RESEARCH ARTICLE

Cost-Benefit Assessment and Industrial Scale-Up Variability of Low Carbon Hydrogen Energy Production

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Abstract

In a booming global economy, through the use of a fair share of conventional energy sources, converting the current economy into a low-carbon hydrogen economy is an exigent problem. Several policies and economies have failed to implement a fully circulating hydrogen economy. This paper provides a novel policy framework from the grassroots to the global level to achieve free-flowing hydrogen production, storage, and transport. Such a policy framework is thoroughly proposed through a cost–benefit analysis of a plant producing 1 tonne of low-carbon hydrogen per day using several mathematical and computational models. This paper showcases the operations, development and tangible and intangible benefits of the hydrogen economy through which a final cost–benefit mechanism and a global policy framework are formulated. Along with such formulations, a varied industrial scalability is also portrayed, which significantly portrays the industrial requirements from 0.5 to 10 TPD through cost–benefit analysis parameters.

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1. Introduction

With its current global energy transition role, hydrogen energy is one of the most crucial future potentials for sustaining a net-neutral future. Hydrogen energy can be used as a commercial and industrial scaled-up renewable energy source because of its high energy density, versatility, storability, transportability, decarbonization and energy security. For a significant decrease in the cost of hydrogen production, several economic assessments are vital along with the sustainable modern computational characterization of hydrogen, which involves life cycle assessment, environmental impact assessment, health cycle assessment, SWOT analysis, environmental risk assessment and health impact analysis (W. Liu et al. 2022; Duan et al. 2023; Maestre, Ortiz, and Ortiz 2021; Yanxing et al. 2019; Chew et al. 2023; Mittal and Kushwaha 2024b).

The assessment of cost specifically for hydrogen energy globalization policy involves the analysis of various methods of hydrogen production, which require steam reforming, partial oxidation, autothermal reforming, biophotolysis, dark fermentation, photo fermentation, gasification, pyrolysis, thermolysis, photolysis, and electrolysis (Mittal et al. 2024; Amin et al. 2022; Minja et al. 2024; J. Zhang et al. 2022; Ji and Wang 2021; Dincer and Acar 2015). The main goal of such economic analysis is to determine the cost-to-efficiency info graphical representation. To evaluate such representations, deciding on the capital investment, environmental potential parameters, impact categories, and operational expenses is highly essential. The viability of such hydrogen production is mainly calculated through advancements, technological factors, industrial readiness scales, regional factors involving carbon emissions costs, and energy prices (Veras et al. 2017; Singh et al. 2022; Parkinson et al. 2019).

