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Life Cycle Assessment of Hydrogen for Heavy-duty Vehicles: Hydrogen Environment Protection, Analysis, Awareness and Review (HEAR)

Authors: James G. Carton, Greg McNamara, Sevda Sabernia, Kevin Murphy, Corné Muilwijk and Sneha Sabu

Lead organisation: Dublin City University

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Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The EPA is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing

> Large-scale industrial, waste and petrol storage activities;
> Urban waste water discharges;
> The contained use and controlled release of Genetically Modified Organisms;
> Sources of ionising radiation;
> Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

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> Audit and inspection of EPA licensed facilities;
> Drive the implementation of best practice in regulated activities and facilities;
> Oversee local authority responsibilities for environmental protection;
> Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
> Assess and report on public and private drinking water quality;
> Coordinate a network of public service organisations to support action against environmental crime;
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> Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
> Develop and implement the National Waste Prevention Programme;
> Implement and report on legislation on the control of chemicals in the environment.

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> Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
> Support National, EU and UN Climate Science and Policy development activities.

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> Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
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> Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
> Oversee the implementation of the Environmental Noise Directive;
> Assess the impact of proposed plans and programmes on the Irish environment.

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> Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
> Collaborate with national and EU environmental research activity.

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> Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
> Assist in developing national plans for emergencies arising from nuclear accidents;
> Monitor developments abroad relating to nuclear installations and radiological safety;
> Provide, or oversee the provision of, specialist radiation protection services.

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> Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
> Promote the link between health and wellbeing, the economy and a clean environment;
> Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
> Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

> Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

Management and Structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

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What did the research aim to address?

Hydrogen can be used as a potential fuel for heavy duty vehicles, however the full life cycle assessment of hydrogen production, delivery and use in Ireland is not well documented in literature.

The findings of this study are important for a range of stakeholders including; government and government agencies who can use the data and the results to inform policy and regulation to aid decarbonisation activities in transport; heavy duty vehicle operators, owners and their clients who rely on these vehicles and who need to make decisions on the future direction of their fleet, fuel or vehicle.

A literature review and desktop environmental Life Cycle Assessment (LCA) was conducted to evaluate the environmental impacts of hydrogen used in transport in Ireland, specifically – the production, transport & refuelling of hydrogen for heavy goods vehicles and compared against diesel.

What did the research find?

As part of the literature & data gathering the team engaged with many stakeholders, agencies and industry to help inform the methodology and also disseminate the results.

Through the LCA the results indicate that Green Hydrogen produced from renewable energy is the least harmful technology / transport fuel in key impact assessment categories including climate change and water pollution compared to diesel, and other production methods of hydrogen.

The LCA results and comparative analysis presented is new to literature. In addition in the process of developing the LCA the team have collected datasets called "inventories" that will assist future researchers to build on the existing findings which have become an important part within our dissemination activities.

Ultimately, there will always be a trade-off when selecting the most environmentally favourable method for hydrogen production and where that hydrogen should be used in application. These trade-offs depend on geographical, economic and social factors, political will and regulatory frameworks. Therefore, further research is needed to assess the whole life cycle costs of hydrogen in addition to the environmental considerations discussed in this work, hydrogen production pathways should also be evaluated from other perspectives, including techno-economic and socio-economic factors.

How can the research findings be used?

Mobility is fundamental in modern society but it must be decarbonised for the benefit of the environment, human health and climate change impacts.

The HEAR Life Cycle Assessment research findings allow stakeholders, including government agencies, researchers, the public and industry, to be informed on the full life cycle assessment of hydrogen production, delivery and use in Ireland, as well as ensure society buy-in is achieved.

The developed Life Cycle Assessment datasets, "inventories", will also assist future researchers to build on the existing research findings for their particular future scenarios.

Therefore policy, regulation and supports can now be developed and implemented to remove fossil fuels such as diesel from our transport fleet and better understand where hydrogen fits in - to further help transform our transport system to have minimum impact on the environment, society and public health.

Project code: 2022-HE-1121

EPA RESEARCH PROGRAMME 2021–2030

Life Cycle Assessment of Hydrogen for Heavy-duty Vehicles: Hydrogen Environment Protection, Analysis, Awareness and Review (HEAR)

(2022-HE-1121)

EPA Research Report

Independent scientific research funded by the Environmental Protection Agency

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Dublin City University

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This report is based on research carried out/data from January 2023 to June 2024. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

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Executive Summary

In the Hydrogen Environment Protection, Analysis, Awareness and Review (HEAR) project, transport in heavy-duty vehicles and technology and fuels to power transport, including various hydrogen production routes, were assessed through a literature review. In addition, the Industrial Emissions Directive (IED) was reviewed and the relevance and scope of hydrogen and its production type were discussed. A desktop environmental life cycle assessment was also conducted to evaluate the environmental impacts of hydrogen used for sustainable mobility in Ireland, specifically the production, transport and refuelling of hydrogen for heavy goods vehicles. A total of 12 process configurations/scenarios based on four distinct technologies to produce hydrogen were assessed – steam methane reforming, steam methane reforming with carbon capture and storage, methane pyrolysis and renewable-energy-powered polymer electrolyte membrane electrolysis. These technologies are commonly referred to as grey, blue, turquoise and green hydrogen production, respectively.

It was shown that transport in Ireland accounts for approximately 36% of total energy consumption. Heavy goods vehicles are large consumers, responsible for 9.2 TWh of energy consumption. Potential sustainable ways to fuel/power transport vehicles include biofuels, hydrotreated vegetable oil, biomethane, and battery and hydrogen fuel cells, which offer reduced greenhouse gas emissions compared with fossil fuel diesel or petrol fuels. Implementing a mix of these technologies can lead to a cleaner and more sustainable future for transport, reducing reliance on fossil fuels and mitigating climate change impacts.

Through the life cycle assessment, it was found that green hydrogen production is the least harmful technology in terms of climate change and water pollution in key life cycle impact assessment categories – global warming potential, acidification potential, eutrophication potential and marine aquatic ecotoxicity potential – compared with diesel and grey, blue and turquoise hydrogen production (e.g. global warming potential is under 1 kg CO_2 eq/kg H_2 compared with between 5 and 11 kg CO_2 eq/kg H_2 for the other methods).

A new version of the IED was implemented in 2024, encompassing hydrogen production from electrolysis. It was noted that large-scale electrolysis-based hydrogen production installations in the EU with a capacity to produce over 50 tonnes of hydrogen per day must adhere to the IED, making the production of hydrogen safer while reducing the impact on the environment and resources such as water and materials. The project outputs aim to inform decision-making and facilitate effective strategies for sustainable decarbonisation in transport.

1 Introduction

The transport sector in Ireland has found it difficult to steer away from the use of fossil fuels. To decarbonise the transport sector multiple solutions must be implemented, including active travel, public transport and electric vehicles. For heavy-duty vehicles (HDVs), which are weight sensitive, require a long range and demand fast refuelling to accommodate their logistical requirements, hydrogen is a solution that can help meet forthcoming targets for reducing fossil fuels, committed to under Ireland's Climate Action Plan 2025 (DCEE, 2025).

Through a literature review, transport in HDVs was assessed, as well as technology and fuels to power transport. Hydrogen was then reviewed and various hydrogen production routes, including grey, blue and green hydrogen, summarised, with recent developments provided and compared with the current use of fossil fuels. An in-depth analysis of the various technologies is also presented. Finally, a desktop environmental life cycle assessment (LCA) to evaluate the environmental impacts of hydrogen used for sustainable mobility in Ireland, specifically the production, transport and refuelling of hydrogen for heavy goods vehicles (HGVs), was conducted.

1.1 Objectives

The objectives of the Hydrogen Environment Protection, Analysis, Awareness and Review project were as follows:

- Conduct a critical international review to inform the direction and potential role, scale and timeline of hydrogen use in the transport sector in Ireland.
- Conduct a critical international review on the implications and environmental impact of the various hydrogen production routes for Ireland: green hydrogen, grey hydrogen, blue hydrogen and turquoise hydrogen.
- Conduct a desktop LCA study to examine the environmental burden/benefit of hydrogen use as a transport fuel. The study consisted of a cradle-to-gate scope for the production of green, blue, turquoise and grey hydrogen, and then a use-phase analysis benchmarked against conventional fossil fuels.
- Identify the relevance and scope of hydrogen and its production type or application with regard to the EU's Industrial Emissions Directive (IED) as transposed into Irish law.
- Share the learnings with the EPA, academic stakeholders, policy and regulatory networks, industry and the public.

2 Literature Review

Our climate is changing rapidly, transforming our world, due to our societies' use of fossil fuels and release of fossil fuel and industrial emissions (Gentile and Gupta, 2025). The necessity for an energy transition is inevitable and should be hastened when considering the ongoing energy security issues around the world. Ireland has directly witnessed the impacts of climate change, as outlined in the Climate Action Plan Progress Report for Ireland 2023 (Government of Ireland, 2023). Aligned with the EU's ambitions, Ireland's Programme for Government and the Climate Action Plan 2025 (DCEE, 2025) make firm commitments to achieving a 51% reduction in the country's overall greenhouse gas (GHG) emissions between 2021 and 2030 and effective zero emissions no later than 2050.

2.1 Transport

Mobility has become fundamental in modern society for economic progress and social interaction, as it enables the movement of people and goods in a cost-effective and efficient manner. Nevertheless, it is crucial not to overlook the environmental and public health consequences associated with transport. According to a United Nations Environment Programme report, the transport sector alone accounts for 19.2% of carbon emissions. Global carbon emissions are estimated to be over 57 Gt of carbon dioxide equivalent (Gt CO_2 eq), with transport playing a significant role in contributing to climate change (Pal *et al*., 2023). In 2023, global transport-related CO_2 emissions continued to rise, increasing by 4% compared with 2022. This increase brought total transport sector emissions to 8.24 billion metric tonnes (Gt CO_2) globally (EPA, 2024).

Between 1990 and 2023, Ireland witnessed a staggering 126.2% increase in GHG emissions from the transport sector, soaring from 5143.3 kt CO_2 eq to 11,634.0 kt CO_2 eq. Particularly concerning was the rise in road transport emissions, which increased by a significant 130.2%. In 1990, the transport sector contributed to 9.2% of the nation's total GHG emissions, but this figure had jumped to 19.1% by 2022.

The rise in emissions up to 2007 was driven by Ireland's economic growth, population expansion, motorway expansion and heavy reliance on private car travel, accompanied by a rapid increase in road freight transport. During this period, the number of passenger cars rose by 181%, and commercial vehicles saw a 171% increase. GHG emissions from the transport sector arose from various transport activities, including aviation, road and railway transport and water-borne navigation.

Although emissions from road transport remained relatively stable between 2015 and 2019, averaging 11.6 Mt CO_2 eq, travel restrictions in 2020 led to a decrease to 9.7 Mt CO_2 eq. As travel restrictions eased in 2021 and 2022, road transport emissions rebounded to 10.3 Mt CO_2 eq and 11.0 Mt CO_2 eq, respectively, but remained below pre-Covid-19 levels (EPA, 2024).

According to a Sustainable Energy Authority of Ireland report (see Figure 2.1), the top three contributors to total transport final energy demand are private cars (39.7%), aviation (21.8%) and road freight, also known as HDVs (15.3%) (SEAI, 2024a). It is important to investigate the possibility of decarbonisation options for these sectors.

The most important point to note is that transport remains almost completely dependent on fossil fuels, particularly oil products. This lack of fuel diversity is unique among the energy-using sectors. Renewables made up a very small share of transport energy use in 2023. Electricity also remains a tiny share of transport energy use (0.3%), which is split between electric rail (Dublin Area Rapid Transit and Luas) and a minimal number of private battery-powered electric cars. This has meant that there has been very little decarbonisation of the transport fuel mix to date, with transport CO_2 emissions remaining tightly coupled to energy use (SEAI, 2024b).

There was a clear shift from petrol to diesel over a decade, due to the switch to private diesel cars accelerated by the changes to the private car tax system from 2008 onwards. The Covid-19 pandemic resulted in significant restrictions on personal mobility during 2020 and 2021 (Figure 2.2), which had

Energy [TWh]	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
Road private car	24.45 (48.4%)	25.08 (47.7%)	25.19 (45.3%)	24.81 (43.0%)	24.35 (41.0%)	24.34 (40.0%)	24.60 (40.1%)	20.11 (44.3%)	21.33 (43.9%)	23.08 (39.6%)	24.14 (39.7%)
Road freight	6.76 (13.4%)	7.23 (13.8%)	7.28 (13.1%)	8.55 (14.8%)	8.70 (14.7%)	8.53 (14.0%)	9.18 (15.0%)	8.43 (18.5%)	9.25 (19.0%)	9.17 (15.7%)	9.32 (15.3%)
Road unspecified	2.07 (4.1%)	1.52 (2.9%)	1.55 (2.8%)	2.41 (4.2%)	5.31 (9.0%)	5.68 (9.3%)	4.52 (7.4%)	4.68 (10.3%)	3.88 (8.0%)	5.19 (8.9%)	5.23 (8.6%)
Road light goods vehicle	4.13 (8.2%)	4.33 (8.2%)	4.39 (7.9%)	4.18 (7.2%)	4.10 (6.9%)	3.97 (6.5%)	3.82 (6.2%)	3.45 (7.6%)	3.20 (6.6%)	3.51 (6.0%)	3.48 (5.7%)
Road fuel tourism	2.44 (4.8%)	2.81 (5.4%)	4.51 (8.1%)	4.47 (7.7%)	1.92 (3.2%)	2.17 (3.6%)	2.89 (4.7%)	0.94 (2.1%)	2.41 (5.0%)	2.29 (3.9%)	2.05 (3.4%)
Road public passenger	1.65 (3.3%)	1.58 (3.0%)	1.55 (2.8%)	1.54 (2.7%)	1.51 (2.5%)	1.59 (2.6%)	1.59 (2.6%)	1.38 (3.0%)	1.40 (2.9%)	1.45 (2.5%)	1.51 (2.5%)
International aviation	7.80 (15.4%)	8.65 (16.5%)	9.79 (17.6%)	10.04 (17.4%)	11.82 (19.9%)	12.77 (21.0%)	12.91 (21.1%)	4.58 (10.1%)	5.12 (10.5%)	11.76 (20.2%)	13.28 (21.8%)
Navigation	0.67 (1.3%)	0.84 (1.6%)	0.83 (1.5%)	1.00 (1.7%)	0.88 (1.5%)	0.98 (1.6%)	1.04 (1.7%)	1.27 (2.8%)	1.36 (2.8%)	1.15 (2.0%)	1.08 (1.8%)
Rail	0.45 (0.9%)	0.41 (0.8%)	0.42 (0.7%)	0.42 (0.7%)	0.44 (0.7%)	0.44 (0.7%)	0.46 (0.8%)	0.37 (0.8%)	0.40 (0.8%)	0.45 (0.8%)	0.47 (0.8%)
Pipeline	0.04 (0.1%)	0.03 (0.1%)	0.05 (0.1%)	0.25 (0.4%)	0.24 (0.4%)	0.26 (0.4%)	0.20 (0.3%)	0.18 (0.4%)	0.18 (0.4%)	0.19 (0.3%)	0.17 (0.3%)
Domestic aviation	0.06 (0.1%)	0.06 (0.1%)	0.06 (0.1%)	0.07 (0.1%)	0.07 (0.1%)	0.07 (0.1%)	0.07 (0.1%)	0.05 (0.1%)	0.08 (0.2%)	0.08 (0.1%)	0.09 (0.1%)
Total	**50.52** (100%)	**52.54** (100%)	**55.62** (100%)	**57.74** (100%)	**59.33** (100%)	**60.80** (100%)	**61.28** (100%)	**45.43** (100%)	**48.60** (100%)	**58.31** (100%)	**60.81** (100%)

Figure 2.1. Final energy demand in the transport sector by subsector (share), 2013–2023. Source: SEAI (2024a).

direct effects on transport energy use, especially for international aviation and private cars. Although there was a 13% reduction in CO_2 emissions from private cars from 2011 to 2021, private cars, with a 45% share of emissions (almost 5000 kt CO_2), remain the highest contributors in the transport sector (SEAI, 2024b).

2.1.1 Heavy goods vehicles

In Ireland, approximately 40% of road transport emissions stem from the combined contribution of light and heavy goods vehicles, with private cars accounting for the remaining portion (52%) and a small fraction (8%) attributed to buses. HGVs are vehicles designed for long-distance transport of goods weighing between 3.5 and 46 tonnes. They encompass various types of vehicles (Figure 2.3), including articulated trucks (semi-trailers) for long-haul transport, rigid trucks for regional deliveries, delivery vans for urban courier services, tanker trucks for transporting liquids or gases, refrigerated trucks for perishable goods, box trucks for weather-protected transport, flatbed trucks for carrying large or irregularly shaped items, dump trucks for loose materials, and lorry trailers for heavy or oversized loads.

HGVs are crucial for global trade and supply chains, but their significant size and weight (Table 2.1) means that they are required to adhere to strict safety and environmental standards. The carrying capacity of HGVs can influence the drivetrain, fuel and range of the vehicle.

HGVs typically use diesel engines (see Figure 2.4) and these engines consume large amounts of fuel due to the vehicles' size and weight. The combustion of diesel fuel releases CO_2, a major GHG, along with harmful pollutants like nitrogen oxides (NO_x) and particulate matter (PM). NO_x contributes to smog formation, worsening respiratory issues, while fine particulate matter ($PM_{2.5}$) can lead to severe health problems, including cardiovascular disease and lung cancer. These emissions degrade air quality, particularly in urban areas, posing significant public health risks. Reducing diesel-related emissions is critical for improving environmental health and meeting global air quality standards (EPA, 2025a).

