in alignment with the Paris agreement. The goal of attaining 49% reduction in* CO_2 *emissions was sealed in the Climate Agreement in June 2019, and aims for industry to reduce emissions by 14.3 Mt by 2030, with 10Mt coming from Rotterdam/Moerdijk industrial cluster alone.*

While most of the investment would be private, subsidies or other forms of policy support are still required.

H-Vision can abate 5.4 $MtCO_2$ *per year, equal to approximately 10% of the overall industrial emission in the Netherlands.*

b. Transport

In the light duty transport segment (which includes passenger cars and small vans), electrification is now the dominant decarbonisation route. Electric vehicles are getting better, more efficient and approaching cost parity with internal combustion engine vehicles.

In the heavy-duty vehicle (HDV) segment, hydrogen could play a role in transporting heavier loads over longer distances. However, compared to industry use, total hydrogen demand is likely to be much lower.

Hydrogen is attractive for HDVs for several reasons, including longer range, higher payload capability without loss of power, and fast refuelling. In 2023 several companies unveiled trucks that can run more than 1,000km before needing to refuel, giving them an advantage over battery-electric options for the very longest-distance journeys. Moreover, refuelling of an FCEV regional delivery truck would take 3-8 mins compared to 60 minutes for a battery electric vehicle (BEV) with a 600 kW charger. However, higher running costs and continuing improvement of battery technology have already begun to erode the advantages of FCEV trucks in many geographies.

Hydrogen is also being trialled for buses. As with trucks, hydrogen fuel cell buses can be refuelled much faster and have a longer range than battery-electric buses.

Hydrogen opportunities also exist in other niche transport segments.

- High efficiency and low emissions can make hydrogen attractive for the large haulage trucks which move ore in large opencast mines. For example, the mining company Anglo American is piloting forty hydrogen fuel-cell mining trucks at the Mogalakwena mine in South Africa. Each truck can carry up to 315 tons of ore, with about a million litres of fossil fuel replaced by green hydrogen (using solar power) each year.
- Regional ferries are particularly suitable for hydrogen. As they complete several sailings daily with a short turnaround time, short refuelling times are critical and give hydrogen a substantial advantage over full battery electric ferries. Regions with access to abundant renewable power are already trialling hydrogen technologies in ferries, supported by public procurement. For example, the MF Hydra is a liquid hydrogen-powered ferry which operates in Norway and can accommodate up to 300 passengers and 80 vehicles. Norway does also have hybrid and full electric ferries in operation, so over time, a good comparison of the relative advantages of the different systems will emerge.
- Low labour and servicing cost mean hydrogen forklift trucks can be profitable today. Low downtime, fast refuelling, absence of power loss and low maintenance requirements allow hydrogen (FCH) forklifts to compete against battery-electric alternatives in North American and European markets, both in terms of productivity and overall cost. Economies of scale suggest that only large warehouse operators can currently profitably operate FCH forklift fleets (compared to currently more cost-effective LPG forklifts). For example, Amazon (one of the largest operators of FCH forklift fleets) signed an agreement in 2022 to be supplied with over 10kt/a (10,000 tons per year) of green hydrogen starting in 2025. This is enough annual power for 30,000

forklifts or 800 heavy-duty trucks used in long-haul transportation).

c. Energy for Isolated Areas

There is a potential use for hydrogen is as an energy source for isolated areas such as islands or remote communities. Hydrogen can be produced locally with renewables and then transported over short distances to power local transport and to heat residential and commercial buildings. For example, the UK Orkney Islands have been producing all their electricity from renewables for nearly ten years. However, grid capacity constraints means that renewable energy created can be lost or wasted, so new projects are being developed that use the excess electricity for hydrogen generation which can then be used in several applications or stored. The activities have led to exploratory projects, such as a hydrogen/diesel dual fuel conversion system on a local commercial ferry, and the decarbonisation of a medium range small passenger aircraft to allow a 250-mile, zero-emission hydrogen-powered trial flight.

III. Hydrogen Supply and infrastructure

Hydrogen production is today dominated by fossil fuels, with relatively negligible global supply of zero-carbon green, and blue hydrogen at around 1% of global supply.

