2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

Hydrogen as a potential energy vector: current overview of its economic and environmental viability in public transport

Flavia Paladino Biaty[1], Patrícia Andrea Paladino[2], Arthur Pires Julião[3], Gaianê Sabundjian[4] and Eduardo Lobo Lustosa Cabral [5]

[1]*flabiaty@gmail.com, Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN) Av. Professor Lineu Prestes, 2242*
CEP 05508-000 - São Paulo, SP, Brazil

[2] *patricia.paladino@yahoo.com, Instituto Federal de Educação, Ciência e Tecnologia (IFSP- SP) - Rua Pedro Vicente, 625*
CEP 01109-010 - São Paulo, SP, Brazil

[3]*pjarthur@fatecsp.com, Faculdade de Tecnologia de São Paulo (FATEC– SP) Av. Tiradentes, 615 CEP 01124-060 - São Paulo, SP, Brazil*

[4]*gdjian@ipen.br, Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN) Av. Professor Lineu Prestes, 2242*
CEP 05508-000 - São Paulo, SP, Brazil

[5]*elcabral@ipen.br, Instituto de Pesquisas Energéticas e Nucleares (IPEN/CNEN) Av. Professor Lineu Prestes, 2242*
CEP 05508-000 - São Paulo, SP, Brazil

1. Introduction

In the 1950s, the first concerns arose about the unwanted environmental effects caused by the uncontrolled exploitation of natural resources. Furthermore, since the 1973 oil crisis, it has become evident that dependence on a particular energy source would not be the best alternative from economic, social, and geopolitical viewpoints. Since then, the search for other energy sources and the importance of building a sustainable development model got prominence in government, academic and commercial agendas.
Hydrogen stands out as an energy option for the future, for its use in fuel cells, producing energy in a clean way, since the only combustion product resulting from its association with oxygen is water. This alternative to fossil fuels is part of the context of the so-called “hydrogen economy”, which advocates its commercial production for energy supply [1]. In this sense, its use as an energy vector by means of fuel cells can be highlighted, including for urban public transport, such as buses and trains.
The burning of fossil fuels, still very present in the transport sector, contributes to the global problems of global warming and the greenhouse effect, promotes local air pollution, and poses risks to the health of the population. Thus, a clean alternative for this sector will improve the environmental and social quality of the population.
However, the use of hydrogen as a clean and sustainable alternative, without using fossil sources at any

stage of its production, transport, and storage cycle, still has high financial costs and technological limitations. Thus, besides technological development, economic and environmental feasibility studies, carried out jointly, are essential to prove its efficiency in replacing fossil fuels.
So, economic and environmental feasibility studies do become parameters for commercial and political decisions. Thus, should the benefits of replacing fossil fuels be measured and justified, it would be necessary to take into account the environmental costs of their damage. Since replacement entails costs, measured in monetary terms, the valuation demands its parcel to be accounted for in financial terms so that the measures become comparable and analyzed in terms of feasibility.
This work aims to present an overview of the use of hydrogen as a potential energy vector for the urban public transport sector, as well as to consider its economic and environmental viability.

2. Methodology

This work is a qualitative research conducted by bibliography reference available in books, articles, reports, dissertations, and theses. The theme was exploited, investigating its history, the means of production, transport and storage of hydrogen, as well as its economic and environmental viability in the urban public transport sector.

3. Results and Discussion

In order to overcome all barriers in the transition from the use of fossil fuels to the hydrogen economy, it is necessary that all stages of its cycle, that is, its production, transport and storage, be economically viable and sustainable. Many methods for hydrogen production are used and known, but they all need energy, which even today comes mostly from fossil fuels, thus conflicting with the main benefit of using hydrogen as a clean source. Each method has its own advantages and disadvantages, requiring technical, economic, and environmental analysis according to its intended end use.
From an economic point of view, the costs involved on the production routes based on fossil sources (reforming natural gas steam and coal gasification) are still the most competitive ones, but they do not meet the criteria of complete decarbonization. However, according to the International Energy Agency (IEA) the cost of hydrogen from renewable energies could drop 30% by 2030 [2]. Unfortunately, in the current market context, the most economical alternatives tend to be the ones that pollute the most.
An economically and environmentally viable alternative to the hydrogen production would be the nuclear source, in a combination between the sulfur-iodine thermochemical cycle and a reactor that provides high temperatures. The best current option would be the fourth-generation reactors, however, its technical feasibility should be considered as a barrier, since its use depends on their very technological development [1].
Regarding hydrogen storage and transport, its costs depend on the application, location, and storage duration. From an environmental point of view, once the issues of production, storage and transport have been figured out, they are comparable to any other product that needs to be stored and moved, so that the shorter transport distance, the smaller the environmental waste [3].
The economic and environmental feasibility of replacing the current diesel-powered bus fleet in the city of São Paulo with fuel-cell buses was studied previously [3]. The proposal involved the production of hydrogen via electrolysis, in a distributed manner, that is, in the garage of each bus company. In addition, the electricity available in the interconnected system would be used during periods of low peak consumption, thus not emitting additional pollutants. The results indicated technological, environmental, and economic viability, because although it is more expensive at first, it has zero environmental costs,

with a longer useful lifetime equipment. Table I presents a summary of the economic and environmental analysis carried out.

