Towards Zero Emission Mobility in Ireland: Life Cycle Assessment of Moving Green Hydrogen

S. Sabernia(✉), S. Sabu, A. S. Adekanbi, C. Muilwijk, G. McNamara, and J. G. Carton

School of Mechanical and Manufacturing Engineering, Dublin City University, Dublin, Ireland
sevda.sabernia@dcu.ie

Abstract. In Ireland, transportation accounts for 36% of total energy consumption, mainly due to private cars and heavy goods vehicles, responsible for 70% of transportation sector carbon emissions. Despite some progress in new car carbon intensity, petrol and diesel vehicles remain dominant. Hydrogen (H_2) is a non-toxic, highly combustible gas, holds significant potential, especially for heavy-duty vehicles, as a mean to reduce carbon emissions. However, realising this transition requires targeted policies and infrastructure development.

A crucial tool for evaluating hydrogen-based transportation is a comprehensive life cycle assessment (LCA). This assesses the full process, from production, transport and use, to disposal, providing insights into environmental impact, including carbon footprint, energy consumption, air pollution, material use and vehicle efficiency. By assessing different hydrogen sources like green and blue hydrogen, the LCA informs decision-makers and aids in developing sustainable transportation strategies.

This work highlights the importance of the method to transporting the hydrogen fuel. Fuelling stations show a substantial carbon footprint (1.75 kg CO_2 eq./kg H_2), while hydrogen transportation through pipelines has minimal emissions (0.0000235 kg CO_2 eq./kg H_2) compared to moving it in compress cylinders by diesel truck. This underscores the need for careful planning to minimise environmental impacts when deploying hydrogen in transportation systems.

Keywords: green hydrogen · transport · life cycle assessment · CO_2 emissions

1 Introduction

Climate change, driven by GHG emissions from fossil fuels, requires urgent solutions. The Paris Agreement and IPCC have underscored the need to limit warming to 1.5 °C [1, 2]. Transitioning to cleaner renewables, like wind power, offers eco-friendly benefits and energy security. Republic of Ireland relies significantly on wind energy, just over 300 wind farms totalling 4,332.5 MW capacity in 2022 [3]. However, wind energy's reliability depends on weather conditions, impacting yearly generation. The growth of variable renewables has fuelled interest in hydrogen as a long-term electricity storage solution that can also decarbonise other sectors [4].

C. McNally et al. (Eds.): TRAconference 2024, LNMOB, pp. 51–58, 2025.
https://doi.org/10.1007/978-3-031-89444-2_8

1.1 Transportation Challenges

For the case of Ireland, the transport sector in Ireland accounts for nearly 12 Mt CO_2,eq in 2022 [5], positioning it as the second-highest emitting sector, closely following the agricultural sector. Diesel retained its dominant position as the largest fuel type, comprising 70% of the total, followed by petrol at 15% and jet kerosene at 10% in 2022 [6].

1.2 Heavy Goods Vehicles (HGVs)

Heavy goods vehicles (HGVs), also known as commercial trucks, contribute to 14% of Ireland's road transport emissions, equivalent to 1.6 MtCO_2eq, with the majority powered by diesel fuel. Approximately 61% of HGVs in Ireland were 10 years old or younger as of the end of 2022 [7]. On average, a long-distance HGV emits about 102.9 g of CO_2 per tonne-kilometre [8].