	2021		1-year change (2020–2021)		5-year change (2016–2021)		10-year change (2011–2021)		20-year change (2001–2021)	
	Quantity ($ktCO_2$)	Share (%)	($ktCO_2$)	(%)	($ktCO_2$)	(%)	($ktCO_2$)	(%)	($ktCO_2$)	(%)
Private car	5,178	48.1%	+465	+9.9%	-1,020	-16.5%	-780	-13.1%	+325	+6.7%
HGV	2,307	21.5%	+211	+10.1%	+117	+5.3%	+427	+22.7%	-171	-6.9%
LGV	811	7.5%	-51	-5.9%	-260	-24.3%	-199	-19.7%	+811	-
Domestic aviation	9	0.1%	+1	+9.1%	-8	-48.8%	-16	-65.1%	-60	-87.6%
Public passenger	338	3.1%	-5	-1.5%	-56	-14.3%	-116	-25.5%	+38	+12.8%
Rail	137	1.3%	+9	+6.7%	-4	-2.7%	-14	-9.5%	-19	-12.1%
Navigation	370	3.4%	+35	+10.4%	+106	+40.4%	+198	+115.3%	+282	+319.0%
Pipeline	0	0.0%	0	-	0	-	0	-	0	-
Fuel tourism	597	5.6%	+364	+156.3%	-546	-47.8%	-86	-12.6%	-1,396	-70.0%
Unspecified	986	9.2%	-343	-25.8%	+357	+56.8%	+349	+54.9%	-71	-6.7%
Total (excl. international aviation)	**10,754**	**100.0%**	**+686**	**+6.8%**	**-1,336**	**-11.0%**	**-217**	**-2.0%**	**-239**	**-2.2%**
International aviation	1,326		+142	+12.0%	-1,255	-48.6%	-742	-35.9%	-867	-39.5%
Total (incl. international aviation)	**12,080**		**+828**	**+7.4%**	**-2,591**	**-17.7%**	**-960**	**-7.4%**	**-1,107**	**-8.4%**

Source: SEAI

Figure 2.2. Quantity and share of CO_2 emissions in the transport sector by subsector. LGV, light goods vehicle. Source: SEAI (2022).

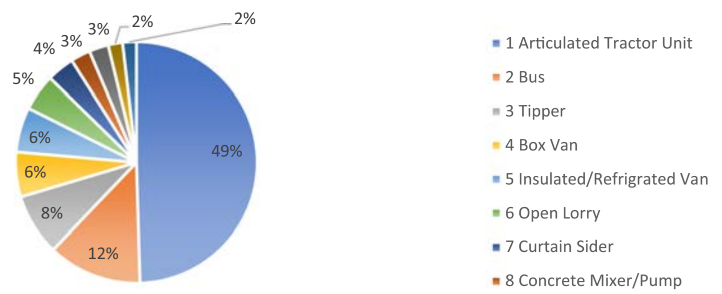

Figure 2.3. Heavy commercial vehicles in Ireland by body type, 2023. Source: Motorstats (2024).

Due to their size and weight, HGVs face higher aerodynamic resistance, which means they need more energy (fuel) to overcome air resistance while moving. The higher weight also contributes to increased rolling resistance, further impacting fuel consumption. HGVs often travel long distances, frequently on highways and motorways. This continuous travel at high speeds and for long durations leads to significant fuel consumption and subsequent GHG emissions. While there have been improvements in the efficiency of HGV engines over the years, they are generally less efficient than smaller passenger vehicle engines. This is partly due to the emphasis on power and torque required to transport heavy loads. While some advancements

Table 2.1. Number of heavy commercial vehicles in Ireland by gross weight, 2023 and 2024

Weight (kg)	2023 units	2024 units
1–3500	1	9
3501–5000	1	2
5001–6000	4	18
6001–8000	137	262
8001–10,000	28	36
10,001–12,000	85	179
12,001–14,000	38	55
14,001–17,000	47	92
≥17,001	1853	2788

Source: Motorstats (2024).

have been made in introducing alternative fuels like biomethane gas or electric powertrains for trucks, diesel remains the dominant fuel for HGVs. This limits the reduction of GHG emissions in the sector. HGVs often spend considerable time idling or stuck in traffic, especially in urban areas and at loading/unloading points. Idling consumes fuel without contributing to distance covered, leading to unnecessary GHG emissions. To mitigate the impact of HGVs, efforts are also being made to optimise logistics and routing, and explore electrification options for short-haul urban deliveries.

Between 1990 and 2019, emissions from trucks and buses showed a 28% increase. Based on existing policies and without further actions, HDVs are expected to consume 60.9% of the EU's remaining carbon budget to limit global warming to 1.5°C.

By 2030, there is projected to be a 3.8% rise in oil consumption by HDVs due to the continued growth in their activity (T&E, 2023) . In Ireland, which has considerable freight activity, HGVs or "trucks" (which fall under the category of HDVs) contribute 14% of road transport emissions (equivalent to 1.6 Mt CO_2 eq).

Most HGVs run on diesel fuel, and 61% of all HGVs licensed in Ireland at the end of 2022 were 10 years old or younger (Department of Transport, 2022). To provide perspective, an average long-distance HGV with four wheels emits approximately 102.9 g of CO_2 per tonne-kilometre. At the end of July 2022, there were 41,850 taxed HGVs (greater than 3.5 tonnes) in Ireland. Out of this total, 22,796 were designated for licensed haulage and 19,054 were allocated to the own account sector (Department of Transport, 2022). Moreover, there were 3847 licensed road haulage operators in Ireland. Around 64% of these hauliers and 70% of the licensed HGVs can operate internationally, indicating the long-range distances at which these vehicles operate. Most haulage companies are classified as small operators (fewer than five HGVs), while those engaged in international operations tend to have slightly above-average fleet sizes. Furthermore, around 53% of hauliers within Ireland, which primarily operate domestically, possess just a single HGV, totalling approximately 2000 vehicles (Department of Transport, 2022). Among the provinces, Dublin leads with the highest proportion of taxed HGVs, at 52%, followed by Cork, with 27%.

After fuel expenses, taxes constitute a significant operational cost in the freight industry, which may rise

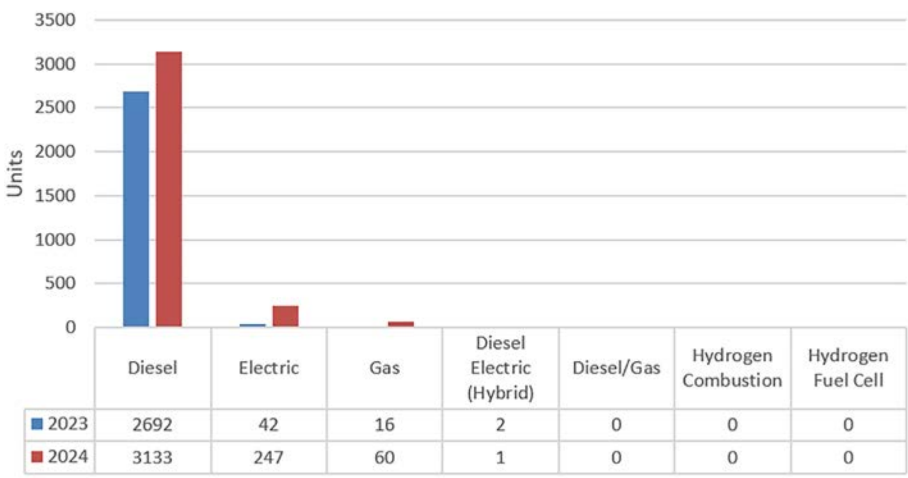

Figure 2.4. Heavy-duty vehicles purchased in Ireland by engine type, 2023. Source: Modified from Motorstats (2024).

when linked to emissions from the vehicle's exhaust. In Ireland, the tax on purchasing a new vehicle includes 23% value added tax prior to applying the vehicle registration tax. For commercial vehicles, the vehicle registration tax is calculated using two factors: a percentage based on the open market selling price and the NO_x calculation. The NO_x calculation method is outlined in the European Automobile Manufacturers Association *Tax Guide*, as shown in Table 2.2.

It is apparent that Ireland exhibits a notable dependence on its road infrastructure for freight transport, as illustrated in Figure 2.5, which shows the distribution of road freight among EU Member States. If a bar reaches 100% on the graph, it means that all freight in that country is moved by road. Ireland has about 99% of its freight transport handled by road, with very little reliance on rail. It is worth highlighting that Cyprus and Malta, the only nations with a larger share than Ireland, are devoid of rail networks entirely.

Table 2.2. Vehicle registration tax for commercial goods vehicles in Ireland

Weight (kg)	Annual tax due to weight (€)
≤3000	333
3001–4000	420
4001–12,000	500
≥12,001	900
Electric (not over 1500)	92

Source: ACEA (2016).

In recent times, there has been substantial uncertainty regarding the technological direction for decarbonising HGVs. The optimal choice among alternatives like compressed biomethane gas, battery electric vehicles, hydrogen fuel cell electric vehicles, electrofuels (e-fuels) and advanced biofuels remains unclear. The course and speed of the transport sector's transition remain ambiguous, as internal combustion engine (ICE) vehicles are projected to form a significant majority of the on-road fleet up to and beyond 2030 (Department of Transport, 2022). During this transition, strategies from the EU and national governments, such as employing renewable transport fuels and fleet-wide average CO_2 emissions, will be essential to curbing emissions from existing and new vehicles, while the widespread adoption of electric trucks may gain momentum in the latter part of this decade (Meade, 2021; Córas Iompair Éireann, 2024). The role of hydrogen as a fuel in the road freight sector's decarbonisation is not expected to be prominent before 2030 (Department of Transport, 2022).

Prominent original equipment manufacturers have committed publicly to ramping up the availability and supply of electric trucks, both battery electric and hydrogen fuel cell electric, in the market by the mid-2020s. Notable examples include Scania's goals of making 10% of its truck sales electric vehicles by 2025 and aiming for 50% by 2030. Renault Trucks anticipates that 10% of its sales will be electric by 2025 and 35% by 2030. Daimler envisages that

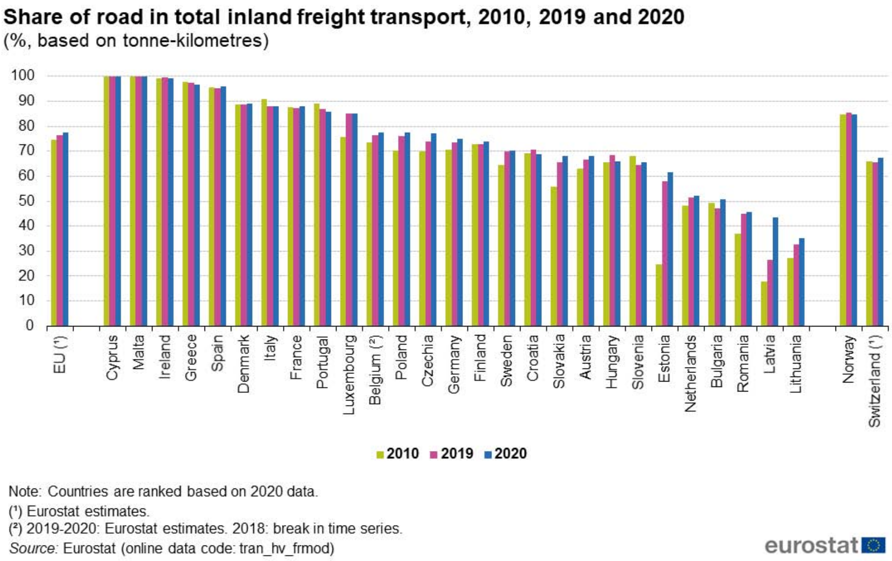

Figure 2.5. Share of road in total inland freight transport in the EU (percentage based on tonne-kilometres). Source: Eurostat (2021).

60% of its truck sales will be zero emission by 2030. Furthermore, major original equipment manufacturers have pledged to sell trucks powered entirely by renewable sources by 2040.

Analysis by the European Federation for Transport and Environment suggests that European truck manufacturers' declarations point to a potential range of outcomes, with a less favourable scenario foreseeing around 480,000 zero-emission vehicles on roads by 2030, while a more optimistic outlook projects up to 630,000.

Figure 2.6 shows typical HGV daily traffic levels on national roads in 2021 and projected levels for 2030. These projections are derived from analysis employing the Transport Infrastructure Ireland National Transport Model. The model's existing HGV traffic levels have been validated against observed data from over 350 traffic sensors located on national roads. The road network in Ireland consists of a combined length of 5306 km, encompassing motorways, dual carriageways and single-lane roads. Road transport plays an important role in freight movement, accounting for a remarkable percentage of freight transport. Transport Infrastructure Ireland approximates that 80–90% of transported freight utilises the national primary and national secondary road network, while the remainder uses regional and local roads. Although there is potential for an increased rail freight share, the dispersed population and relatively short route distances in Ireland suggest that road transport will persist as the predominant mode. The distribution of freight traffic is particularly concentrated on specific routes, which is evident in the maps.

2.2 Powering Sustainable Transport

In recent years, technologies such as battery electric vehicles, biofuels, synthetic e-fuels and hydrogen fuel cell vehicles have emerged as key options for reducing GHG emissions from transport. Hydrogen is one solution for HDVs that can provide long-range capabilities and fast refuelling, making it a good potential choice for future low-emission transport systems (European Commission, 2020a).

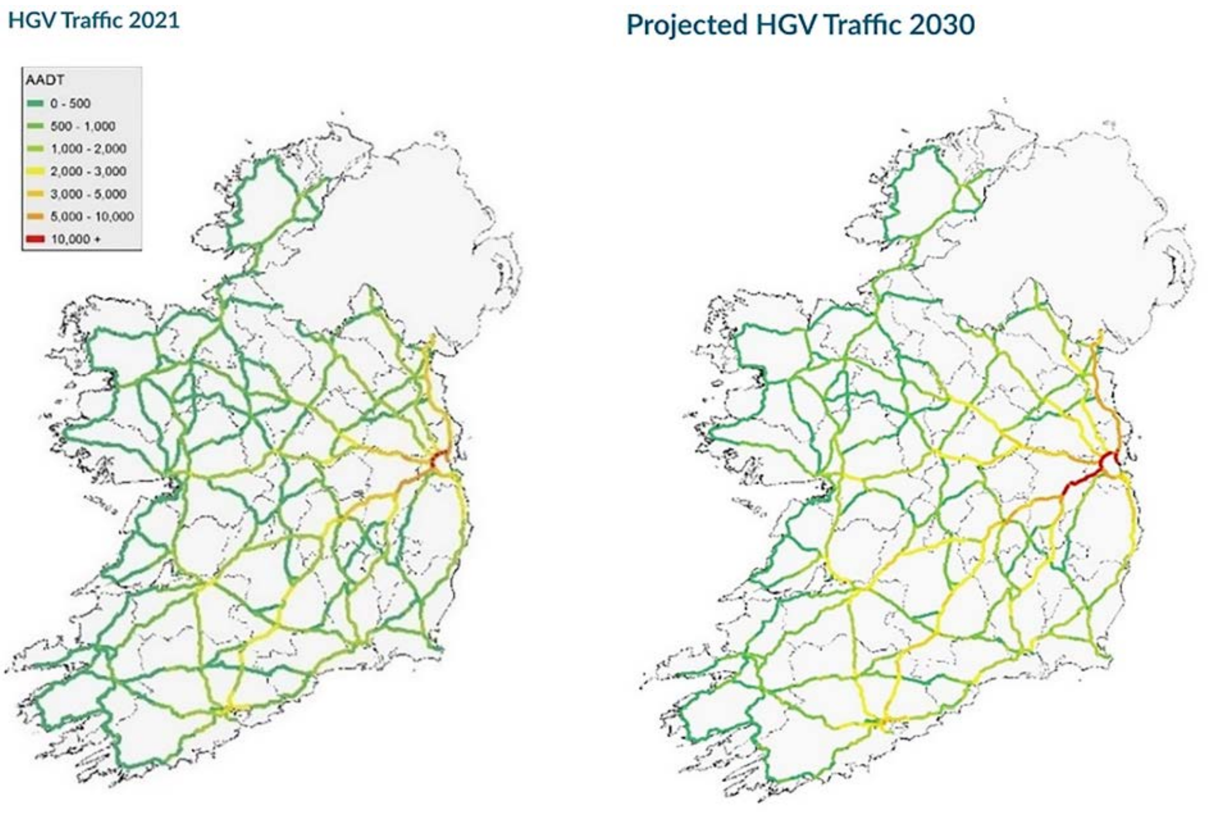

Figure 2.6. Typical HGV daily traffic levels on Irish national roads in 2021 and projected levels for 2030. AADT, annual average daily traffic. Source: Department of Transport (2022).

2.2.1 Technologies to decarbonise transport

Decarbonising transport to address climate change requires a multifaceted approach. This entails promoting zero-emission vehicles and improved fuel efficiency. Utilising biofuel vehicles offers a potential short-term renewable alternative to conventional fuels, while e-fuels, generated from renewable electricity and captured CO_2, can provide carbon-neutral solutions. Hydrogen fuel cell electric vehicles offer zero tailpipe emission travel and low overall emissions by using renewable hydrogen. In addition, investments in public transport, active transport and thoughtful urban planning reduce reliance on individual vehicles. Government intervention through policies, incentives and regulations can further accelerate the adoption of low-carbon transport methods, fostering a sustainable and environmentally friendly mobility system.

Biofuels

Biofuels include biomethane, biodiesel, bio-methanol and hydrogenated vegetable oil (processed using hydrogen and waste vegetable oil). Biofuels are simple drop-in fuels for vehicle users, but can be more expensive than fossil fuels. Biofuels play a particularly important role in decarbonising transport by providing a low-carbon solution for existing technologies, such as light-duty vehicles in the near term and heavy-duty trucks, ships and aircraft with few alternative and cost-effective solutions in the long term. Biofuels present a transitional solution for HDVs and are already in use, but, in the long term, zero-emission technology is required.