Table I: Estimated costs (US$ millions) for São Paulo's bus fleet.

Costs	Hydrogen	Diesel
Initial investment	**5,623.61**	**-**
Fuel (annual)	589.82	369.56
Environmental and social (annual)	-	85.00
Annual costs	**589.82**	**454.56**
Life cycle	**15 years**	**4.6 years**
Equivalent annual cost (0-15 years)	**1,168.82**	**836.80**
Equivalent annual cost (15-30 years)	**852.80**	**824.00**

For example, the diesel bus fleet in São Paulo is adverse from an environmental point of view for it harms public health and the environment. The environmental and social costs presented in Table I were calculated from the valuation of negative externalities caused by air pollution from diesel buses. The Economic Valuation of Environmental Resources (VERA) methodology was used, considering the pollutants emitted by the fleet, the economic value of air degradation by local effects and greenhouse gases, and the valuation of negative social externalities. This analysis stresses the importance of clean and sustainable alternatives, mainly in the public transport sector, which stands out as an important market for the application of hydrogen.

As shown in Table II, valuation by means of monetary measures aims to show how much individuals are losing from the degradation of the environment. In an environment of scarcity, as presupposed by economics, choices must be made to obtain maximum satisfaction (well-being). The gain in welfare (utility) is therefore a benefit, and its loss is a cost. Choices are always made when resources are scarce, so money is a viable way for measuring them [4].

Table II: Valuation of externalities of diesel buses

Factor	Value (US$/ton)	Quantity (ton/year)	Cost (US$/year)
NOx	1,289.91	11,867.00	15,307,361.97
HC	1,312.95	2,967.00	3,895,522.65
CO	218.82	14,837.00	3,246,632.34
MP	1,048.05	412.10	431,901.40
Total Local VERAair			**22,881,418.36**
CO_{2eq}	6.75	1,103,136	7,446,170.70
Total Greenhouse VERAair			**7,446,170.70**
Environmental Costs			**30,327,589.06**
Hospital Admissions			282,000.00
Lost Working Days			48,830,043.00
Increased consultations			86,240.00
Mortality			5,240,976.00
Social Costs			**54,439,259.00**
Social and Environmental Costs			**84,766,848.06**

Regarded as the energy of the future for many years, nowadays hydrogen (as a potential energy vector) still presents itself as a strategic objective of governments and companies around the world, and it is believed that, with the post-pandemic economic recovery, the energy transition may be accelerated. The world market still has its main demand focused on the industrial sector, however, an increase in trade aimed at energy use is expected, mainly due to the policies announced by some countries in the European Union. However, there are still limitations in several sectors for this development, both technological, economic, and regulatory [5].

4. Conclusions

The hydrogen economy has been explored since the end of the last century, however, in terms of concrete applications, too much still remains to be done. As with all strategies related to energy discussion, it is important to consider that the theme involves not only technological issues, but also social, economic, environmental, and especially political issues. The solution, mainly in the financial domain, presents itself in the establishment of partnerships between the private and public sectors, industry, academia and governments, with investment in research, development and innovation for an economically and environmentally viable production, transport and storage infrastructure for its dissemination and magnification as an energy vector.

Acknowledgements

To Instituto de Pesquisas Energética e Nucleares / Comissão Nacional de Energia Nuclear (CNEN) – Brazil and Instituto Federal de Educação, Ciência e Tecnologia for financial support.

References

[1] X. L. Yan, R. Hino, *Nuclear Hydrogen Production: Handbook - Green Chemistry and Chemical Engineering*, CRC Press Taylor & Francis Group, Ohio, USA (2011)

[2] "The future of hydrogen: seizing today's opportunities", https://www.iea.org/reports/the-future-of-hydrogen (2019).

[3] P. A. Paladino, *Uso do hidrogênio no transporte público da cidade de São Paulo,* Instituto de Pesquisas Energéticas e Nucleares, São Paulo, Brasil (2013).

[4] D. W. Pearce et al., *Blueprint for a Green Economy*. Earthscan Publication, London, England (1991).

[5] Empresa de Pesquisa Energética, *Bases para a consolidação da estratégia brasileira do hidrogênio, Nota técnica n. 003,* Ministério de Minas e Energia, Rio de Janeiro, Brasil (2021).