The H2Haul project [9] has demonstrated that there is a possibility for fuel cell trucks to make up approximately 17% of the new truck sales in 2030. This projection is based on a significant reduction in technology costs. As the production of fuel cell hydrogen trucks increases and the cost of hydrogen falls below 6 EUR/kg, these fuel cell hydrogen-fuel cell heavy-duty trucks offer operational performance that closely matches diesel trucks in terms of daily range, refuelling speed, payload capacity, and total cost of ownership. In Ireland, during an 8-week trial period on Irish roads, a hydrogen fuel cell electric bus covered a distance of 3,086 km. This bus, with a refuelling time of under 9 min and a range of 400km, garnered significant approval from the traveling public, as indicated by passenger satisfaction surveys [10]. Wróbel et al. [11] found that hydrogen internal combustion engines (ICEs) are cost-effective and practical for specific vehicle applications, particularly in construction and agriculture. Although they emit nitrogen oxides and require exhaust gas treatment, hydrogen ICEs adapt well to varying hydrogen quality and exhibit reliability in demanding conditions. Their potential for reducing urban CO_2 emissions is significant but hinges on hydrogen infrastructure and regulatory advancements. Zhang et al. [12] introduced a collaborative planning model to promote hydrogen vehicle adoption, integrating energy, hydrogen, gas, and transportation systems to reduce carbon emissions through green hydrogen production. This model optimises hydrogen vehicle traffic flow and hydrogen station locations, minimising congestion and travel time within the integrated network, thus lowering carbon emissions and traffic duration.

1.3 Role of Hydrogen in Decarbonisation

Hydrogen, despite being the most abundant element in the universe, is typically found in compounds like water and hydrocarbons due to its small molecular size. Producing hydrogen involves breaking these chemical bonds and storing the hydrogen, requiring energy input, often in the form of electricity or heat. It has been proved that it is the clean, light, and most highly flammable fuel on combustion producing only water. The source of this energy input and the resulting by-products influence the carbon footprint of hydrogen production.

Hydrogen can be generated using various methods, each with different technological maturity levels, environmental impacts, and greenhouse gas emissions [13]. One such method is electrolysis, which uses electrical energy to split water molecules into hydrogen and oxygen, with oxygen being a by-product. When renewable energy sources like wind or solar power the electrolysis process, it produces high-purity hydrogen with no associated CO_2 emissions, often referred to as "green hydrogen".

1.4 Present Research, Aims and Objectives

Extensive literature review reveals the significant potential of hydrogen for transportation. Hydrogen can be produced on-site or off-site, with various transportation technologies to refuelling stations. Economic analyse is crucial to assess viability and technical intricacies.

Life Cycle Assessment (LCA) is used for the evaluation of the environmental impact across the product's entire lifecycle, from raw material acquisition to disposal. This includes processes like generating green hydrogen from wind power via water electrolysis and subsequent transport and compression for refuelling. This research investigates two distinct hydrogen transportation scenarios, focusing on delivering hydrogen from production hubs to refuelling stations for convenient vehicle refuelling.

2 Methodology

Life Cycle Assessment is a systematic approach to assess the ecological impact of products, processes, or projects from raw material extraction to disposal. It is crucial for sustainability evaluations. LCA involves Goal and Scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. LCA guides informed decisions to reduce environmental impact. In this study, GaBi software for LCA is utilised.

The objective is to develop a comparative LCA of a hydrogen production system, starting from renewable energy (wind turbines) to the fuel filling station, considering two transportation methods: trucks and HDPE pipelines. The cradle-to-gate and gate-to-gate processes in two scenarios as examined, as shown in Fig. 2. The study's boundary includes energy consumption for transportation and hydrogen compression (Fig. 1).

The description outlines two modelling scenarios. Both start with 'Electricity from Wind Power,' a clean and renewable source, powering a highly efficient 50 KW Proton exchange membrane (PEM) electrolyser for hydrogen production.

Scenario 1 transports hydrogen via 'GLO Trucks Euro 5,' considering environmental impacts. It ends at the refuelling station. In contrast, Scenario 2 explores hydrogen transportation via pipelines, using polyethylene material data from external sources. Both approaches assess environmental impacts and sustainability throughout the hydrogen production and transportation life cycle. The simulation process for both scenarios is developed using Gabi software, is presented graphically in Fig. 2.