Biofuel demand in 2022 reached a record high of 4.3 EJ (170,000 million litres), surpassing levels seen in 2019 prior to the Covid-19 pandemic. However, a significant increase in biofuel production is needed to align with the net zero emissions by 2050 scenario and achieve the associated emission reductions. Biofuel production must exceed 10 EJ by 2030 in the net zero energy scenario, requiring an average growth rate of approximately 11% per year. This rapid expansion, while critical for meeting climate goals, is unsustainable and counterproductive if not managed carefully, as it could lead to fraud, further deforestation and biodiversity loss, and reduced food availability for humans. Without stringent sustainability and regulation measures, biofuel production risks exacerbating environmental degradation, undermining its potential benefits. These challenges are not limited to the EU, but represent a global issue, as increased biofuel demand can place pressure on ecosystems worldwide and affect food security across regions (Prasad *et al.*, 2024).

Synthetic electrofuels

Electrofuels, also known as e-fuels or synthetic fuels, are a category of fuels produced through electrochemical conversion powered by renewable energy sources like wind or solar power to produce hydrogen, which is then combined with carbon (or nitrogen) to produce a chemical energy carrier, usually liquid hydrocarbons (using sustainable carbon in the process or nitrogen). E-diesel, e-jet fuel, e-methanol and e-ammonia are common examples. These fuels provide a low-carbon alternative to conventional fossil fuels, especially in hard-to-electrify sectors such as aviation, heavy industry and long-haul transport. However, the e-fuels industry must overcome hurdles like the vast amounts of renewable hydrogen necessary, sourcing sustainable CO_2, and the high carbon capture costs for viable e-fuel production.

Hydrogen internal combustion engine vehicles

Hydrogen vehicles utilise either an ICE to create motive force or fuel cells to generate electricity from hydrogen gas and oxygen from the air. Each option presents distinct advantages and challenges in terms of efficiency, emissions and overall feasibility.

Using hydrogen in ICEs is an option that involves adapting existing engine technology to run on hydrogen fuel. Like gasoline, hydrogen is burned within the engine to create the combustion needed to generate power and drive the vehicle. This approach has the advantage of potentially utilising the existing infrastructure, such as service and maintenance facilities, that is already in place for gasoline vehicles (Acar and Dincer, 2020). However, there are challenges associated with this approach. New hydrogen refuelling infrastructure is still necessary and, while hydrogen combustion produces significantly fewer GHG emissions compared with gasoline combustion, it can still result in emissions of NO_x, which contribute to air pollution. Achieving emission reductions comparable to those achieved by fuel cells may require incorporating emission control technologies. Additionally, the efficiency of hydrogen combustion in ICEs is 30–50% lower than in the case of fuel cells, limiting the overall energy efficiency of the vehicle (Wróbel *et al.*, 2022). Wróbel *et al.* (2022) concluded that hydrogen ICEs are a cost-effective and practical solution for specific vehicle applications. While they emit NO_x and, therefore, need exhaust gas treatment, hydrogen ICEs excel in adapting to varying hydrogen quality, with proven reliability in demanding conditions. Their potential in areas like construction and agriculture is notable, leveraging local hydrogen storage and production (Kelly, 2025). While hydrogen ICEs have the potential to power some classes of vehicles, ICEs are outside the scope of this work and its focus on hydrogen fuel cells for HDVs/HGVs.

It is important to recognise that while e-fuels and biofuels, such as biomethanol, biomethane, biodiesel, hydrogenated vegetable oil, e-diesel, e-jet fuel, e-methanol and hydrogen combustion (to a lesser extent), aim to lower "net" carbon emissions, and are often considered as alternatives, these fuels are still combusted in conventional thermal engines. Therefore, these fuels still emit pollutants like NO_x and PM from the exhaust systems. NO_x and PM can negatively impact local air quality and public health. Proper management of these emissions is crucial to fully realising the benefits of alternative fuels (Ozkan *et al.*, 2024).

Electric vehicles

Electric vehicles are automobiles powered by electric motors instead of traditional ICEs that are fuelled using gasoline, diesel or biofuels. Electric vehicles use electricity stored in either batteries or fuels like hydrogen (via a fuel cell) to drive the electric motor to move the vehicle. Ireland's 2030 policy target is for there to be 944,600 electric vehicles on Irish roads (Pal *et al.*, 2023).

Battery electric vehicles

Battery electric vehicles have a battery pack installed in the vehicle, typically located at the bottom to provide a low centre of gravity for better vehicle stability. When the driver activates the vehicle by turning it on, electricity from the battery is sent to the electric motor. The motor then converts this electrical energy into mechanical energy, which drives the wheels, propelling the vehicle forward.

To recharge the batteries, battery electric vehicles can be connected to the electricity grid at charging stations or outlets. Charging times can vary depending on the battery capacity and charging speed, but advancements in charging technology have significantly reduced charging times.

Battery electric vehicles have seen a consistent gradual upward trajectory in the passenger car market, with *c.*196,000 on the roads to date (including plug-in hybrid). However, in a fleet of *c.*2.8 million vehicles and growing, its small impact on emissions reduction has raised concerns about meeting the national emissions targets and the target of having 944,600 electric vehicles on Irish roads by 2030 (Kelly, 2025).

Hydrogen fuel cell electric vehicles

Hydrogen fuel cells are electrochemical devices that facilitate the conversion of hydrogen gas and oxygen from the surrounding air into electrical energy through a chemical reaction. This process results in the generation of water liquid and vapour as benign by-products.

Hydrogen fuel cell electric vehicles have a similar design and layout and components to battery electric vehicles; both have electric motors and batteries, with the fuel cell electric vehicle having a smaller battery and the additional space being taken up with the fuel cell and hydrogen tank (see Figure 2.7).

Hydrogen fuel cell electric vehicles exhibit a heightened level of energy conversion efficiency, signifying that a substantial proportion of the energy contained within hydrogen is harnessed to generate propulsive power for the vehicle. The remarkable efficiency of fuel cells, coupled with the inherent compactness of hydrogen storage tanks, empowers fuel cell vehicles with significantly extended driving ranges. Hydrogen fuel cell electric vehicles present various advantages, including higher efficiency and performance, reduced emissions and minimal pollution, in comparison with hydrogen ICE vehicles.

Hydrogen fuel cell vehicles can contribute to transport decarbonisation through many avenues; zero tailpipe emissions (except water), carbon-emission-free operation, extended driving ranges, rapid refuelling and fuel source diversity. However, challenges such as

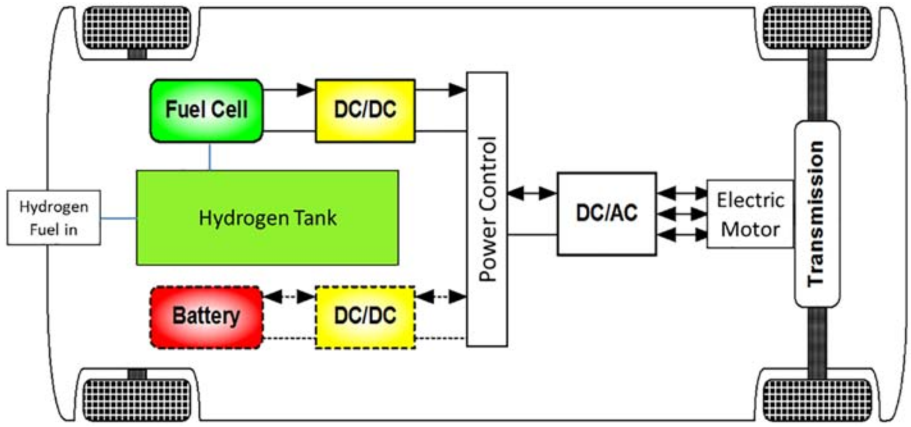

Figure 2.7. Schematic diagram of a hydrogen vehicle, including hydrogen tank, fuel cell and the interconnectors. AC, alternating current; DC, direct current.

establishing infrastructure, reducing costs, enhancing hydrogen storage and increasing regulatory/policy support must be met. The establishment of a comprehensive network of hydrogen refuelling stations stands out as a pivotal hurdle. Unlike the widespread infrastructure of gasoline stations, the deployment of hydrogen refuelling points remains restricted, potentially impeding consumers' access to fuel. Furthermore, the sustainable and cost-effective production of hydrogen, along with its safe storage and distribution, are essential dimensions demanding intricate deliberation. The initial capital outlay associated with fuel cell technology and the hydrogen production process remains relatively elevated when compared with alternative solutions, potentially influencing the affordability of hydrogen fuel cell electric vehicles.

Wang *et al*. (2024) introduced a collaborative planning model to boost hydrogen fuel cell electric vehicle adoption. This model integrated energy, hydrogen and transport systems, focusing on carbon reduction through green hydrogen production. It optimised traffic flow and hydrogen station locations to minimise congestion and travel time, effectively lowering carbon emissions and traffic duration within the integrated network, making it a potentially valuable tool for fleet operators.

Electric vehicles can play a vital role in decarbonising transport for several reasons (Razi and Dincer, 2022):

- Electric vehicles, whether battery or hydrogen fuel cell electric vehicles, produce zero carbon or NO_x or other tailpipe emissions (except water), meaning they do not release CO_2 or other harmful pollutants while being driven. This significantly reduces air pollution and GHG emissions, leading to improved air quality and a lower carbon footprint.
- The adoption of hydrogen fuel cell or battery electric vehicles can complement renewable energy sources like solar and wind power. When charged using electricity from renewable sources, hydrogen fuel cell and battery electric vehicles' life cycle emissions improve.
- Hydrogen fuel cell and battery electric vehicles are generally more energy efficient than ICE vehicles, as both use electric motors for traction. They convert a higher percentage of the energy from the fuel or the battery into electricity and into actual propulsion, reducing energy waste and improving overall energy efficiency.
- As hydrogen fuel cell and battery electric vehicle technologies advance, battery efficiency will increase and the cost of batteries will decrease. This makes electric cars more accessible and attractive to consumers, accelerating the transition away from fossil-fuel-powered vehicles.
- Hydrogen fuel cell and battery electric vehicles have higher upfront costs than diesel vehicles; however, total operating costs of battery electric vehicles are much lower than both diesel and hydrogen vehicles.
- Battery electric vehicles have the potential to act as mobile distributed energy storage units. Through smart charging and vehicle-to-grid technology, battery electric vehicles can help balance the electricity grid by storing excess energy during times of low demand and feeding it back into the grid when demand is high.

- The hydrogen used for hydrogen fuel cell electric vehicles can act as a store at a large-scale storage facility to help balance the electricity grid by storing excess energy during times of low demand and feeding it back into the grid when demand is high.

However, several challenges still exist for battery and hydrogen fuel cell electric vehicles that are relevant to operators of heavy-duty transport vehicles:

- Range anxiety. One of the primary concerns of battery electric truck operators is the fear of running out of battery power before reaching a charging station, particularly on long-haul routes. While the range of battery electric trucks is improving, they still often do not match the distances covered by diesel trucks, especially for long-distance freight transport. This limitation could significantly impact logistics and scheduling in heavy-duty transport.
- Charging infrastructure. The availability of charging infrastructure is a critical issue for truck operators. While battery electric vehicle charging networks are expanding, they are still primarily designed for passenger vehicles in urban areas. Truck operators need specialised, high-capacity charging stations at key logistics hubs and along major freight corridors to ensure the viability of electric trucks for long-distance and heavy-duty applications. Certainly, in a country like Ireland where electricity grid constrains are common, grid capacity can also limit the location of and power available to battery charging stations or the number of chargers at a location.
- Hydrogen refuelling infrastructure. The availability of hydrogen refuelling infrastructure is a critical issue for truck operators. There are no public hydrogen refuelling stations in Ireland as of 2025. Truck operators need hydrogen refuelling infrastructure on key routes and hubs to commit to hydrogen technology. This issue is compounded by the lack of suitable hydrogen policy and industry support to enable the market and provide certainty of a green hydrogen production and supply to potential refuelling infrastructure.
- Battery charging time. Although fast-charging technology is being developed, recharging battery electric trucks still takes significantly longer than refuelling diesel trucks. Given the tight schedules in logistics, reducing charging times will be crucial to making battery electric trucks practical for long-haul operations and minimising downtime.
- Upfront costs. The initial costs of battery and hydrogen fuel cell electric trucks are similar; however, battery electric trucks are seeing a faster decrease in cost. Both battery and fuel cell electric vehicles are more expensive than conventional diesel trucks, an investment that can be a barrier for fleet operators, especially those managing large fleets.
- Operating costs. Operational (including electricity cost) and maintenance costs are generally lower for battery electric trucks than diesel and hydrogen vehicles. For hydrogen fuel cell electric trucks, maintenance costs can vary, and the cost of hydrogen in Ireland is relatively unknown, but presently across the UK and Europe hydrogen is more expensive than diesel per 100 km driven.
- Battery technology. Battery technology plays a vital role in the performance of battery electric and hydrogen fuel cell electric trucks. Factors such as range, charging speed and overall durability are critical to their success in heavy-duty transport. Ongoing research is needed to improve energy density, reduce costs and enhance battery and fuel cell life to meet the demands of long-haul trucking.
- Hydrogen technology. Electrolysis technology that produces green hydrogen is vital to enable a sustainable hydrogen supply chain, but, currently, Ireland imports some of its hydrogen needed for industry. This issue is compounded by the lack of suitable hydrogen policy and industry support to enable the market and provide certainty of green hydrogen production and supply.
- Raw material supply. The increasing demand for battery electric trucks raises concerns about the availability of raw materials such as lithium, cobalt and nickel, which are essential for battery production. This is less of a concern for fuel cell electric vehicles; however, the supply of platinum required for fuel cells may be constrained in the future if large volumes of fuel cells are manufactured. Electrolysis technology also has material requirements such as platinum and palladium for the most efficient technology. A sustainable and ethical supply chain for these materials is necessary to support the transition to

electric heavy-duty transport without exacerbating environmental and social issues.

- Resale value. The resale value of battery and hydrogen fuel cell electric trucks may be a concern for fleet operators, especially due to uncertainties regarding battery longevity and the rapid pace of technological advancements. A strong secondary market for electric trucks is essential to provide fleet operators with confidence in their long-term investments.
- Performance perception. Some operators may perceive battery electric trucks as lacking the power and performance of diesel trucks. While battery and hydrogen fuel cell electric trucks offer instant torque and smooth acceleration, further efforts are needed to demonstrate their capability in handling heavy loads and long-distance freight, thus overcoming any hesitancy within the industry.

2.3 Hydrogen

Despite rising interest across the globe, hydrogen remains underutilised in its role as a decarbonisation solution. At present, approximately 90% of global hydrogen production, totalling 70–100 Mt annually, primarily serves petrochemical industries, with half of it directed towards ammonia production for agricultural use. The remaining 10% serves various sectors, including fat hydrogenation and glass manufacturing (World Nuclear Association, 2024).

Hydrogen is an energy carrier; it is produced by input energy that can be then stored or moved and used later to expel its energy at a certain efficiency. A significant challenge lies in the current hydrogen production process, which generates around 830 Mt CO_2 eq yearly due to its heavy dependence on fossil fuels. Within the EU, hydrogen consumption amounts to roughly 10 Mt annually, with notable production hubs in Germany, the Netherlands and the UK. While low-carbon hydrogen production currently stands at nearly 0.5 Mt, projections suggest that demand will rise significantly, reaching 16.4 Mt by 2030 (BloombergNEF, 2024).

A review article by Nemmour *et al*. (2023) shows that, in the realm of sustainable hydrogen production via electrolysis, solid oxide electrolysis, while at the research stage, holds potential for water electrolysis. It also highlights the efficacy of alkaline electrolysis cells for large-scale commercial use, while proton exchange membrane (PEM) electrolysis (PEMEL) is found to have benefits in terms of its cost-efficiency and adaptable performance.

For hydrogen to fully realise its potential as a low-carbon energy carrier, substantial progress in developing sustainable hydrogen production methods is imperative. These methods involve leveraging renewable energy sources to create hydrogen through processes like electrolysis. This transition towards green hydrogen and other colours of hydrogen has the potential to considerably curtail carbon emissions, expediting the integration of hydrogen as a cleaner energy alternative across diverse industries.

The EU hydrogen strategy promotes hydrogen fuel cell electric vehicles by supporting their adoption in public transport, such as buses, and in heavy-duty logistics. It provides incentives and support mechanisms to boost the use of hydrogen-powered commercial fleets, with a focus on sectors where direct electrification is not feasible, such as trucks, buses and specialised transport. The strategy aims to accelerate the deployment of hydrogen refuelling infrastructure across Trans-European Transport Network (TEN-T) corridors to support fuel cell electric vehicles effectively (European Commission, 2020b, 2025a).

In addition, the EU's ambitious hydrogen strategy is anchored in a series of regulatory frameworks and strategic initiatives designed to accelerate the adoption of renewable hydrogen as a cornerstone of its clean energy transition. Regulations (EU) 2023/1184 and 2023/1185 (European Union, 2023a) establish stringent criteria and methodologies for the production of renewable hydrogen and calculating its GHG emissions, ensuring its alignment with the EU's decarbonisation goals. The Renewable Energy Directive (European Commission, 2025b) and regulations on renewable fuels of non-biological origin (European Commission, 2022) set clear mandates for integrating green hydrogen, particularly in challenging sectors such as industry and heavy transport. These efforts are amplified by the REPowerEU plan (European Commission, 2025c), which, in response to the energy crisis, set an ambitious target of producing 10 Mt of renewable hydrogen domestically and importing an additional 10 Mt by 2030. This holistic approach not only supports the EU's vision of energy independence but also underscores hydrogen's critical role in achieving a climate-neutral Europe by 2050, fostering resilience and creating new economic opportunities in the green energy sector.