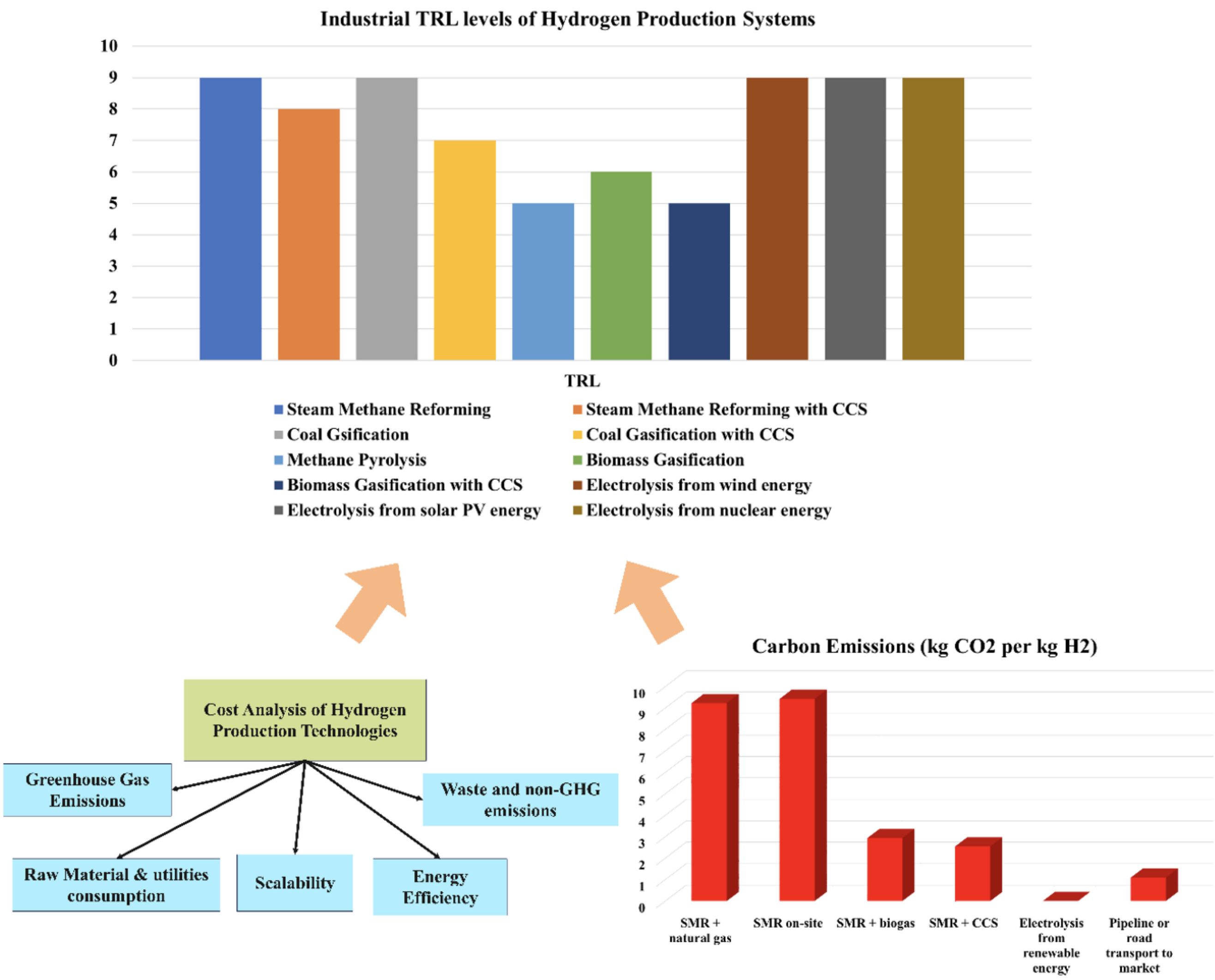


Figure 1. Industrial scale-up analysis of hydrogen production via cost analysis (Griffiths et al. 2021; Atilhan et al. 2021; Manna et al. 2021; Beasy, Lodewyckx, and Mattila 2023; Sadeghi, Ghandehariun, and Rosen 2020; Yang et al. 2023; Wenderich et al. 2020).

It is easier to determine the industrial scale-up of potential hydrogen production methods through such cost analysis. **Figure 1** (Griffiths et al. 2021; Atilhan et al. 2021; Manna et al. 2021; Beasy, Lodewyckx, and Mattila 2023; Sadeghi, Ghandehariun, and Rosen 2020; Yang et al. 2023; Wenderich et al. 2020) demonstrates the connection between different hydrogen production models for carbon emissions and impact categories for the cost analysis of hydrogen production to calculate the industrial technical readiness level. Considering the importance of cost analysis, there has not been significant research on the economic analysis of hydrogen compared to the overall laboratory-scale hydrogen production system setups. **Figure 2** shows the number of publications annually for hydrogen production systems (at the laboratory scale) and an economic analysis of hydrogen energy for the global circulation of hydrogen energy. From the infographics, we can observe that there is a wide gap in research on the monetary aspect of hydrogen, which needs to be given at most observations for a free-flowing green hydrogen economic framework (Mittal and Kushwaha 2024a; Sharma et al. 2023; Zhuang et al. 2023; Braga et al. 2013; Tarun et al. 2007). Through such infographics, we can discover the need for our study toward cost–benefit analysis for a low hydrogen production framework. This paper, hence, provides an overall cost–

benefit analysis of the low-carbon hydrogen production framework (Kim, Lee, and Lim 2022; Ajanovic, Sayer, and Haas 2022b; 2022a).