This schematic offers a clear representation of the sequential stages involved in Scenario II, where wind power is the energy source for green hydrogen production and a pipeline system is utilised for the transportation of the produced hydrogen to the hydrogen refuelling station. Since the approach is hypothetical, the distances for the transportation

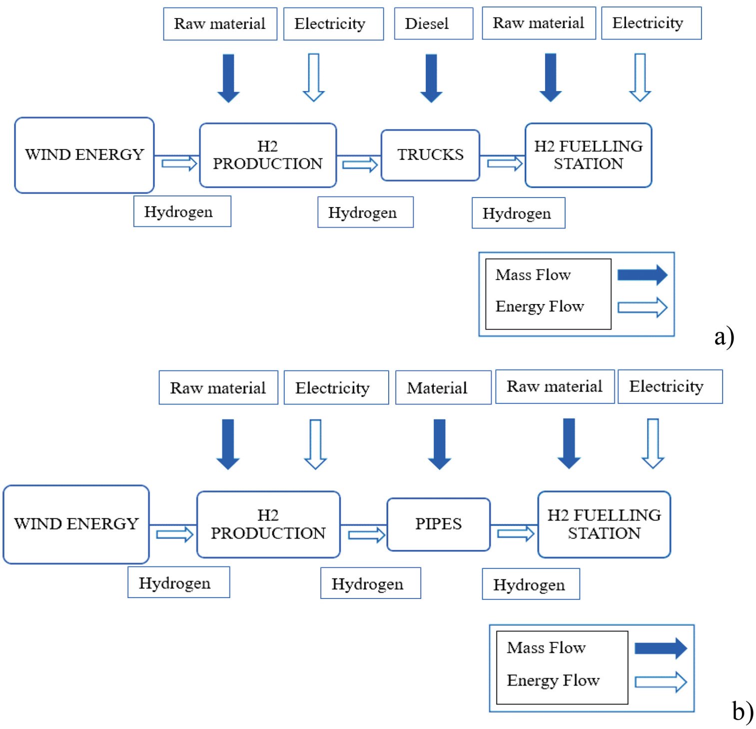

Fig. 1. System boundary of Life Cycle Assessment of hypothetical hydrogen system, a)using trucks, b) using pipeline

of hydrogen from the production subsystem to the fuelling station subsystem is taken as 6km.

Furthermore, Table 1 provide the inventory data for the utilised electrolyser and refuelling station, respectively. Notably, all materials employed in the simulation are presented in terms of kilograms per kilogram of hydrogen produced. It is worth mentioning that that we used database for the subsystem: electricity from wind power, diesel, and trucks from GaBi software for the diesel truck, and the life cycle inventory data for the hydrogen pipeline consists of just 1.37 E-5 kg of polyethylene after normalising with 1 kg of Hydrogen.

Examining the PEM electrolyser in particular, it is evident that cast iron stands out with an approximate usage of 8 g per kilogram of hydrogen. Additionally, it is worth noting that the assumption here is that the production of 1 kg of hydrogen consumes 10 kg of fresh water. Turning attention to the refuelling station, the predominant materials are low alloy steel, followed by high alloy steel in terms of usage.

Table 1. Life Cycle Inventory Data for PEM Electrolyser and for fuelling Station

Electrolyser		Fuelling Station	
Materials	Mass	Materials	Mass (kg)
Aluminium	0.00105 kg/kg H_2	Low alloy steel	0.07889 kg/kg H_2
Cast Iron	0.008 kg/kg H_2	High alloy steel	0.0081 kg/kg H_2
Polyethylene	0.0015 kg/kg H_2	Cast iron	0.0023 kg/kg H_2
Steel Billet	0.0037 kg/kg H_2	Copper	0.000910 kg/kg H_2
Graphite	0.0045 kg/kg H_2	Aluminium	0.000384 kg/kg H_2
Polypropylene Granulate	0.0025 kg/kg H_2	Polymer	0.00028 kg/kg H_2
Polyvinylidenchloride Granulate	0.0011 kg/kg H_2	Carbon fibers	0.00135 kg/kg H_2
Steel	0.0011 kg/kg H_2	Electricity	14.2 kWh/kg H_2
Fresh Water	10 kg/kg H_2	Hydrogen	1 kg
Electricity from wind	180 MJ/kg H_2		

3 Result and Discussion

The environmental performance throughout the life cycle is characterised by quantifying the environmental effects using indicators such as Global Warming Potential over a 100-year horizon (GWP), Ecotoxicity Potential (ETP), and Acidification Potential (AP) as developed by CML 2001 – JAN 2016.