According to Ireland's National Hydrogen Strategy, Ireland's short-term strategy (before 2030) focuses on enabling the development of the hydrogen sector by producing hydrogen from grid-connected electrolysis using surplus renewable energy, targeting specific end-use sectors such as transport to meet EU targets. The strategy aims to remove barriers to early hydrogen projects and enhance knowledge through targeted research and innovation, with a 2 GW target of offshore wind for hydrogen production by 2030. In the long-term strategy (post 2030), Ireland plans to scale up hydrogen production using its extensive offshore wind resources, aiming to become a net exporter of renewable hydrogen. The strategy also envisages the development of a national hydrogen network and large-scale geological storage to support the transition to a net zero energy system by 2050 (DECC, 2023).

2.3.1 The colours of hydrogen

Green hydrogen

A highly promising and flexible approach for producing hydrogen on a large scale is water electrolysis. This process involves using electrical power to split water into hydrogen and oxygen using an electrolyser. Importantly, this method does not result in direct carbon emissions. Water electrolysis can achieve an efficiency of over 75% based on the input power. The fundamental operational concept of the three most advanced electrolysis technologies, namely alkaline electrolysis, PEM electrolysis and solid oxide electrolysis, are shown in Figure 2.8. A brief comparison of these three technologies is also presented in Table 2.3.

The carbon intensity of the hydrogen produced through electrolysis depends on the origin of the electricity used to power the electrolysis process. In the case of Ireland, the current electricity grid is not the best energy source for electrolysis because most of the electricity comes from burning fossil fuels, which leads to GHG emissions.

By the third quarter of 2021, the carbon intensity of Ireland's electricity grid rose to 375 g CO_2/kWh, from 296 g CO_2/kWh in 2020. This increase was largely driven by the impact of the Covid-19 pandemic, which led to a higher reliance on fossil fuels such as coal, oil and gas to meet energy demands (EirGrid, n.d.). However, as of 2024, projections indicate a significant reduction in carbon intensity to 234 g CO_2/kWh, attributed to a decline in coal-fired power generation and a rise in electricity imports from lower-emission sources (CCAC, 2024). This improvement would also extend to the carbon intensity of hydrogen produced from grid electricity. Therefore, using renewable energy technologies, either independently or as a growing portion of the grid's energy mix, would make it possible to generate clean hydrogen through electrolysis.

The CertifHy certification system has been useful in categorising the carbon intensity of hydrogen from

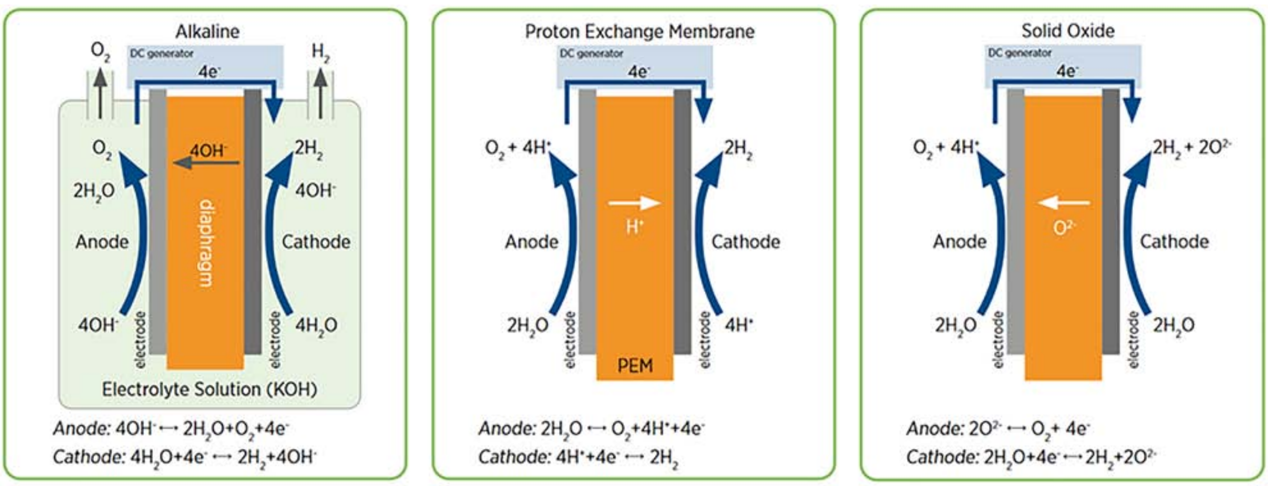

Figure 2.8. Schematic of alkaline, PEM and solid oxide electrolysis, with associated equations. DC, direct current; KOH, potassium hydroxide. Source: IRENA (2020).

Table 2.3. The main features, advantages and disadvantages of each electrolysis technology

Parameter	Alkaline electrolysis	PEM electrolysis	Solid oxide electrolysis
Electrolyte	Potassium hydroxide	Solid polymer (Nafion, Fumapem)	Solid oxide (ceramic)
Anode material	Nickel	Iridium	Perovskite or nickel-based materials
Cathode material	Nickel	Platinum	Nickel-based materials
Operating temperature (°C)	60–100	50–80	500–1000
Pressure	Low	High	Moderate
Key advantage	Low cost; mature technology	Fast response; high-purity hydrogen	High efficiency; can produce syngas
Key disadvantage	Slow response to dynamic loads	High cost due to precious metals	High temperature leads to material degradation

different sources. More recently, the Renewable Energy Directive established rules on the manufacture of hydrogen and identified low-carbon hydrogen as having a carbon intensity of less than 3 kg CO_2 eq/kg H_2 (European Commission, 2025b). When hydrogen is created through water electrolysis that is entirely powered by non-biological renewable energy it is categorised as green hydrogen (Figure 2.9).

Water electrolysis is a well-established technology, although it has encountered historical cost challenges that are now gradually being resolved. As the technology gains global traction, considerable cost reductions are anticipated. The International Renewable Energy Agency's insights indicate that, presently, the cost of green hydrogen is notably higher, around two to three times, than that of fossil-based hydrogen. However, a substantial decrease to below \$2/kg H_2 (€1.74/kg H_2) by 2030 is projected in scenarios of low electricity costs, aligning the cost with current cost levels of fossil-based hydrogen. Similarly, Al-Qahtani *et al*. (2021), through life cycle analysis, estimated the 2019 cost of green hydrogen derived from wind energy at \$5.61/kg H_2 (€4.88/kg H_2), aligning with the International Renewable Energy Agency's and others' findings (European Commission, 2025a). However, with continued global energy security challenges and political shocks, as well as inadequate EU and national hydrogen policy and support, green hydrogen costs could stay stubbornly high (BloombergNEF, 2024).

Growing interest in hydrogen production and the deployment of electrolysers is becoming increasingly evident across Europe and on the island of Ireland. In Northern Ireland, the electricity provider Energia has initiated the operation of an electrolyser that generates green hydrogen from surplus electricity. This hydrogen is then supplied to a refuelling station for hydrogen buses situated in Belfast. Several other companies have also publicly declared their involvement in this burgeoning sector. For instance, Indaver and Bord na Móna have outlined plans in the eastern region of Ireland. In the west, the Electricity Supply Board is making advances and, in the north-west region, Hone and Mercury Renewables are advancing hydrogen-related projects. Furthermore, progress is being made in establishing the Galway Hydrogen Hub and SH2AMROCK, an initiative centred around the Galway Harbour area. This initiative aims to create a nucleus for hydrogen-related activities and is anticipated to commence operations in a number of years' time (Martins and Carton, 2023).

Figure 2.9. Simplified process of green hydrogen production.

Blue hydrogen

Steam methane reforming (SMR) is currently the most common method for producing hydrogen, but it relies on fossil fuel natural gas, emitting significant amounts of CO_2, 10–20 kg CO_2 eq/kg H_2, in the process. This creates a contradiction: while hydrogen is promoted as a clean energy carrier solution, using SMR shifts emissions from the point of energy use to the point of hydrogen production, merely relocating the carbon emissions rather than eliminating them.

Experts emphasise the need to adopt cleaner methods, such as green hydrogen or blue hydrogen production. In this context, low-carbon approaches have gained more attention and become more economically feasible in recent years. Some of these methods still use fossil fuels as starting materials but capture most of the GHGs, like CO_2, and store them geologically underground, a process called carbon capture and storage (CCS). This results in what is known as blue hydrogen and emits significantly fewer carbon emissions than traditional methods (see Figure 2.10). Blue hydrogen, depending on the storage location, methane release and other factors, releases 4–20 kg CO_2 eq/kg H_2 (Mehmeti *et al*., 2018).

Bauer *et al*. (2022) suggest that blue hydrogen is only synonymous with “low carbon” hydrogen if two conditions are met. Firstly, natural gas supply must have minimal GHG emissions, achieved by minimising methane leaks across the supply chain. Secondly, effective CO_2 capture technology should be employed, with capture rates ideally exceeding 90%. The integration of hydrogen production and CO_2 capture is crucial to minimise energy demand and, if necessary, low-carbon electricity should be used for any net electricity import.

However, a recent analysis of blue hydrogen conducted by Howarth and Jacobson (2021) raised concerns about methane emissions during the production process. Their study indicated that the total CO_2-equivalent emissions of blue hydrogen could be almost as high as those of grey hydrogen. There is no clear agreement yet about the full environmental impact and commercial feasibility of CCS or blue hydrogen. The UK Government has committed £21.7 billion over the next 25 years to support blue hydrogen and carbon capture initiatives, such as the HyNet and East Coast Cluster projects. These efforts are aimed at reducing carbon emissions in heavy industries by capturing and storing CO_2 emissions, making blue hydrogen a key part of the UK’s strategy to reach net zero by 2050 (House of Commons Science and Technology Committee, 2022).

Grey hydrogen

One well-established production method used worldwide is SMR, as mentioned previously (Bhat and Sadhukhan, 2009), with over 80% of global hydrogen coming from SMR. This involves natural gas reacting with steam to make hydrogen, but it also produces CO_2, which can be as much as 29.33 kg CO_2-eq/kg H_2 (Kakoulaki *et al*., 2021). This results in what is known as grey hydrogen, which is mainly used because it is the cheapest type of hydrogen to produce for industries. In the process, hydrocarbons, along with methane, undergo heating and sulfur removal in a steam system to prevent contamination and hinder catalyst activity (Van Beurden, 2004). Methods like hydrodesulfurisation and activated carbon-based adsorption can effectively eliminate sulfur (Mochida and Choi, 2004). Then, steam and purified methane are led through a catalyst, transforming into hydrogen through an endothermic reaction, as illustrated in Figure 2.11.

Navas-Anguita *et al*. (2021) suggested that, in the short to medium term, grey hydrogen from SMR could meet road transport demand, but electrolysis could take over by around 2035 due to lower costs and favourable carbon impact. SMR might play a role during the transition to green hydrogen, but international strategies should consider broader factors outlined in the EU hydrogen strategy. There are

Figure 2.10. Simplified process of blue hydrogen production.

$$CH_4 + H_2O \text{ (+heat) } 700–900°C \rightarrow CO + 3H_2$$

Figure 2.11. Simplified process of grey hydrogen production.

no SMR facilities in Ireland, as there has not been a large demand for hydrogen from major petrochemical or chemical industries.

Turquoise hydrogen

Turquoise hydrogen, also referred to as teal hydrogen, is generated using a technique called methane pyrolysis (MP) or methane splitting (Figure 2.12). This process involves breaking down natural gas (methane) into its fundamental components – hydrogen and solid carbon – without directly emitting CO_2. The significance of turquoise hydrogen lies in its potential to notably diminish the carbon emissions linked with hydrogen production (–10 to 0.91 kg CO_2 eq/kg H_2), achieved by avoiding the release of CO_2 and using renewable natural gas as an input over fossil fuel natural gas, a major GHG.

The importance of turquoise hydrogen stems from its ability to act as a bridge between grey and blue hydrogen (created with CCS) and green hydrogen (formed using renewable energy sources). By utilising turquoise hydrogen one can work towards reducing the carbon impact of hydrogen production without depending solely on renewable energy inputs. This method effectively utilises the existing fossil fuel natural gas infrastructure while markedly decreasing carbon intensity in comparison with conventional grey hydrogen production. It is crucial to note that the technology and its scalability are currently in development, and the extent of its environmental benefits hinges on factors such as methane leakage, the efficiency of the pyrolysis process and the practical utilisation, disposal or storage of the solid carbon by-product.

2.3.2 Hydrogen storage – medium scale

Compressed hydrogen

To store hydrogen for transport, e.g. in tube trailers or transport applications, hydrogen gas is compressed at high pressure in containers. Makridis (2017) explored the correlation between pressure and volumetric density to enhance storage capacity, utilising lightweight composite cylinders capable of withstanding pressures of up to 800 bar. Makridis (2017) also investigated the pressure–density relationship at three temperatures (273 K, 298 K and 373 K).

Makridis (2017) showed that at these three different temperatures the volumetric density increases with pressure but does not follow a linear pattern (Faye *et al.,* 2022). Also, achieving a high volumetric density requires very high pressure, which poses safety concerns (Sorensen and Spazzafumo, 2018).

Liquid hydrogen

Liquid hydrogen (LH_2) presents an appealing solution due to its remarkable energy density at temperatures below 21 K, resulting in a density of 71 kg/m^3. Nonetheless, the energy-intensive liquefaction process, requiring 12–15 kWh/kg (Reuß *et al.*, 2017), poses a significant challenge, accounting for 36–45% of total hydrogen energy. Despite this

Figure 2.12. Simplified process of turquoise hydrogen production.

hurdle, LH_2 storage employs cryogenic tanks with low pressure (< 10 bar) and high energy densities, demanding careful management of hydrogen boil-off (evaporation due to heat transfer). These tanks are designed with robust insulation to minimise heat transfer, addressing hydrogen boil-off due to inevitable heat inflow (Reuß *et al*., 2017). The liquefaction process involves compressors, heat exchangers, expansion engines and throttle valves. Two primary techniques are the Linde cycle and Joule–Thomson expansion cycle. In the Linde cycle, gas undergoes compression and cooling before a throttle valve induces Joule–Thomson expansion, resulting in liquid formation. Cryogenic cooling is necessary for hydrogen, involving temperatures below –150°C (123 K). Cryogenic liquefaction transforms a gas under atmospheric conditions into a liquid under both atmospheric pressure and cryogenic temperature. Cooling hydrogen below –253°C (20 K) employs gases like helium, neon, nitrogen, oxygen or air at atmospheric or higher pressures. Liquid hydrogen has a density of 70.9 g/L, surpassing compressed gas, at 42 g/L. However, challenges associated with liquid storage encompass boil-off and potential leakage. Effective solutions to combat energy loss during liquefaction include refrigeration and insulating containers (Reuß *et al*., 2017; Faye *et al*., 2022).

2.3.3 Transporting hydrogen

Piped hydrogen

Carrying gases in pipe networks allows for the cost-effective transport of sizeable amounts of energy over distances of hundreds to thousands of kilometres. Hydrogen pipelines aim to be rated for transporting pure hydrogen safely. An EU study of 28 countries found that the cost of transporting 1 kg of hydrogen by pipeline over a distance of 1000 km in 2040 would be €0.11–0.21 over land and €0.17–0.32 by sea (EHB, 2022).

Some proponents of gas systems have suggested converting existing pipe networks to carry hydrogen, which could be feasible, to reduce capital infrastructure investment. Others suggest using existing pipe networks that carry fossil fuel gases, e.g. methane, and blending in hydrogen, but this has its own challenges once the blend reaches even small percentages by volume.

The length of China's hydrogen transport pipeline network is currently *c*.400 km, and the construction of future pipeline networks across the world is accelerating (Sun *et al*., 2022). Currently, the European Hydrogen Backbone pipe network, which Ireland is part of, has in excess of 6000 km of new or repurposed hydrogen pipe network planned. In Ireland, gas network operator Gas Networks Ireland has published a 2050 roadmap, *Pathway to a Net Zero Carbon Network*, which aims to repurpose the existing pipe network by splitting it into two networks, one dedicated to biomethane (30%) and one to hydrogen (70%), to accommodate indigenous hydrogen production, as well as export via the interconnectors to Europe through the UK (Gas Networks Ireland, 2024).

Trucked hydrogen

Commercial tube trailers consist of around 12–20 elongated steel cylinders placed on a trailer bed and are subject to regulation. These trailers are regulated with a gas pressure limit of 160 atm (approximately 2400 psi), although some higher-pressure trailers (up to 400 atm) have received special certification. The hydrogen capacity per trailer is relatively small (~300 kg), but can be increased with higher-pressure systems. Tube trailers are widely used in commercial settings due to their well-established technology and safety measures. Tube trailers can also serve as secondary storage at hydrogen refuelling stations. For transporting hydrogen to a refuelling station, a full tube trailer can be exchanged with an empty one to enhance loading and unloading efficiency, taking about 1 hour. In point-to-point hydrogen distribution, a truck and tube trailer move hydrogen between the hydrogen production plant and the refuelling station. The number of trucks and trailers depends on factors like hydrogen demand, trailer capacity, transit time, loading/unloading time and truck availability (Martins and Carton, 2023). At the central plant, stationary compressors fill the trailers, which are then driven to refuelling sites where extra compression is applied to meet the pressure requirements for onboard vehicle storage. Tube trailers are cost-effective for small hydrogen markets due to their lower capital costs but have limited capacity (Mehmeti *et al*., 2018). Transporting hydrogen by truck is also a flexible solution for delivering hydrogen to areas without pipeline infrastructure. While trucking gaseous hydrogen is more common for shorter distances, liquid hydrogen is more economical for longer routes due to its higher energy density. However, when transporting hydrogen by truck several challenges arise that need to be addressed.