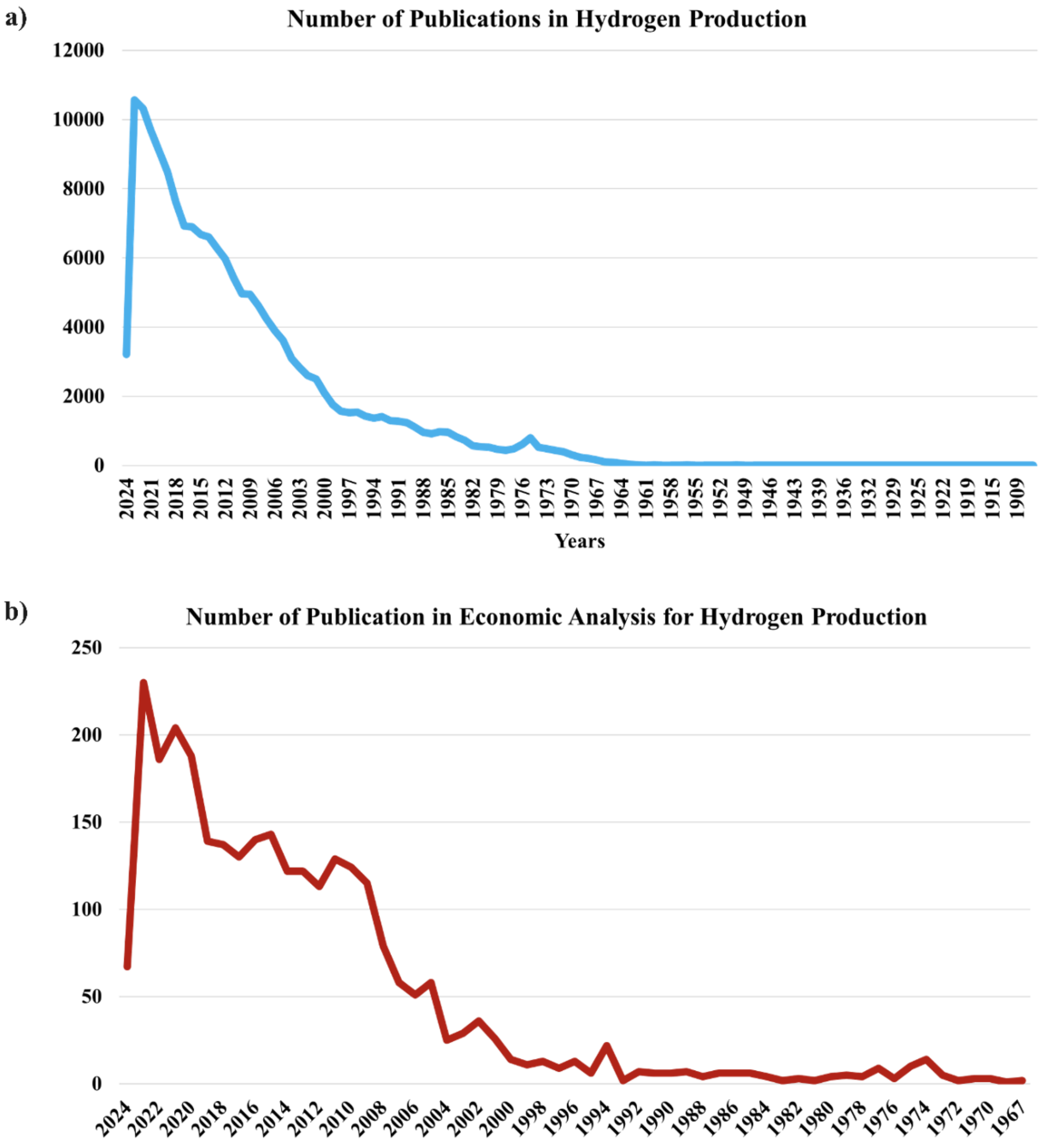


Figure 2: Number of Publications in Hydrogen Production and Economic Analysis for Hydrogen Production. [Source: PubMed through 5 August 2024]

2. Methods to Assess Cost–Benefit Analysis

To analyse the methods for cost–benefit analysis of hydrogen production, there is a specific pathway for performing the calculations. The significant steps through which analysis takes place involve the life cycle cost procedure, data collection, major calculation procedures and assumptions of hydrogen production, and operational and maintenance costs. The equations for capital costs, capital recovery factors, life cycle costs, operational costs, maintenance costs, and future life cycle costs are shown in **Equations 1-8** (Shih and Tseng 2014; Snyder and Kaiser 2009; Xiang et al. 2020; J. Liu et al. 2020; Barghash et al. 2022). The major significance of these equations is the fundamentals through which industrialists can calculate the major parameters that are required for cost–benefit analysis. The major parameters that are determined from the equations are the current values of benefits and the current values of costs.