The assessment comprises two scenarios: one utilising electricity sourced from wind power and transporting the generated hydrogen by diesel-fuelled trucks to the fuelling station (Scenario 1) and the other relying on electricity from the pipeline to transport hydrogen to the refuelling station (Scenario 2). The results indicate that Scenario 2 has a lower environmental impact when compared to Scenario 1. A comprehensive breakdown of the inflow and outflow of the hydrogen systems can be found in Table 2.

Table 2. Breakdown of the inflow and outflow of the hydrogen systems

INPUT	SCENARIO 1	SCENARIO 2
Resources	1.3×10^3kg	1.3×10^3kg
OUTPUT		
Deposited Goods	3.09 kg	3.09 kg
Emissions to air	22.9 kg	22.6 kg
Emissions to freshwater	1.32×10^3kg	1.3×10^3kg
Emissions to seawater	2.38 kg	2.37kg
Emissions to agricultural soil	4.03×10^{-6}kg	4×10^{-6}kg
Emissions to industrial soil	1.34×10^{-5}kg	1.34×10^{-5}kg

3.1 Contribution Analysis

The contribution analysis helps to analyse the results of the life cycle of the hydrogen system by evaluating the contribution of polluting elements to the surroundings. From the Table 3, it is visible that the Scenario 2 has less emissions compared to the Scenario 1. It can be interpreted that the trucks cause more pollution to the environment than the pipelines. The most significant pollution is observed in the marine aquatic system potential in both scenarios with the value 210 kg DCB eq per kg of H_2. This is due to the extraction of fresh water for hydrogen production through electrolysis. Moreover, the sources of grid electricity in Ireland varies from renewable, waste, natural gas etc. The most minor pollution is Ozone Depletion Potential with the value 6.21E-13 kg R11 eq per kg of H_2, which is negligible.

Table 3. LCA results for the proposed two scenarios in the present work

Emission/kg H_2	Scenario 1	Scenario 2
GWP 100 years (kg CO_2 eq.)	2.17	2.14
AP (kg SO_2 eq.)	3.14×10^{-3}	3.36×10^{-3}
EP (kg Phosphate eq.)	3.84×10^{-4}	3.69×10^{-4}
ODP, steady state (kg R11 eq.)	6.21×10^{-13}	6021×10^{-13}
ADP elements (kg Sb eq.)	1.1×10^{-5}	1.1×10^{-5}
ADP fossil (MJ)	25.1	24.8
FAETP inf. (kg DCB eq.)	4.69×10^{-3}	4.58×10^{-3}
HTP inf. (kg DCB eq.)	0.713	0.713
MAETP (kg DCB eq.)	210	210
POCP (kg ethene eq.)	2.66×10^{-4}	2.83×10^{-4}
TETP (kg DCB eq.)	0.0222	0.0222
GWP exc. Bio (kg CO_2 eq.)	2.16	2.14
GWP inc. Bio (kg CO_2 eq.)	2.17	2.15
GWP LUC (kg CO_2 eq.)	1.3×10^{-3}	1.13×10^{-3}

3.2 Dominance Analysis

The most impacting process in the hydrogen system can be identified through the dominance analysis. The graph below represents the global warming potential polluting processes in the system. The filling station has a significant quantity among the others with a value of 1.75 kg CO_2 eq./kg H_2. The least emitting process is the transportation through pipelines with 0.0000235 kg CO_2 eq./kg H_2. The trucks and the hydrogen production exhibit certain quantities of carbon dioxide equivalent to the atmosphere.