Capacity limitations. Trucks transporting hydrogen, particularly gaseous hydrogen, face limitations due to the low energy density of the gas. For example, steel tube trailers typically carry only about 300 kg of hydrogen, which is a relatively small amount considering the energy requirements of industrial applications and heavy-duty transport (Ali *et al.*, 2024).

Weight constraints. The weight of the storage tanks themselves significantly reduces the available payload capacity. Hydrogen needs to be stored either under high pressure (gaseous form) or at cryogenic temperatures (liquid form), which requires specialised and heavy equipment, impacting the overall efficiency of hydrogen transport by road.

Safety concerns. Transporting hydrogen introduces significant safety risks, as hydrogen is highly flammable and requires specialised containment. Leaks or exposure to embrittled materials could lead to dangerous situations, especially during long-distance transport where constant monitoring is difficult (Calabrese *et al.*, 2024).

High delivery costs. Due to the limited carrying capacity and the need for frequent trips, the cost of delivering hydrogen by truck can be prohibitively high compared with other delivery methods, such as pipelines. The cost per kilogram of hydrogen increases as the distance grows, making it less economical for longer trips.

2.3.4 Hydrogen refuelling

The significance of hydrogen refuelling within the broader hydrogen supply chain cannot be overstated. As hydrogen gains traction, establishing a well-developed refuelling network will become pivotal. Hydrogen refuelling stations serve as critical nodes, ensuring the accessibility and viability of hydrogen-powered vehicles across various sectors, especially heavy-duty transport and captive fleets. Hydrogen delivery mechanisms are also crucial, necessitating efficient distribution systems to ensure a reliable and steady supply to these refuelling stations. Strategically positioned refuelling hubs along major transport routes and in urban centres, e.g. the European TEN-T, offer convenient access, encouraging broader adoption. The industry group Hydrogen Mobility Ireland has indicated that the establishment of between 20 and 70 hydrogen refuelling stations across the island of Ireland could enable an all-island hydrogen transport sector, which holds immense significance for advancing sustainable transport in Ireland. With the growing interest in hydrogen as a clean energy carrier, having strategically located refuelling hubs is vital to support widespread adoption. The Alternative Fuels Infrastructure Regulation is one of the EU's frameworks to support the shift towards sustainable transport in Europe. It includes a mandatory target for Member States on charging and refuelling infrastructure development. Commencing in April 2024, the initiative aims to encourage zero-emission passenger and freight road transport, enabling sustainable trade and engineering economic growth within the EU. Specifically, it aims to generate economies of scale for producers and managers of infrastructure for alternative fuels. The regulation includes having HDV charging stations with a minimum 350 kW output placed every 60 km along the TEN-T core network and every 100 km on the TEN-T comprehensive network starting in 2025. It also requires at least one hydrogen refuelling station every 200 km on the TEN-T core network and at least one hydrogen refuelling station in every urban node by the end of 2030 (European Union, 2023b).

2.4 Irish Industrial Emissions Directive and Hydrogen Review

Industrial pollution is a major environmental concern, accounting for approximately 27% of emissions affecting air, water and soil quality. Sources of such pollution include the combustion of fossil fuels, chemical manufacturing processes and agricultural practices. The damage caused by industrial emissions to human health and the environment in Europe alone costs between €277 and €433 billion per year (EEA, 2021). The IED, published by the EU in 2010, was transposed into Irish law in 2013, replacing the previous Integrated Pollution Prevention and Control Directive along with seven other directives, and amended in 2024. The IED is a cornerstone regulation aimed at reducing pollution from industrial activities across Europe (European Union, 2010, 2024).

2.4.1 IED background and scope

The IED's primary goal is to protect human health and the environment by integrating and enhancing the efficiency of previous directives. The directive focuses on emissions to air, water and land, highlighting the importance of minimising the impact of industrial pollution. The IED introduces a comprehensive legal framework to significantly reduce harmful emissions from industrial operations within EU Member States, ensuring a high level of protection for human health and the environment.

The IED sets emission limit values and other requirements for a wide range of industrial activities, including energy production, metal production, the mineral industry, the chemical industry and waste management. A central aspect of the IED is its permit system, requiring around 52,000 industrial installations, listed in Annex I to the directive, to operate under strict conditions. These permits, issued by national authorities like the EPA in Ireland, mandate conditions that consider integrated environmental performance, including emissions, waste generation, energy efficiency and accident prevention. The IED is built upon several key pillars that ensure a comprehensive approach to environmental protection (see Figure 2.13).

The IED (Directive 2010/75/EU) has direct and indirect links and connections to several other important EU directives and regulations, including:

- the Cleaner Air for Europe Directive (Directive 2008/50/EC) – this Directive sets limits and targets for air pollutants, which are relevant for the IED, as it regulates emissions from industrial sources;
- Directive 2004/107/EC relating to arsenic, cadmium, mercury, nickel and polycyclic aromatic hydrocarbons in ambient air;
- Directive (EU) 2024/2881 on ambient air quality and cleaner air for Europe (recast);
- the Water Framework Directive (Directive 2000/60/EC) – the IED requires industrial installations to have permits that address water-related aspects, such as water usage and wastewater discharges, the impacts of which must meet the requirements of the Water Framework Directive;
- Regulation (EC) No. 166/2006 concerning the establishment of a European Pollutant Release and Transfer Register (E-PRTR) – the IED requires industrial installations to report their emissions and transfers of pollutants, which are then included in the E-PRTR;
- the Waste Framework Directive (Directive 2008/98/EC) – the IED includes requirements for the management and disposal of waste generated

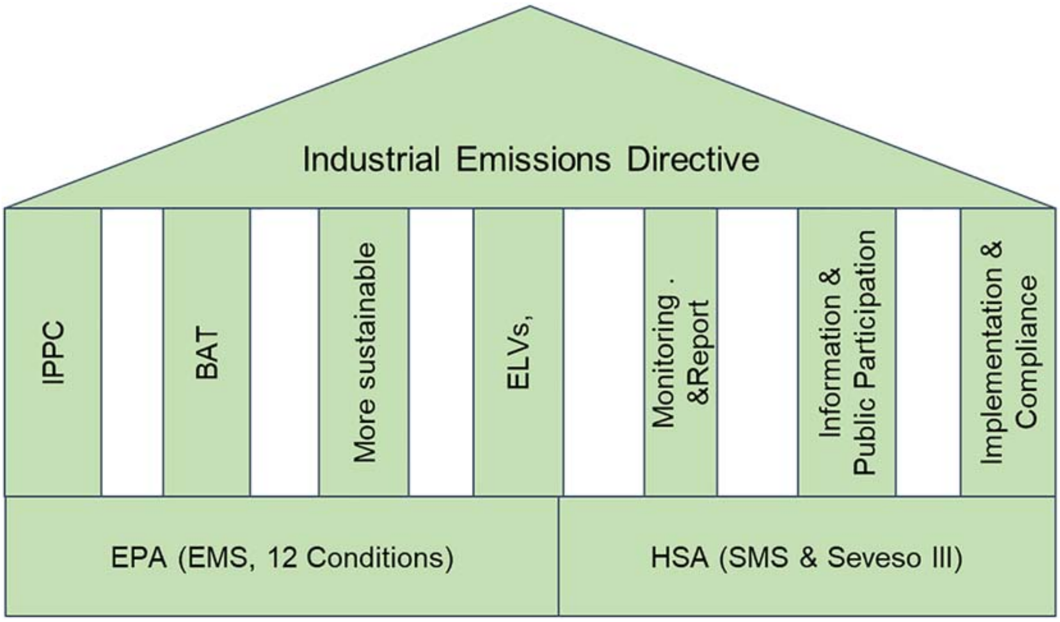

Figure 2.13. The pillars of the IED, which work together to minimise industrial emissions and their impact on the environment. BAT, best available techniques; ELV, emission limit value; EMS, environmental management system; HSA, Health and Safety Authority; IPPC, Integrated Pollution Prevention and Control; SMS, safety management system.

by industrial activities, which are further regulated by the Waste Framework Directive;

- Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (the Habitats Directive);
- the Environmental Impact Assessment Directive (Directive 2011/92/EU) – the IED requires certain industrial activities to undergo an environmental impact assessment, which is regulated by this directive.

The IED's linkages with these other directives and regulations ensure that it is part of a broader framework of EU environmental legislation, addressing issues such as air quality, water protection, waste management and biodiversity conservation. This is part of the integrated approach to pollution reduction across the EU. The IED requires industries to have this integrated approach, requiring permit authorisers to consider the entire environmental performance of a plant. This includes:

- emissions to air, water and land;
- generation of waste;
- use of raw materials;
- energy efficiency;
- noise levels;
- prevention of accidents;
- restoration of the site upon closure;
- best available techniques (BAT).

Permit conditions, including emission limit values, must be based on BAT. BAT is defined through an exchange of information between Member States, industry and environmental organisations, coordinated by the European Integrated Pollution Prevention and Control Bureau. BAT conclusions, as summarised and described in detail in the resulting BAT reference documents, are adopted by the European Commission as implementing decisions. Flexibility is a key element in getting full adaptation of BAT by industries, as a one-size-fits-all approach may not be applicable. While the IED sets strict standards, it allows for some flexibility. Authorities can set less stringent emission limit values in specific cases where achieving BAT-associated levels would lead to disproportionately higher costs compared with the environmental benefits, e.g. due to the age of a facility. Across the EU, emission limit values have been set at the same level for certain activities, such as large combustion plant activities and waste incineration, and the IED sets EU-wide emission limit values for selected pollutants, for example mercury, lead, NO_x and sulfur. This is to drive down pollution across the Union. National authorities are required to conduct regular inspections of the installations to ensure compliance with the permit conditions. Non-compliance with licence conditions (not just emission limit values) may be subject to legal action, which may be at district or circuit court level, with the possibility of substantial financial penalties and/or custodial sentences, high court action such as an injunction (which may result in orders to cease all or part of an activity), or suspension of the licence.

2.4.2 IED 2.0 and hydrogen

With climate change and energy security becoming more urgent, the EU has set a "net zero" target for 2050 and energy, climate and circular economy policy goals under the European Green Deal and the Zero Pollution Action Plan. In addition, green hydrogen (produced from renewable energy through water electrolysis) is seen by the EU as a potential energy carrier to assist the EU (and Ireland) to decarbonise and secure its energy system.

A proposal to revise the IED was tabled in April 2022, aimed at bringing the IED in line with climate change urgency, energy security needs and necessary decarbonisation targets. The European Parliament and the Council reached a provisional agreement in November 2023. The agreed text was endorsed by Member State representatives in December 2023 and by the European Parliament's Environment Committee in January 2024. The Revised IED, or IED 2.0, was formally adopted by the co-legislators in April 2024 (EEA, 2021). The main changes include expanding the IED's scope, strengthening permit requirements and adding measures to foster innovation.

In relation to hydrogen, the committee recognised that electrolysis-based hydrogen production should be distinguished from high-emission industrial processes. A number of new pieces of text were added to accommodate hydrogen production by electrolysis, subject to the IED.

The IED, as amended by Directive (EU) 2024/1785, includes reference to hydrogen production;
activity 4.2(a) for hydrogen production excluding

electrolysis on an industrial scale and 6.6. for electrolysis of water for the production of hydrogen where the production capacity exceeds 50 tonnes per day. The capacity requirement is noted; for example, if a facility in practice produces 5 tonnes per day but has the capacity to produce 50 tonnes per day, this is an IED activity. IED 2.0 will be transposed into Irish law in the coming months. Member States have until 1 July 2026 to adapt their national laws to the revised directive.

2.4.3 Thresholds and requirements for IED compliance

In the EU, hydrogen production installations face specific compliance thresholds under the IED to ensure environmental protection. Key points include the following.

- The production threshold for IED compliance. Installations with the capacity to produce over 50 tonnes of hydrogen per day must adhere to the IED, while electrolyser plants with a hydrogen capacity of below 50 tonnes per day or 50 MW electricity input are not considered an IED class of activity. As guided by the BAT reference documents for large volume inorganic chemicals, installations must implement BAT to minimise pollution across emissions, resource use and energy efficiency.
- Compliance with the Medium Combustion Plant Directive (Directive (EU) 2015/2193). This applies to combustion plants with a rated thermal input between 1 and 50 MW, including those using hydrogen for combustion purposes.

Other related directives that should be considered by hydrogen production operators include the following.

- The Seveso III Directive (Directive 2012/18/EU). Installations capable of producing or storing 5 tonnes or more of hydrogen per day are subject to the Seveso Directive (involving the Health and Safety Authority), which focuses on the prevention and mitigation of accidents involving dangerous substances.
- The ATEX Directive (2014/34/EU). This ensures a safe working environment when handling or storing chemicals. It primarily applies to industries that deal with flammable gases, vapours and dust, and this will also apply to hydrogen.
- The Ecodesign Directive (Directive 2009/125/EC) and Regulation (EU) 2024/1781. These apply to installations producing hydrogen-powered devices or systems, targeting products that use energy or impact energy consumption indirectly.
- EU water abstraction regulations of 2018. An abstraction is the removal or diversion of water from a river, lake, stream, spring, groundwater well, borehole or estuary for any purpose, including hydrogen production from electrolysis. If an installation abstracts 25 m^3 (25,000 L) of water or more per day, you must register this abstraction with the EPA (EPA, 2025b).

For hydrogen installations that fall under the IED, the directive allows flexibility in achieving compliance, encouraging operators to select cost-effective, environmentally friendly solutions. Regular inspections by national authorities and provisions for public participation in environmental permitting processes are mandatory. Implementation of robust environmental management systems, safety management systems and energy management systems are required.
For hydrogen production installations in the EU, understanding and adhering to these compliance requirements is crucial for legal operation and environmental stewardship, aligning with the EU's goals for a sustainable, low-carbon future.

2.4.4 Producing hydrogen under the IED

To be granted a licence to produce hydrogen in large volumes, the facility operator will have to go through the same process as any facility operator applying for a licence to produce something that does not occur naturally and has potential to generate waste or pollution. The following steps are required to get approval to produce hydrogen under the IED (it is illegal to do so without the correct permits and licence).

The licensing process, governed by the EPA's 2013 regulations, involves a comprehensive review, including the submission of detailed plans, environmental impact assessments and strategies for emission management and waste minimisation. The process may also entail public notifications, the opportunity for objections and, potentially, an oral hearing. Applicants must demonstrate the implementation of BAT to minimise emissions and environmental impact, ensuring compliance with section 83(5) of the Environmental Protection Agency Act 1992.

Applicants should register on the EPA's online system, the Environmental Data Exchange Network (EPA, 2025c). Applications are submitted to the EPA, including comprehensive details of the project, environmental management plans and evidence of compliance with emission limits and environmental quality standards and relevant legislation. The EPA reviews the application, may request further information and has the authority to amend licences if necessary. As hydrogen production is regulated under the IED, it is an IED licence that is issued. The licensing process is designed to ensure that hydrogen production installations operate responsibly, prioritising environmental protection and safety.

An Integrated Pollution Control licence is a single licence covering all emissions from and environmental management of an installation, that are not IED classes of activity. The EPA issues Integrated Pollution Control licences with strict conditions to keep pollution to a minimum. The EPA is prohibited from granting a licence if it would lead to significant environmental damage by an industry. Any installation operator in Ireland that is granted a licence will be registered on the Licence and Enforcement Access Portal by the EPA. Provisions for the facility operator to consider are the following.

- Integrated approach. Permits/licences must consider the plant's overall environmental performance, including emissions, waste generation, raw material use, energy efficiency and accident prevention.
- BAT. Permit conditions, including emission limit values, are based on BAT, defined through an exchange of information coordinated by the European Integrated Pollution Prevention and Control Bureau. BAT conclusions are adopted by the European Commission as implementing decisions and are the reference for setting permit conditions.
- Flexibility. Under specific circumstances, authorities can set less stringent emission limits, provided that they justify the decision.
- Emission limit values. The IED sets EU-wide emission limit values for certain pollutants from specific activities, allowing for flexibility in specific cases where achieving BAT-associated levels would lead to disproportionately higher costs.
- Environmental inspections. Member States must establish a system of environmental inspections, with site visits at least every 1–3 years based on risk criteria.
- Public participation. The IED ensures public participation in the decision-making process and access to environmental information through the E-PRTR.
- Emission reporting. Through the E-PRTR, emissions data are made publicly available.

2.4.5 Future of the IED

The IED will be revised every 5 years from 2028. Going forward, more installations will be brought under its scope; stricter controls will be implemented; and permits will be made more effective, while allowing innovative approaches and greater focus on energy efficiency, circular economy and decarbonisation, as well as aiming to reduce administration while increasing data transparency for all stakeholders.

3 Life Cycle Assessment

3.1 Goal and Scope

The aim of this study was to complete a desktop environmental LCA to evaluate the environmental impacts of the production, transport and refuelling of hydrogen for HGVs.

3.1.1 Intended audience

The study aimed to provide policymakers, industry stakeholders and researchers with valuable insights into the environmental sustainability of hydrogen in the transport sector. The findings will help inform decision-making processes in future sustainable infrastructure development and sustainable fuel policy.

3.1.2 Function

The function of the product system is to produce and transport hydrogen as a fuel for HGV use.

3.1.3 Functional unit

The functional unit is defined as production of 1 kg of hydrogen, compressed and delivered to the hydrogen refuelling station.