2.1. Life Cycle Costs

Life Cycle Costs can be expanded into well-to-tank, tank-to-wheel, and Social Costs. These Costs can be further expanded into capital, operational, vehicle purchasing, taxes, and insurance costs. The relation between these variables is mentioned in **Equation 1,2,3.**

Life cycle costs (LCCs) (US $/functional unit) = well to tank costs + tank to wheel + social costs (1)

Well-to-tank Costs = Capital Costs + Operation and Maintenance Costs + Other Costs. (2)

Tank-to-wheel Costs = Vehicle Purchasing Costs + Operation and Maintenance Costs + Taxes + Insurance (3)

2.2. Capital Costs

To calculate the overall capital costs for the analysis of life cycle costs, capital recovery factor is one of the important factors, the correlations between capital costs, life cycle costs and capital recovery costs are mentioned in **Equation 4 and 5**.

$$\text{Capital Costs} = crf(I\text{-}R) + iR \qquad (4)$$

$$\text{Capital recovery factor (CRF)} = [i(1+i)^n]/[(1+i)^n - 1] \qquad (5)$$

2.3. Operational and Maintenance Costs

Similar to capital costs, to analyse the operational and maintenance costs for evaluating life cycle and future life cycle costs, which are important parameters in cost-benefit analysis, it is highly exigent to determine the relation between operational and maintenance costs. These relations are thoroughly examined in **Equations 6, 7 and 8.**

$$\text{Operational Costs} = \sum IMi \times PMi + IEj \times ECj + AWk \times TCWk - ACPI \times RCPI \qquad (6)$$

Maintenance Costs ($/kg H2) = [Replacement Costs + Regular Repair Costs]/[Hydrogen Production Amounts] (7)

$$\text{Future Life Cycle Costs} = \sum (C \times AR) \qquad (8)$$

2.4. Cost Benefit Analysis Ratio

Once these calculations are made, the main cost–benefit analysis is calculated for the cost–benefit analysis ratio, which is the ratio of the present value of the benefit to the present cost value, as shown in **Equation 9** (J. Liu et al. 2020; Xiang et al. 2020).

Cost–Benefit Analysis Ratio = [Current Value of Benefit]/[Current Value of Cost] (9)

A cost–benefit analysis systematically evaluates a specific plant or project's economic, technological and social performance. For cost–benefit analysis in LCH, it is necessary to complete the analysis process, as shown in **Figure 3.** The process includes different steps to thoroughly analyse the cost–benefit analysis of low-carbon hydrogen, which provides for the following:

1. Identification of the scope of low-carbon hydrogen production
2. Cost determination of production
3. Determination of low-carbon hydrogen benefits
4. Computational analysis of calculations for cost-benefit analysis of low-carbon Hydrogen,
5. Making recommendations and implementing the analysis in LCH projects or industrial plants.