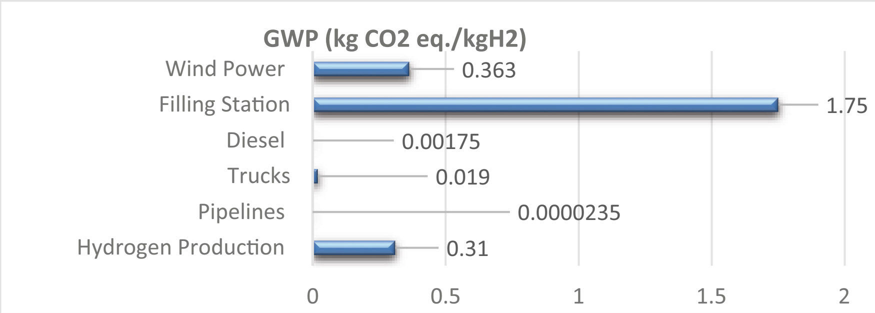

Fig. 2. Global warming potential of the main stages in the system

4 Conclusion

Hydrogen exhibits substantial potential as a transportation fuel, but its utilisation requires thorough examination. It can be produced on-site or off-site, utilising various transportation technologies to reach refuelling stations, necessitating rigorous economic and technical analyses. This research employs LCA to comprehensively evaluate the environmental impact of hydrogen production and transportation, focusing on indicators like GWP, ETP, and AP.

The study explores two scenarios: Scenario 2, using pipeline for moving hydrogen, shows lower environmental impact than Scenario 1 with diesel trucks. In conclusion, hydrogen holds promise for transportation, but careful consideration of production and transportation methods is essential to minimise environmental impacts. Scenario 2 exhibits a better environmental profile. This research underscores the importance of tools like LCA and specific impact indicators for informed decision-making in transitioning to hydrogen-based transportation systems.

Acknowledgements. This research & collaborative work is funded by Irish EPA Project: Hydrogen Environment protection, Analysis, Awareness & Review (HEAR) [Grant No: HEAR (2022-HE-1121)].

References

1. Li, Y., Alharthi, M., Ahmad, I., Hanif, I., Ul Hassan, M.: Nexus between renewable energy, natural resources and carbon emissions under the shadow of transboundary trade relationship from South East Asian economies. Energy Strategy Rev. **41** (2022). https://doi.org/10.1016/j.esr.2022.100855
2. Welsby, D., Price, J., Pye, S., Ekins, P.: Unextractable fossil fuels in a 1.5 °C world. Nature **597**, 230–234 (2021). https://doi.org/10.1038/s41586-021-03821-8
3. https://windenergyireland.com/about-wind/the-basics/facts-stats (n.d.)
4. González, G., Daly, J.: Gleeson, congested spaces, contested scales - a review of spatial planning for wind energy in Ireland. Landsc. Urban Plan. **145**, 12–20 (2016). https://doi.org/10.1016/j.landurbplan.2015.10.002

5. https://www.epa.ie/news-releases/news-releases-2023/irelands-2022-greenhouse-gas-emissions-show-a-welcome-decrease-but-much-work-remains-to-be-done.php#:~:text=Transport%3A%20Emissions%20increased%20by%206,the%20impact%20of%20electric%20vehicles (n.d.)
6. SEAI, ENERGY IN IRELAND 2022 Report (2022)
7. Department of Transport, Ireland's Road Haulage Strategy (2022)
8. ACEA, CO2 emissions from heavy-duty vehicles preliminary CO2 baseline, Assoc. Des Constr. Eur. d'Automobile (March) (2020)
9. M.B.T.Z.A.M.J.R. Yvonne Ruf, Fuel Cells Hydrogen Trucks – Heavy-Duty's High Performance Green Solution (2020)
10. Carton, J.: Ireland's 1 st Hydrogen Fuel Cell Bus Trial 2020-Rev 0 Exploring Low Emissions Public Transport (2021)
11. Wróbel, K., Wróbel, J., Tokarz, W., Lach, J., Podsadni, K., Czerwiński, A.: Hydrogen internal combustion engine vehicles: a review. Energies (Basel) **15** (2022). https://doi.org/10.3390/en15238937
12. Zhang, X., Gao, X., Zheng, Y., Xu, Y., Chung, E., Sayed, A.R.: Low-carbon oriented collaborative planning of electricity-hydrogen-gas-transportation integrated system considering hydrogen vehicles. IEEE Trans. Netw. Sci. Eng. (2023)
13. Department of the Environment, Climate & Communications, National Hydrogen Strategy (2023). www.gov.ie