3.1.4 System boundary

This study focused on multiple hydrogen production pathways, including green, blue, grey and turquoise hydrogen, and the scope of this study was cradle to gate, i.e. the technical boundaries cover processes from raw material extraction to hydrogen production and delivery to the refuelling stations for use as a fuel in HGVs. The plant construction, infrastructure set-up and fugitive emissions were excluded from the boundaries of this system. The geographical boundaries of the hydrogen production study were focused in Ireland. The datasets for hydrogen production, transport and refuelling were sourced from the GaBi database, with additional data from literature specific to Germany. The study began in January 2023 and ran until June 2024. The life cycle inventory (LCI) datasets used in this study ranged from 2020 to 2023.

Hydrogen was defined as:

- PEMEL from renewable energy – green hydrogen;
- SMR with CCS (SMR-CCS) from fossil fuel natural gas – blue hydrogen;
- SMR from fossil fuel natural gas – grey hydrogen;
- MP from fossil fuel natural gas – turquoise hydrogen.

Twelve scenarios were proposed in this study (Figure 3.1): four scenarios for the four categories of hydrogen and three scenarios for moving hydrogen in the system.

The first three scenarios are related to green hydrogen. In green scenario 1, hydrogen is produced from the PEM electrolyser with a capacity of 1 MW per stack, with a specific electricity consumption of 55 kWh/kg H_2 (η_{HHV} = 71.59%) assumed as well as 12 kg of water needed in the process (Hermesmann and Müller, 2022).

In this case, the annual operating hours of 8000 h/y were considered. The lifetime of the stack was estimated at 10 years and the plant lifetime at 20 years (Calabrese *et al*., 2024). According to green scenario 2, hydrogen produced from a PEM electrolyser is compressed and transported to the refuelling station by truck for utilisation as fuel in HGVs. In green scenario 3, the compressed hydrogen produced from the PEM electrolyser is transported to the refuelling station by pipeline.

Blue scenario 4 refers to blue hydrogen production via SMR-CCS. The system operates at a capacity of 100,000 Nm^3/h H_2, with 8000 operating hours per year and a lifetime of 20 years. CO_2 sequestration from the shifted syngas is achieved through chemical absorption, utilising state-of-the-art pre-combustion capture technology, reaching a capture efficiency of approximately 56% (Calabrese *et al*., 2024).

Methyldiethanolamine (MDEA) is a liquid amine and solvent widely used for capturing CO_2. MDEA is not explicitly considered in the LCA software, as no reliable information could be referenced during the study. However, during the literature review we

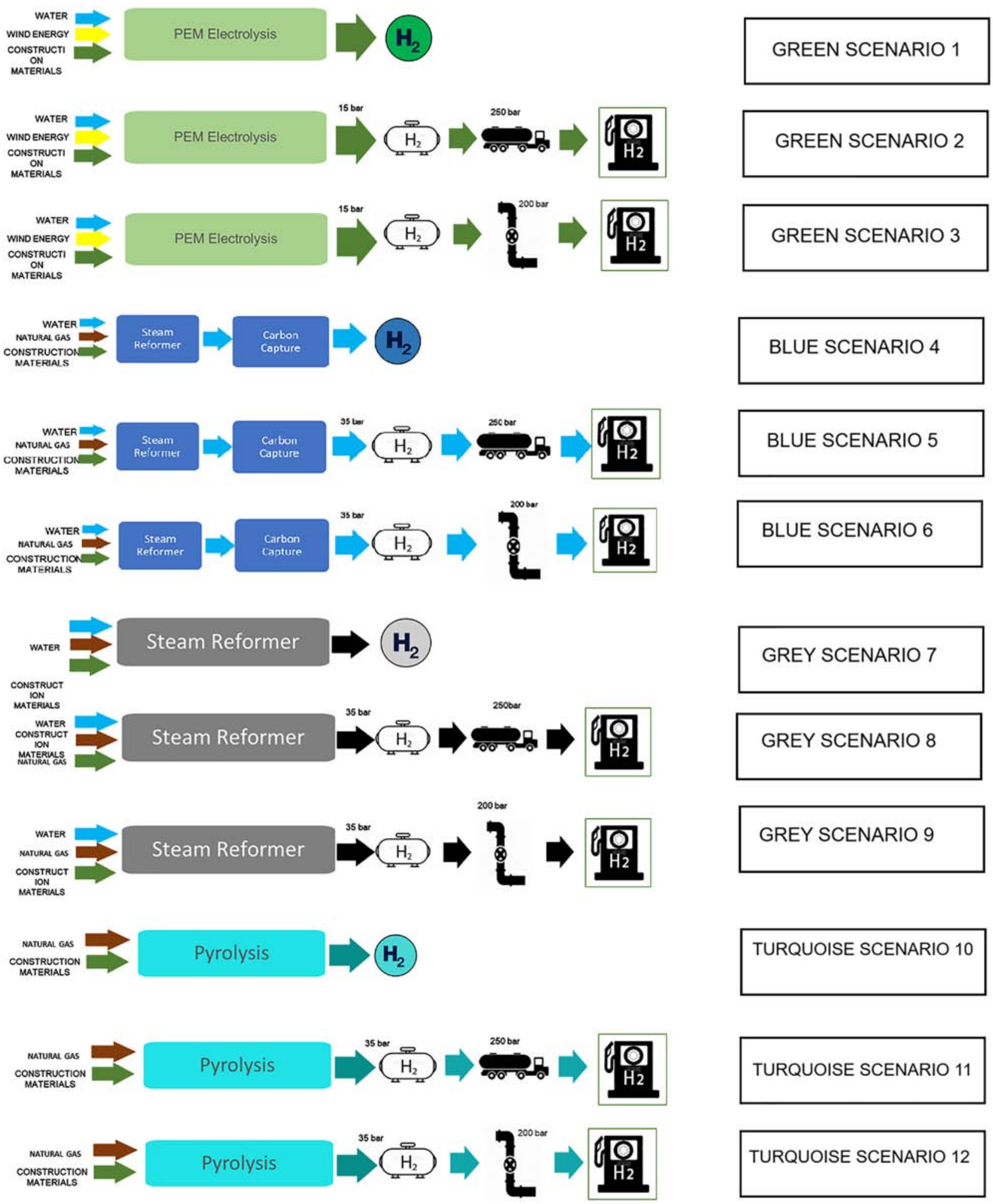

Figure 3.1. Scenarios developed based on various hydrogen production, transport and delivery pathways.

determined the following, subsequently using the best data to inform our inventory and results.

- The additional energy requirements for CO_2 capture and solvent regeneration indirectly affect the overall process efficiency, leading to changes in fuel and water demands – these have been accounted for in the study.
- MDEA is not typically categorised as a GHG but can degrade over time, indirectly contributing

to global warming potential (GWP), but specific data on its GWP contributions are limited and the indirect effects of MDEA's degradation products on GWP remain uncertain. MDEA's primary environmental concern lies in its potential ecotoxicity, particularly in affecting marine environments. While its degradation products could theoretically influence GWP, current data are insufficient to quantify this effect – for the purposes of this study MDEA's GWP is deemed to have a low/negligible impact compared with other parts of the SMR-CCS process.

- With regard to the marine aquatic ecotoxicity potential (MAETP) for MDEA, this can be referenced as 1.3 kg 1,4-dichlorobenzene (DCB) eq/kg of MDEA used. Considering that *c*.0.15 kg of fresh MDEA is required per kg of CO_2 captured in a well-managed system, adding *c*.1 kg DCB eq/kg H_2 to MAETP (see Figure 4.5). It is noted that MDEA regeneration significantly reduces its environmental impact (Orangi, 2021).

The use of MDEA in CO_2 capture presents environmental challenges, particularly in terms of toxicity, water pollution and emissions. MDEA exhibits moderate toxicity to aquatic organisms, with an EC_{50} (half maximal effective concentration) of 35 mg/L for algae and 190 mg/L for *Daphnia magna*. If released into waterbodies, it can degrade into nitrosamines, which are highly carcinogenic and have been detected at levels exceeding 1 µg/L in industrial wastewater, far above the World Health Organization drinking water limit of 0.1 µg/L. MDEA degradation in high-temperature environments also releases ammonia (5–50 ppm) and formaldehyde (0.1–5 ppm), contributing to air pollution and secondary aerosol formation. Given these environmental risks, careful waste management, emission control and alternative solvent exploration are necessary to mitigate long-term impacts (Karl *et al*., 2011; Eide-Haugmo *et al*., 2012; Zahedi *et al*., 2022).

Grey hydrogen produced from SMR with a capacity of 100,000 $Nm^3/h\ H_2$, annual operating hours of 8000 h/y and a lifetime of 20 years were assumed in grey scenario 7. In scenarios 8 and 9, the hydrogen is produced from SMR transport to the compressor, then, at the end of this process, it is moved to the refuelling station by truck and pipeline.

In the case of turquoise hydrogen, which is produced by MP, the product hydrogen connects to a compressor and then, at the end of this process, it connects to the refuelling station in turquoise scenarios 10, 11 and 12. For the MP plant, a lifetime of 20 years with 8000 hours of operation per year was assumed.

3.2 Allocation

Allocation in LCA is the process of dividing the environmental impacts of a production process among multiple outputs and can be based on factors like physical production quantities or economic value. In this study, the carbon black by-product from the turquoise hydrogen production pathway was found to be the only by-product from the production systems that warranted consideration of any type of allocation or system expansion. The first and most logical approach considered, given the disparity between the values of the hydrogen and the carbon black, was for allocation by economic value. However, after a preliminary investigation, it was found that the low value of the by-product prior to material processing would have a negligible impact on the emissions profile of the hydrogen product system. System expansion was also considered; however, there was no available LCI for the carbon black product system.

3.3 Data for Life Cycle Assessment

The life cycle impact assessment (LCIA) methodology used in this study was the Institute of Environmental Sciences at Leiden University midpoint methodology (CML2001-Jan 2016). The data used in the study came from a mix of academic literature sources, technical reports and LCA software datasets.

3.3.1 Life cycle inventory analysis

The elementary flow datasets for this study were provided by Sphera's LCA for Experts 2023 version 10.7.1.28. The LCI data included inputs for chemicals, thermal energy, electricity and wastewater treatment.

The assumptions regarding the LCI data for hydrogen production through SMR, SMR-CCS, MP and PEMEL were based on information obtained from referenced literature (Hermesmann and Müller, 2022). In cases where data were incomplete, additional information was sourced from the licensed GaBi database software. The standardisation process involved normalising input and output data for each production method to a common functional unit of 1 kg H_2, considering factors such as operating hours, lifetimes and specific capacities of the technologies. For industrial plants, a standard operating time of 8000 hours per annum was assumed.

Table 3.1 presents LCI data of the PEMEL-based hydrogen production, while Table 3.2 shows data for the compressor, refuelling station and pipeline. The supporting infrastructure is the same for all scenarios.

For blue, grey and turquoise hydrogen production scenarios, the LCI data are provided in Table 3.2.

Table 3.1. Inventory for PEM electrolyser, SMR with CCS, SMR and MP

PEM electrolyser		SMR + CCS		SMR		MP	
Input flows							
Electricity	55 kWh	Natural gas	5.01 m³	Natural gas	4.85 m³	Natural gas	7.44 m³
Deionised water	12 kg	Water	257 kg	Water	387 kg	Electricity	1.67 kWh
Output flows							
Oxygen	8.00 kg	Carbon dioxide	4.12 kg	Carbon dioxide	9 kg	–	–
Construction materials							
Titanium	0.000363 kg	Concrete	0.00000660 m³	Concrete	0.00000660 m³	Copper	0.00000733 kg
High-alloyed steel	0.000722 kg	Steel	0.00506 kg	Steel	0.00506 kg	Silica sand	0.0000804 kg
Copper	0.0000375 kg	Aluminium	0.0000417 kg	Aluminium	0.0000417 kg	Tin	0.0336 kg
Nafion™	0.0000110 kg	Cast iron	0.0000618 kg	Cast iron	0.0000618 kg	Silicon carbide	0.0000042 kg
Activated carbon	0.00000619 kg	–	–	–	–	Palladium	0.0000110 kg
Low-alloyed steel	0.00165 kg	–	–	–	–	Low-alloyed steel	0.00259 kg
Aluminium	0.0000529 kg	–	–	–	–	High-alloyed steel	0.000507 kg

Table 3.2. Inventory for compressor, fuel station and pipeline

Compressor		Fuel station		Pipeline (100 km)	
Input flows					
Electricity	9.4 kWh/kg H²	Electricity	14.2 kWh	Polyurethane	0.0137 kg
Construction materials					
Low-alloyed steel	0.0039757 kg	Low-alloyed steel	0.07889 kg	–	–
High-alloyed steel	0.00069513 kg	High-alloyed steel	0.0081 kg	–	–
Cast iron	0.0002466 kg	Cast iron	0.0023 kg	–	–
Copper	0.00009317 kg	Copper	0.000910 kg	–	–
Aluminium	0.00002577 kg	Aluminium	0.000384 kg	–	–
Polymer	0.00002157 kg	Polymer	0.00028 kg	–	–
Electronics	0.00000867 kg	Carbon fibers	0.00135 kg	–	–

Sources: Burkhardt *et al.* (2016); Ekhtiari *et al.* (2020); Hermesmann and Müller (2022); Sabu (2024).

4 Results

4.1 Life Cycle Impact Assessment

The LCIA phase uses LCI data to assess the environmental impacts of a product system by categorising flows crossing system boundaries into various impact categories. Each flow's contribution is quantified using characterisation factors related to reference indicators, which are determined by the impact assessment model. The selection of impact categories is aligned with the study's goals, scope and relevance to the product system.

The selection of the four key LCIA categories presented in Table 4.1 was driven by their relevance in capturing the environmental impacts associated with hydrogen production. While most previous studies have concentrated on GWP, this research extends the LCA of hydrogen production by including acidification potential (AP), eutrophication potential (EP) and MAETP. GWP is critical for assessing the contribution of carbon emissions to climate change, a key focus in hydrogen production pathways. AP and EP were included due to their ability to capture acidifying emissions and nutrient run-off, both of which are common by-products of energy-intensive processes like hydrogen production. Finally, MAETP was selected to address the ecotoxicity impacts on marine ecosystems, which are particularly important given the potential for effluents and emissions to impact waterbodies. These categories align with global sustainability goals and provide a comprehensive assessment of the environmental footprint of hydrogen technologies.

Table 4.1. LCIA categories used in this study

Impact category	Abbreviation	Unit
Global warming potential over 100 years	GWP100	Kg CO_2 eq
Acidification potential	AP	Kg SO_2, eq
Eutrophication potential	EP	Kg PO_4^{3-}eq
Marine aquatic ecotoxicity potential	MAETP	Kg DCB eq

4.2 Life Cycle Impact Assessment Results for Hydrogen Production

Figure 4.1 and Table 4.2 present the GWP, MAETP, AP and EP of the present-day production of 1 kg of hydrogen in Ireland using the technologies considered in this study.

4.2.1 *Global warming potential of hydrogen production*

The GWP of hydrogen production varies significantly depending on the method used, ranging from 0.773 to

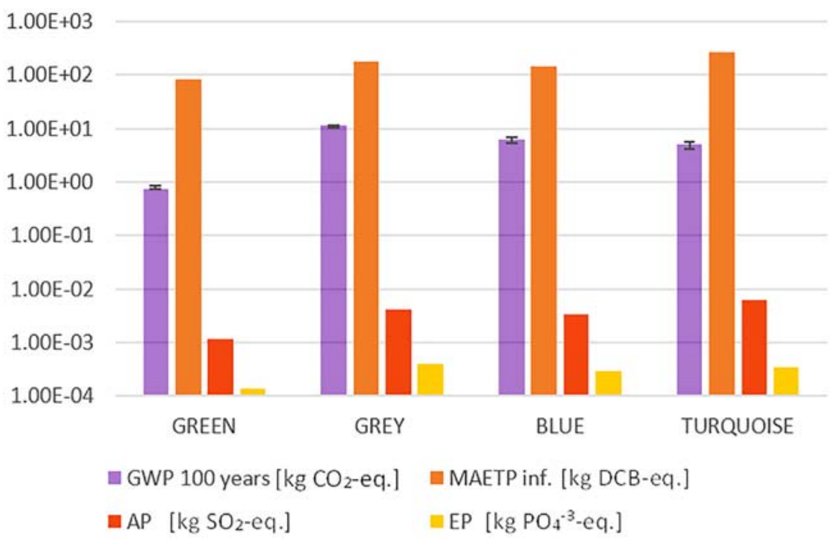

Figure 4.1. GWP, MAETP, AP and EP values for green, grey, blue and turquoise hydrogen production.

Table 4.2. The environmental impacts of hydrogen production

	GWP (kg CO_2-eq)	MAETP (kg DCB-eq)	AP (kg SO_2-eq)	EP (kg phosphate-eq)
Green hydrogen	0.773	85	0.00115	0.000139
Grey hydrogen	11.6	170.013	0.00418	0.000411
Blue hydrogen	6.28	158.31	0.00347	0.000302
Turquoise hydrogen	4.16	271.446	0.00616	0.000341

11.6 kg CO_2 eq/kg H_2. Grey hydrogen, produced by SMR without CCS, has the highest GWP, at 11.6 kg CO_2 eq/kg H_2. This is due to process-related GHG emissions, which contribute 9.0 kg CO_2 eq/kg H_2, accounting for 77% of the total GHG emissions, while the remaining 2.6 kg CO_2 eq/kg H_2 (23%) comes from the supply and processing of natural gas. The 9.0 kg CO_2 eq/kg H_2 refers to the direct emissions generated during the SMR process, where methane reacts with steam, producing hydrogen and CO_2, as well as the additional CO_2 released from the combustion of natural gas to provide the required heat for the reaction. Significant emissions arise from the combustion of methane and reforming reactions, coupled with methane leakage during natural gas extraction and transport, making grey hydrogen particularly carbon intensive.