Blue hydrogen, which is produced from gas with carbon capture, is currently the lowest cost route to low carbon hydrogen, and hence expected to be the largest source of low carbon hydrogen to 2030. Constraints to domestic fossil fuel supply or limited CO_2 storage space mean the opportunities for blue hydrogen are limited in some countries. Limited access to low-cost domestic sources of natural gas can also increase the cost of blue hydrogen. However, some of these constraints, such as on domestic fossil fuel supply, can be addressed through imports. For example, South Korea already has about the fifth largest hydrogen market in the world despite having negligible domestic fossil resources.

While green hydrogen is not yet cost competitive with blue hydrogen, costs are expected to decline and green hydrogen is likely to dominate in the long-term beyond 2030, particularly in Western Europe and other geographies without significant domestic fossil resources.

Countries with access to both ample renewable resources and sufficiently large fossil-fuel reserves are letting market forces define the pathway for scaling low-carbon hydrogen. Norway and the USA are continuing to invest in R&D of key enabling technologies for low-carbon hydrogen – CCS, electrolysers, CHP fuel-cells and modular natural gas plants with hydrogen as a potential fuel.

Rising carbon prices are now approaching levels at which blue hydrogen is cost competitive, and expectations of future carbon price rises are incentivising investments in blue and green hydrogen production capacity. However, long payback periods combined with project, technological and market risks mean government support is still required. For example:

- One of the largest blue hydrogen facilities, Quest in Canada, received $850 million in subsidies and benefited from the revenue stream from enhanced oil recovery revenue.
- Air Liquide added CCUS to an existing (steam methane reforming) hydrogen production plant to abate 55% of the CO_2 emissions, with the hydrogen sold to a nearby refinery and the CO_2 treated and sold to the food and beverage industry. Overall, the project received subsidies amounting to nearly a quarter of the total capital costs.
- Saudi Arabia's Neom megadevelopment includes plans to develop a green hydrogen and ammonia production plant, with the eventual capacity to produce 1.2 million tonnes of green ammonia annually. The $5bn project is one of the kingdom's Public Investment Funds' key megaprojects to diversify the country's economy away from a dependence on oil.
- The NortH2 project is a collaboration between several companies for large scale green hydrogen production, using self-generated offshore wind energy to produce green hydrogen, which is then stored and delivered to industry and heavy mobility clients in the Netherlands and beyond. The project, which will require substantial government support to reach final investment decision, envisions 10GW of offshore wind capacity to power electrolysers and plans to commence hydrogen production in 2027.

Countries are also starting to focus on infrastructure required to support the deployment and scale up of hydrogen. For example, the Netherlands believes it is well positioned to be an energy gateway for hydrogen supply into Northwest Europe and an important low carbon energy hub for Europe more generally. To this end, the country has started construction of a hydrogen network that will span 1,200 kilometres in total. While the first 30-kilometres section is expected to be operational in 2025, the national network will ultimately span 1,200 kilometres and consist largely of repurposed existing natural gas pipelines. The intention is for the network to be linked to large-scale hydrogen production facilities, import terminals at seaports, and companies in the Netherlands and abroad who are switching to hydrogen as part of their low carbon transition.

IV. Enablers for the development of hydrogen

There are a number of policy building blocks which could help the development of hydrogen use, supply, and infrastructure.

- The development of hydrogen strategies with clear long-term objectives and short- and medium-term milestones. For example, the EU hydrogen strategy which was published by the European Commission in July 2020, and the Dutch Klimaat Akkoord (National Climate Act);

- The creation of standards for decarbonised hydrogen production pathways, together with a methodology to calculate life-cycle greenhouse gas emissions and associated certification. For example, the EU taxonomy for sustainable activities;
- Policies to stimulate demand for decarbonised hydrogen in key sectors such as heavy duty transport and industry, including carbon pricing in combination with targets. For example, Canada has proposed regulations for the Clean Fuel Standard to drive investment and growth in its clean fuel sector and the European Commission has proposed a binding target for EU industry as part of the Fit for 55 proposal to switch partly to renewable hydrogen;
- Support for mechanisms that encourage decarbonised hydrogen projects and reduce the cost difference between decarbonised hydrogen and conventionally produced hydrogen. Mechanisms include carbon contracts for difference, increased public funding for projects, supportive taxation of decarbonised hydrogen, production incentives for renewable electricity and funding for research and development;
- Support for infrastructure planning and investment that creates conditions for a hydrogen market. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) Regulations, Codes, Standards & Safety (RCSS) Working Group is acting as a catalyst for international cooperation and to facilitate the harmonisation of codes and standards in infrastructure and transport.

Cautionary Note

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