Blue hydrogen, which combines SMR with CCS, reduces emissions substantially, achieving a GWP of 6.28 kg CO_2 eq/kg H_2 by capturing 56% of CO_2 emissions. Process-related emissions are reduced to 4.12 kg CO_2 eq/kg H_2. On the other hand, turquoise hydrogen, produced via MP, has a lower GWP (4.16 kg CO_2 eq/kg H_2), since it produces solid carbon rather than CO_2, although its fossil fuel natural gas supply and heat source still impact its intensity. Turquoise hydrogen has a GWP of 4.15 kg CO_2 eq/kg H_2. Green hydrogen, produced through electrolysis powered by renewable energy, achieves the lowest GWP, at 0.773 kg CO_2 eq/kg H_2, as it does not rely on fossil fuels and has minimal emissions beyond the electricity source.

4.2.2 Contribution analysis of hydrogen production

The analysis of GWP across the 12 hydrogen production and transport scenarios highlights clear differences in environmental impact, driven primarily by the energy sources, production methods and material inputs used, as shown in Figure 4.2.

Green scenarios 1 to 3 primarily depend on renewable energy, particularly wind-generated electricity, which, despite its zero-carbon nature, still contributes to the overall GWP. The material inputs, including aluminium, steel and copper, are substantial, reflecting the infrastructure needs for electrolysis systems. In scenario 3, additional materials such as polyethylene and fiberglass further increase the GWP slightly. Nonetheless, due to low operational emissions, these green scenarios remain the most sustainable in the long term.

In scenarios related to grey and blue hydrogen, natural gas and steam reforming are the dominant contributors to GWP. However, the use of carbon capture mitigates emissions, reducing the overall environmental impact. The contribution of materials like steel, aluminium and concrete is still high due to the infrastructure needed for carbon capture facilities. The combination of fossil fuels and the need for carbon capture infrastructure results in moderate GWP, positioning these scenarios as intermediate solutions between renewable energy and fossil fuel systems without carbon capture.

Grey scenarios 7–9 exhibit the highest GWP contributions, driven by the emissions from natural gas and the steam reforming. Without carbon capture, the fossil fuel combustion leads to a significant environmental burden, despite similar material use to the carbon capture scenarios. The absence of CO_2 mitigation mechanisms makes these scenarios the least sustainable option for hydrogen production, highlighting the critical role of carbon capture in reducing emissions.

The pyrolysis scenarios introduce new materials such as fibreglass and epoxy resin, which contribute to GWP but are less impactful than fossil fuels. These scenarios show a lower GWP than steam reforming without carbon capture, as pyrolysis generates solid carbon as a by-product, reducing CO_2 emissions. However, the increased material inputs necessary for the process suggest that optimising material use could

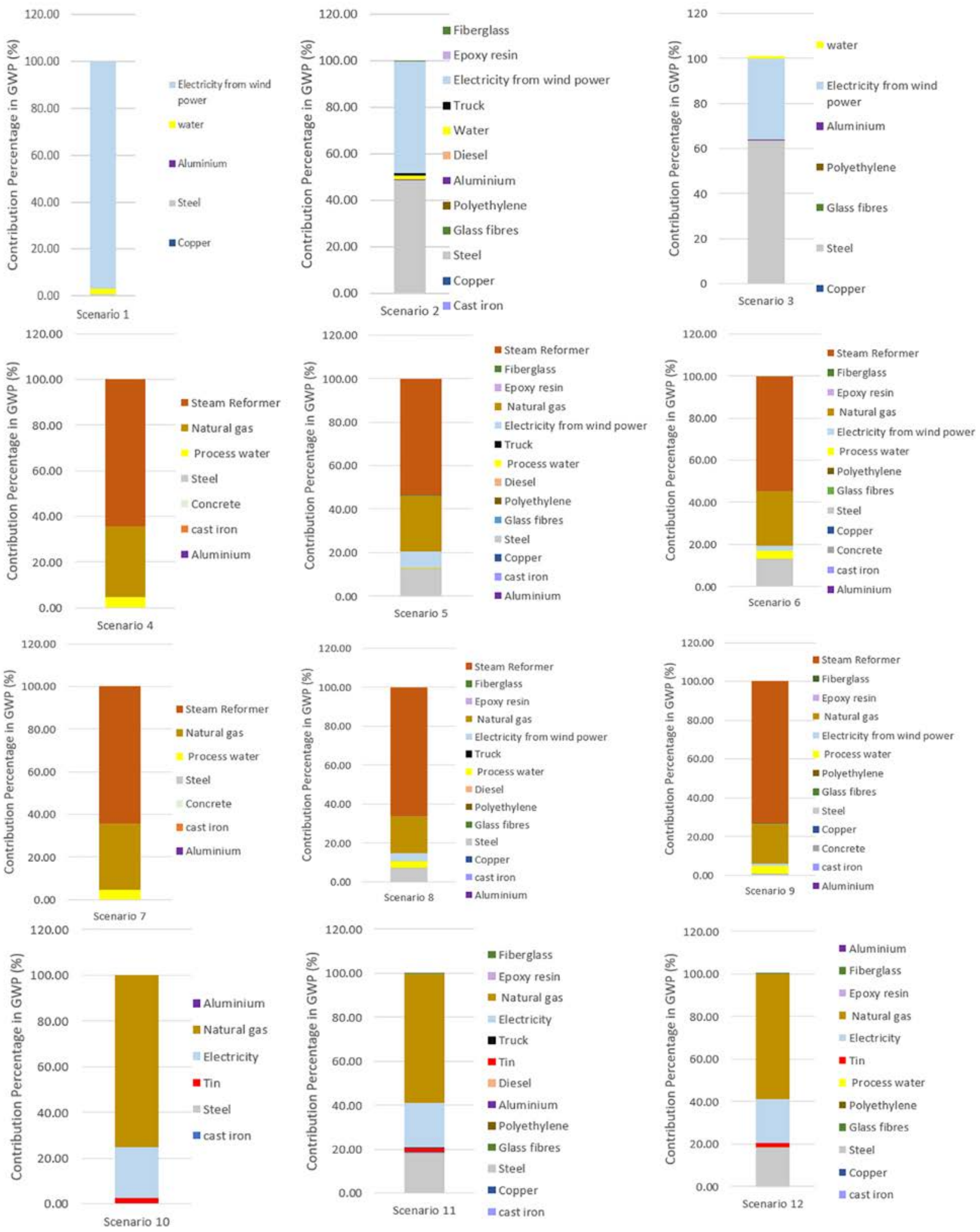

Figure 4.2. Contribution assessment of different components of the proposed scenarios in GWP.

further enhance the environmental performance of pyrolysis-based hydrogen production.

The differences in GWP are primarily driven by the energy sources (renewables vs fossil fuels) and the presence or absence of carbon capture. Renewable-based green scenarios (1–3) have high initial material impacts but much lower operational emissions. Carbon capture in blue scenarios 4–6 significantly reduces GWP, but steam reforming without carbon capture (grey scenarios 7–9) remains highly carbon intensive. Pyrolysis (turquoise scenarios 10–12) provides a promising alternative, with lower emissions, but requires further optimisation of material efficiency.

These results underscore the need for material optimisation and the importance of integrating renewable energy or carbon capture to minimise the environmental impacts of hydrogen production.

4.2.3 Other environmental impacts of hydrogen production

The MAETP is highest for turquoise hydrogen production, at 271 kg DCB eq, followed by grey hydrogen at 181 kg DCB eq and blue hydrogen at 150 kg DCB eq. In contrast, green hydrogen has the lowest MAETP, at 84 kg DCB eq. This suggests that turquoise and grey hydrogen have a significantly higher impact on marine ecosystems due to the energy-intensive processes and pollutants in their production chains, whereas green hydrogen has a reduced environmental burden, reflecting its cleaner energy inputs and fewer associated emissions.

The AP is highest for turquoise hydrogen production, at 6.16×10^{-3} kg SO_2 eq, indicating that this process releases the most acidifying emissions. Grey hydrogen follows closely, with an AP of 4.18×10^{-3} kg SO_2 eq, while blue hydrogen has a slightly lower value of 3.47×10^{-3} kg SO_2 eq. Green hydrogen production, which relies on renewable energy, has the lowest AP, at 1.15×10^{-3} kg SO_2 eq. This pattern shows that fossil-fuel-based and energy-intensive processes, like turquoise and grey hydrogen processes, contribute more to acidifying emissions than the green hydrogen process, which produces significantly fewer emissions due to its reliance on clean energy sources.

The EP tells a similar story, with grey hydrogen having the highest value, at 4.11×10^{-4} kg PO_4^{-3} eq, followed by turquoise hydrogen at 3.41×10^{-4} kg PO_4^{-3} eq. Blue hydrogen shows a slightly lower EP of 3.02×10^{-4} kg PO_4^{-3} eq, while green hydrogen once again has the lowest impact, with an EP of 1.39×10^{-4} kg PO_4^{-3} eq. This suggests that grey hydrogen, due to its reliance on fossil fuels, contributes more to nutrient loading and potential eutrophication of waterbodies, whereas green hydrogen's cleaner production methods result in far less nutrient pollution.

The GWP for green hydrogen is the lowest among all hydrogen production methods, with notable contributions coming from PEMEL at 0.77 kg CO_2 eq/kg H_2, followed by the refuelling station at 0.127 kg CO_2 eq/kg H_2. The contributions from pipeline and truck transport processes are minimal. However, despite its low GWP, green hydrogen shows relatively high MAETP, mainly due to the PEM process, which contributes 85 kg DCB eq. Additional significant contributors include fuel cell electric vehicles, which account for 80.8 kg DCB eq, and refuelling stations, at 51.4 kg DCB eq.

Grey hydrogen exhibits a significantly higher GWP than green hydrogen, primarily driven by the SMR process, which generates 11.6 kg CO_2 eq/kg H_2. While other contributors, such as the refuelling station and compressor, remain consistent with green hydrogen production, the MAETP for grey hydrogen is particularly high, reaching 170.01 kg DCB eq. during the SMR process. This reflects the significant environmental burden associated with the reliance on fossil fuels for grey hydrogen production.

Blue hydrogen has a lower GWP of 6.4 kg CO_2 eq/kg H_2 due to the incorporation of CCS in the SMR process. However, the MAETP remains considerable, at 158.31 kg DCB eq, indicating that, although CCS captures a portion of CO_2 emissions, the environmental impact remains significant. Turquoise hydrogen, which has a GWP of 4.15 kg CO_2 eq/kg H_2, shows an even more pronounced MAETP, with the highest value at 271.44 kg DCB eq, particularly due to the MP process. This underscores the environmental trade-offs of turquoise hydrogen, particularly its severe impact on marine ecosystems.

Green hydrogen is the most environmentally friendly option, with the lowest GWP, while grey hydrogen has the highest GWP due to its reliance on fossil fuels. Blue hydrogen improves on grey hydrogen by incorporating CCS, and turquoise hydrogen falls between blue hydrogen and green hydrogen in terms of GWP. Turquoise hydrogen presents the highest risk for MAETP, largely due to its energy-intensive MP process. Grey and blue hydrogen also show high MAETP values, reflecting the environmental burden of using fossil fuels. Green hydrogen, while not free from MAETP impacts, has a relatively lower but still significant MAETP value due to the PEM process. These results highlight the environmental trade-offs associated with each hydrogen production technology, with green hydrogen emerging as the most sustainable option overall, despite its challenges in MAETP.

4.3 Life Cycle Assessment Results from Hydrogen Production to Delivery (Whole Process)

4.3.1 Green hydrogen pathway

The LCA results for green hydrogen production, from the production through to its delivery to the refuelling station, indicate varying environmental impacts across different stages of the process. As shown in Figure 4.3, the GWP is highest in the PEMEL stage, reflecting the significant carbon emissions associated with the electricity-intensive process. The next largest contributor to GWP is the refuelling station, followed by the compression of hydrogen. Transport of hydrogen by truck and pipeline contributes minimally to GWP, with pipeline transport showing the lowest impact.

In terms of MAETP, the PEMEL process again shows the highest impact, signifying the environmental burden of material and energy use. Fuel cell electric vehicles and refuelling stations also contribute significantly to MAETP, while the compressor, truck and pipeline stages have comparatively lower impacts. Overall, the PEMEL process emerges as the most environmentally impactful stage in terms of both GWP and MAETP, highlighting areas for potential improvement in green hydrogen production.

4.3.2 Grey hydrogen pathway

The LCA results shown in Figure 4.3 for grey hydrogen production, which involves the SMR process, indicate significant environmental impacts across different stages, from production to usage in HGVs.

The GWP for grey hydrogen is predominantly driven by the SMR process, with a value of 11.60 kg CO_2 eq/kg H_2. This high value reflects the substantial carbon emissions associated with the use of fossil fuels in the production process. The next largest contributors to GWP are the refuelling station and the compressor, which is consistent with the green hydrogen results. The transport of hydrogen by truck has a lower GWP impact, similar to the green hydrogen results, while pipeline transport shows the least impact, with a GWP of 0.0005 kg CO_2 eq/kg H_2.

The MAETP is also highest in the SMR process, with a significant impact of 170.01 kg DCB eq. This reflects the environmental burden of using fossil fuels, which leads to the release of harmful pollutants. Fuel cell electric vehicles and refuelling stations also contribute notably to the MAETP, but to a lesser extent than the SMR process. The compressor and truck stages have lower impacts, with pipeline transport again showing the smallest contribution to MAETP at 0.0239 kg DCB eq.

4.3.3 Blue hydrogen pathway

Results for blue hydrogen are represented in Figure 4.3, which is produced through SMR combined with CCS. The GWP for blue hydrogen is primarily driven by the SMR-CCS process, which contributes 6.28 kg CO_2 eq/kg H_2. While this is significantly lower than grey hydrogen's GWP, it still represents a substantial carbon footprint due to the partial capture of CO_2 in the CCS process. The other stages – the refuelling station, compressor and transport – show

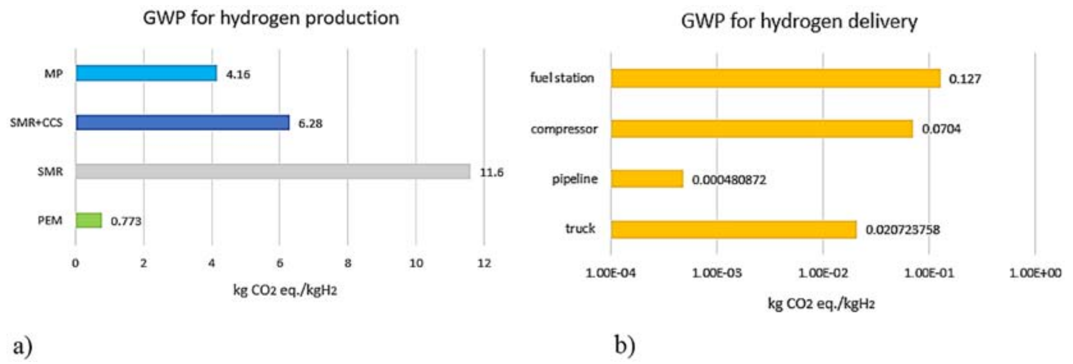

Figure 4.3. GWP results for green, grey, blue and turquoise hydrogen (a) production and (b) delivery scenarios.

similar GWP contributions to those observed for green and grey hydrogen. Specifically, the refuelling station contributes 0.127 kg CO_2 eq/kg H_2 and compression contributes 0.0704 kg CO_2 eq/kg H_2. Pipeline transport remains the most efficient, with the lowest GWP of 0.0005 kg CO_2 eq/kg H_2.

The MAETP for blue hydrogen is significant, especially in the SMR-CCS stage, which contributes 158.31 kg DCB eq. This high value reflects the environmental burden of the CCS process, which involves the handling and storage of captured CO_2. Fuel cell electric vehicles and refuelling stations also contribute to MAETP, at 80.8 kg DCB eq and 51.4 kg DCB eq, respectively. The compression stage adds 14.7 kg DCB eq to MAETP, while truck and pipeline transport have minimal impacts, with pipeline transport being the least impactful at 0.0239 kg DCB eq.

The LCA results for blue hydrogen indicate that, while it offers a lower GWP than grey hydrogen thanks to the CCS technology, it still has a considerable environmental impact, particularly in terms of MAETP. The SMR-CCS process, while reducing carbon emissions, introduces its own set of environmental challenges, particularly in managing the ecotoxicity associated with CCS. These findings suggest that, while blue hydrogen is a step towards reducing the carbon footprint of hydrogen production, there are still significant environmental considerations that need to be addressed to optimise its sustainability.

4.3.4 *Turquoise hydrogen pathway*

The LCA for turquoise hydrogen, which is produced via MP, reveals distinct environmental impacts across its production and distribution stages, particularly when compared with green, grey and blue hydrogen.

Turquoise hydrogen's GWP is significantly influenced by the MP process, which contributes 5.6 kg CO_2 eq/kg H_2, as shown in Figure 4.4. While this is lower than the GWP of grey and blue hydrogen, it is still substantial, reflecting the energy demands and carbon output of the process. The remaining stages, such as the refuelling station, compression and transport by truck, exhibit similar GWP values as those seen in other hydrogen types. Pipeline transport continues to be the most efficient stage, with a minimal GWP of 0.0005 kg CO_2 eq/kg H_2.

The MAETP for turquoise hydrogen is notably high, especially in the MP stage, which contributes 271.44 kg DCB eq. This is the highest MAETP observed among the hydrogen types, indicating significant ecological concerns related to the emissions (methane leakage, CO_2, volatile organic compounds, NO_x and SO_x) and energy used in this production method. Other stages, such as the use in fuel cell electric vehicles and at refuelling stations, also contribute to MAETP, but their impact is considerably lower than that of the MP process. The transport stages, particularly pipeline transport, again show the least impact, with an MAETP of 0.0239 kg DCB eq.

Turquoise hydrogen presents a mixed environmental profile; while it offers a lower GWP than grey and blue hydrogen due to the absence of direct CO_2 emissions, its MAETP is alarmingly high, raising concerns about its overall ecological footprint. The results highlight the MP process as a significant area of environmental impact, particularly in terms of MAETP, underscoring the need for further optimisation and control measures to make turquoise hydrogen a more sustainable option.

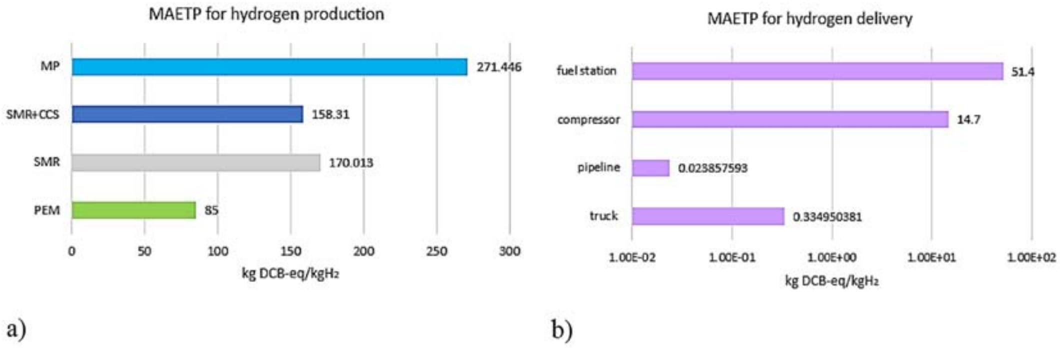

Figure 4.4. MAETP results for green, grey, blue and turquoise hydrogen (a) production and (b) delivery scenarios.

4.3.5 Hydrogen pathway comparison

The results shown in Figure 4.4 indicate that green hydrogen, produced primarily through PEMEL, is the most environmentally favourable scenario. PEMEL demonstrates the lowest GWP, contributing only 0.753 kg CO_2 eq/kg H_2. This highlights the effectiveness of using renewable energy sources to minimise carbon footprint. On the contrary, grey hydrogen, produced via SMR, emerges as the least environmentally friendly option, with the highest GWP of 11.6 kg CO_2 eq/kg H_2. The high GWP for grey hydrogen is due to the extensive use of fossil fuels in the SMR process, leading to significant CO_2 emissions. Technologies such as SMR-CCS and MP offer moderate GWP contributions of 6.28 and 5.6 kg CO_2 eq/kg H_2, respectively. The comparison based on GWP in Figure 4.4 confirms PEMEL as the most environmentally friendly method.

Additionally, in terms of MAETP, MP poses the greatest threat to aquatic ecosystems, contributing the highest impact at 271.446 kg DCB eq, or approximately 39% of the total. SMR contributes significantly to MAETP as well, accounting for 170.013 kg DCB eq, while PEMEL exhibits the lowest MAETP of 84 kg DCB eq. This demonstrates the environmental trade-offs associated with different hydrogen production methods, where the low carbon emissions of some processes may be offset by increased ecological toxicity in others.

Figure 4.5 compares GWP and MAETP contributors post hydrogen production, which remain consistent across all scenarios (PEMEL for green hydrogen, SMR for grey hydrogen, etc.). Key contributors to GWP are the refuelling stations (43%), compressors (24%) and storage systems (20%), while MAETP is most influenced by fuel cell electric vehicles (53%), refuelling stations (34%) and compressors (10%). This analysis highlights the environmental impacts associated with hydrogen delivery infrastructure, emphasising differences in GWP and MAETP across the value chain. The refuelling station stage is identified as the largest contributor to GWP, responsible for 43% of emissions. This is likely to be due to the energy-intensive processes involved in storing and dispensing hydrogen. Conversely, fuel cell electric vehicles have the highest MAETP, at 53%, which may be attributed to the materials and processes used in fuel cell production and operation. On the positive side, pipeline transport stands out as the most efficient stage, with minimal contributions to both GWP and MAETP. This efficiency is likely to be due to the lower energy requirements for transporting

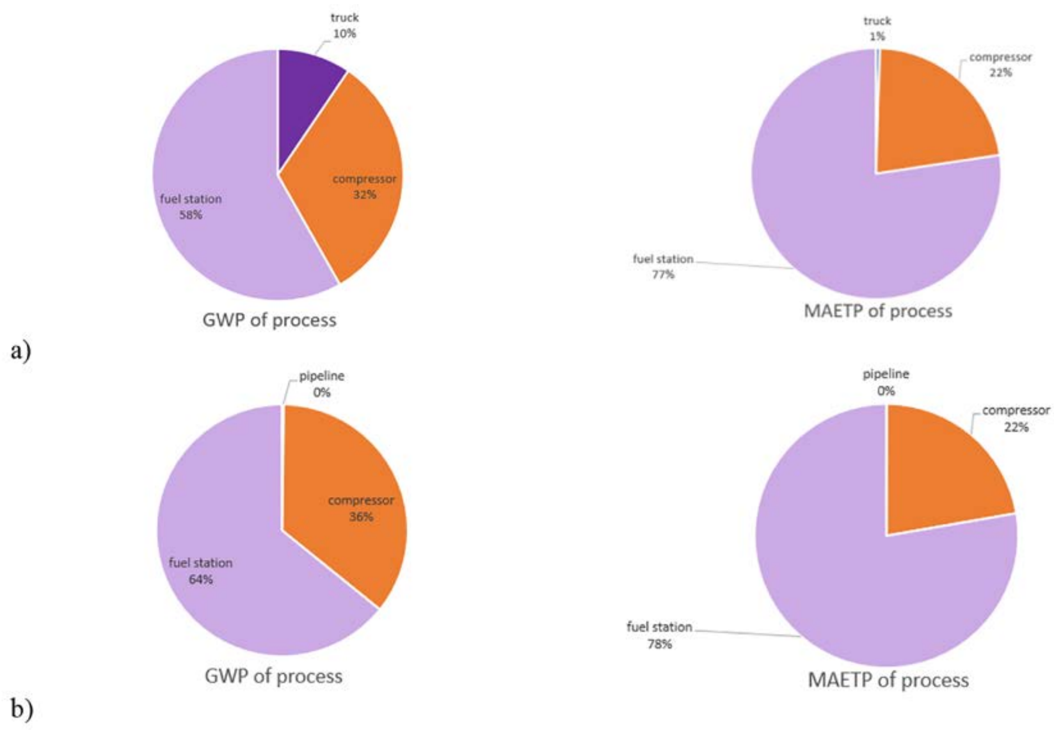

Figure 4.5. Comparison of GWP and MAETP contributions across hydrogen delivery processes by (a) truck and (b) pipeline.

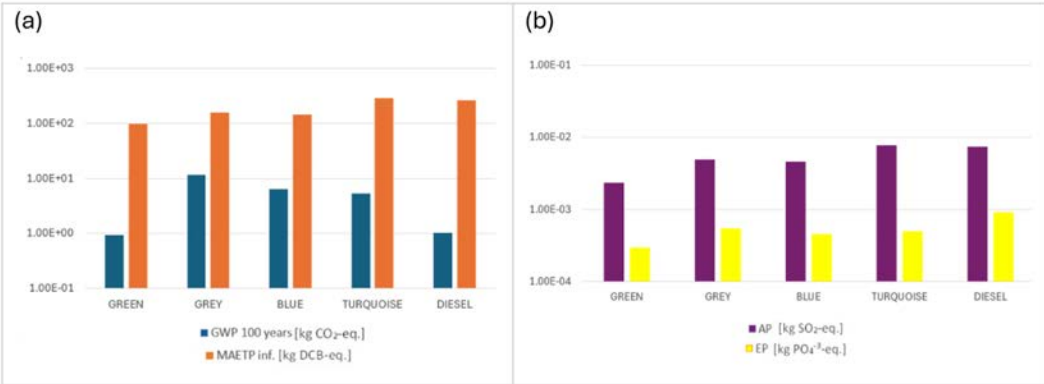

Figure 4.6. (a) GWP and MAETP values for hydrogen and diesel production systems; (b) AP and EP values for hydrogen and diesel production systems.

hydrogen through pipelines compared with other methods. Overall, these findings highlight the critical importance of optimising each stage of the hydrogen value chain to reduce environmental impacts and make hydrogen a truly sustainable energy solution.

4.4 Life Cycle Assessment Results from Hydrogen and Diesel Delivery to the Refuelling Station

To provide some context to the results of the study, the team assessed the environmental impacts associated with the production and delivery of both diesel and hydrogen up to the refuelling station, excluding the combustion phase for both fuels.

The results shown in Figure 4.6 reveal that diesel's GWP falls within a similar range to that of green hydrogen; however, diesel has higher impacts for other environmental metrics, such as MAETP, AP and EP. Diesel's AP and EP values indicate the release of pollutants like sulfur oxides and NO_x, which contribute to acid rain and nutrient pollution in waterbodies, respectively.

Quantitatively, diesel's AP stands at approximately 0.0073 kg SO_2 eq, which is higher than all hydrogen options, including grey and blue hydrogen, which have AP values of around 0.0049 kg SO_2 eq. This suggests that diesel production releases more acidifying pollutants, such as sulfur oxides and NO_x, that also contribute to acid rain and soil degradation.

In terms of EP, diesel again shows a high value of around 0.00092 kg PO_4^{-3} eq, compared with green hydrogen's much lower EP value of approximately 0.0003 kg PO_4^{-3} eq. This reflects diesel's considerable nutrient pollution impact, which can lead to algal blooms and disruption of aquatic ecosystems, particularly in freshwater bodies.

The production infrastructure for diesel is mature while hydrogen's is new. These findings suggest that, while GWP is essential for understanding climate effects, additional metrics like AP and EP are equally important for capturing local ecological and health impacts. This comprehensive perspective emphasises the environmental hazards of diesel beyond global warming, underscoring the need to consider multiple sustainability dimensions in the energy system.

5 Recommendations

This study completed a desktop LCA to evaluate the environmental impacts of the production, transport and refuelling of hydrogen for HGVs to support Ireland's shift to a decarbonised transport system. A total of 12 process configurations/scenarios based on four distinct technologies to produce hydrogen – SMR, SMR-CCS, MP and renewable energy using PEMEL – were assessed. These technologies are commonly referred to as grey, blue, turquoise and green hydrogen production, respectively.

The study concludes with the following recommendations.

- Conventional diesel production and delivery is environmentally damaging when compared with all hydrogen scenarios examined in this study. The impact goes beyond just GHG emissions and is also seen in water and ocean pollution. The move away from fossil fuels to cleaner alternatives in all sectors of the energy system, including transport, must be accelerated.
- Within the hydrogen production scenarios analysed, conventional hydrogen production via SMR, known as grey hydrogen, was found to have the greatest impact on global warming. This method's heavy reliance on fossil fuels results in significant GHG emissions, indicating that this technology should be replaced with more sustainable alternatives.
- Hydrogen production via MP, known as turquoise hydrogen, has a lower impact on global warming than SMR, particularly if the carbon by-product is utilised in industrial applications. However, implementing MP would lead to significant increases in all other environmental impact categories studied, except GWP, resulting in substantial burden shifting. However, dependence on fossil fuel natural gas resources, leakage rates and inaccurate data on fugitive emissions are an issue. Additionally, most MP-based processes are still in the early stages of development, and the marketability of the carbon by-product remains an underdeveloped area that could be researched further.
- Hydrogen production via SMR-CCS, known as blue hydrogen, offers some technological maturity, a lower GWP and less significant increases in other environmental impact categories compared with grey and turquoise hydrogen. However, dependence on fossil fuel natural gas resources, leakage rates, inaccurate data on fugitive emissions and the need for long-term geological CO_2 storage in limited suitable geological sites restrict the suitability of SMR-CCS in Ireland. SMR-CCS could serve as a valuable bridging technology that facilitates the transition to more sustainable hydrogen production methods in some countries with mature SMR infrastructure and limited renewable resources.
- Green hydrogen production uses the least harmful technology in terms of GWP and water pollution in the key LCIA categories considered in the study when compared with diesel and grey, blue and turquoise hydrogen production. Overcoming some of the challenges related to water demand and materials used in electrolysis technology could further improve the environmental profile of the system. Where hydrogen is needed, and where electrical power can be supplied by renewable energy (e.g. wind energy or 100% renewable electricity grid), hydrogen production via electrolysis should be implemented.
- Hydrogen pipe networks have a low environmental impact and provide an efficient method to transport hydrogen from production to end use/refuelling stations. Future infrastructure developments should endeavour to optimise the production–demand relationship and the movement of hydrogen.
- All types of hydrogen production are regulated as inorganic chemical installations under the IED. Large-scale electrolysis-based hydrogen production installations with a production capacity of over 50 tonnes per day must adhere to the IED. Hydrogen production has the potential to release hydrogen, oxygen, steam, chemicals and water effluent to the environment. Hydrogen production installations are different to fossil fuel or biomass thermal energy plants, which

emit GHG emissions. Hydrogen is not a GHG in itself; however, it is deemed an indirect GHG, albeit with a low GWP over 100 years compared with fossil fuels (Derwent *et al*., 2006). It is vitally important that leakages are curtailed for both health and safety and the environment. Electrolysis-based hydrogen production installations consume water and, therefore, the environmental impact on water is a crucial parameter – a very location-specific parameter that is dependent on the local water availability, consumption, degradation and pollution. The IED can ensure the highest standards and that a well-developed environmental management system is implemented in hydrogen production plants. The IED will play a pivotal role in shaping environmentally responsible and safe hydrogen production within the EU.

To align with the ambitious net zero emissions by 2050 scenario, a critical target will be the electrification of vehicles, and in the future every new vehicle sold should be a zero-emission vehicle such as battery electric or hydrogen fuel cell electric vehicles. Such a transition is necessary to combat climate change and significantly reduce GHG emissions from the transport sector. Policymakers and industry stakeholders must work collaboratively to accelerate the adoption of zero-emission vehicles and support the development of the necessary infrastructure to facilitate this transition.

Ultimately, there will always be a trade-off when selecting the most environmentally favourable method for hydrogen production. These trade-offs depend on geographical, economic and social factors, political will and regulatory frameworks. Therefore, further research is needed to assess the whole life cycle costs of hydrogen. In addition to the environmental considerations discussed in this work, hydrogen production pathways should also be evaluated from other perspectives, including the consideration of techno-economic and socio-economic factors.

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Appendix 1 Hydrogen Production Comparison Data

A1.1 Inputs for Life Cycle Assessment

Table A1.1. Comparative analysis of various hydrogen production methods: scale, power source, electrolyser type, hydrogen type, efficiency, water/material consumption, application, loss and analysis approach

	Scale	Power source	Electrolyser type	Hydrogen type	Efficiency (%)	Water/material consumption	Application	Loss	Analysis type	Reference
1	3 MW	Grid/laboratory	Alkaline electrolyser	Green hydrogen	68.5%	Water, 0.2124 kg/s	Industrial use	Impurities, H_2 in O_2 47 kW, burned* in DeOx 7 kW	Dynamic energy/ MATLAB	Sakas *et al.* (2022)
2	2.3 MW	Floating offshore wind, battery	PEM (1.8 MW)	Green hydrogen (17,242 kg H_2 per 31-day period)	56.9%	Not mentioned	Industrial use		31-day dynamic/ MATLAB	Egeland-Eriksen *et al.* (2023)
3	2.5 MW	Methane	SMR	Blue hydrogen (150 Nm^3/h)	75.9%	Not mentioned	CO_2 capturing with PSA	8.62 kg CO_2/kg H_2	Techno-economic	Lee *et al.* (2023)
4	4586 MW	Flare gas 356.5 million standard cubic feet per day	SMR	Blue hydrogen (117,600 kg/h)	81.4%	Not mentioned	Hydrogen stations	CO_2 emissions, 4 kg CO_2/kg H_2	Techno-economic and LCA	Kabeh *et al.* (2023)
5	2 MW to 1 GW in 2050	Wind	Alkaline electrolyser (4.5 MW)	Green hydrogen	Not mentioned	Water, 10 kg/kg H_2 KOH, 2 g/kg H_2 Nickel, 2 kg/kW Steel, 30 kg/kW	Developing scenarios for the Netherlands in 2050	Not mentioned	Environmental analysis and LCA	Delpierre *et al.* (2021)
6	2 MW to 1 GW in 2050	Wind	PEM (1 MW)	Green hydrogen	Not mentioned	Water, 10 kg/kg H_2; Iridium, 0.7 g/kW; Nafion, 0.016 g/kW; Platinum, 0.3 g/kW; Titanium, 500 g/kW	Developing scenarios for the Netherlands in 2050	Not mentioned	Environmental analysis and LCA	Delpierre *et al.* (2021)

DeOx, catalyst palladium deoxidiser; KOH, potassium hydroxide; PSA, pressure swing adsorption.

Abbreviations

AP	Acidification potential
BAT	Best available techniques
CCS	Carbon capture and storage
DCB	Dichlorobenzene
E-fuel	Electrofuel
EP	Eutrophication potential
E-PRTR	European Pollutant Release and Transfer Register
GHG	Greenhouse gas
GWP	Global warming potential
HDV	Heavy-duty vehicle
HGV	Heavy goods vehicle
ICE	Internal combustion engine
IED	Industrial Emissions Directive
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MAETP	Marine aquatic ecotoxicity potential
MDEA	Methyldiethanolamine
MP	Methane pyrolysis
PEM	Proton exchange membrane
PEMEL	Proton exchange membrane electrolysis
PM	Particulate matter
SMR	Steam methane reforming
SMR-CCS	Steam methane reforming with carbon capture and storage
TEN-T	Trans-European Transport Network

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

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