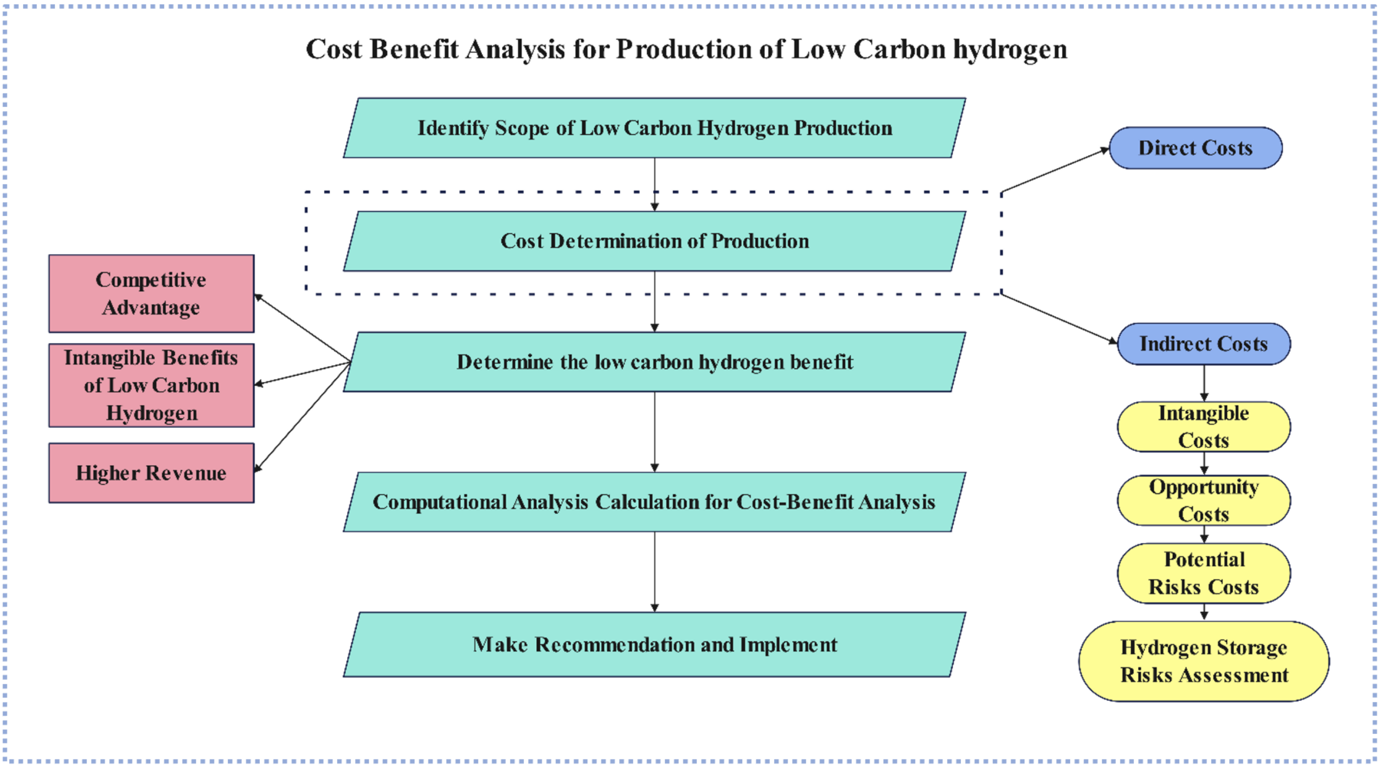


Figure 3. Systematic process of low-carbon hydrogen cost–benefit analysis (Mittal and Kushwaha 2024a).

Specific tools and models are developed specifically for this kind of analysis; one such tool is the H_2 analysis (H2A) discounted cash flow model 1, which can be used to assess how much it will cost to create hydrogen using different technological routes. The dependability of the data and analysis's underlying assumptions determine a CBA's correctness. To guarantee a thorough assessment, conferring with specialists or using proven models is frequently advantageous (Gerloff 2021; Palmer et al. 2021; X. Zhang et al. 2023; Zhuang et al. 2023; Grimm, de Jong, and Kramer 2020; Terlouw et al. 2022; Shih and Tseng 2014). Generally, cost–benefit analysis could be integrated with hydrogen production systems by identifying the costs, quantifying the benefits, calculating the net present value, and performing sensitivity analysis. Once the following steps are taken, the overall performance sensitivity analysis is positive, and the overall hydrogen production system becomes economically viable (Thakur et al. 2020; Osman et al. 2022; Razi and Dincer 2020).

3. Outcomes of the Cost–Benefit Analysis for Low-Carbon Hydrogen Production (1 TPD Plant)

According to the above equations (**Equations 1-9),** a thorough cost–benefit analysis for 1 TPD (tonnes per day) low-carbon hydrogen plants was performed. For such analysis, the operational and development cost analysis of low-carbon hydrogen is performed, which includes various parameters through which the cost analysis takes place. Once the operations and development analysis occurs, the benefit analysis of the 1 TPD plant is performed. After the computational results of the data were thoroughly examined, the overall cost–benefit analysis was assessed following various variations in national government subsidies ranging from 25% to 75%. These subsidies are significant for the smooth, free flow of the hydrogen economy because they accelerate the rapid production of low-carbon hydrogen.

3.1. Development and Operational Cost Analysis of Low-Carbon Hydrogen Production

The cost–benefit analysis of low-carbon hydrogen production first requires operational and development cost analysis, including hardware, services, software, labour, system requirements, infrastructure, and management costs. The industrial plant for low carbon hydrogen production is assumed to be a 1 tonne per day (1TPD) plant, which is used for the analysis. The operational and development costs of the 1 TPD are shown in **Figure 4**.

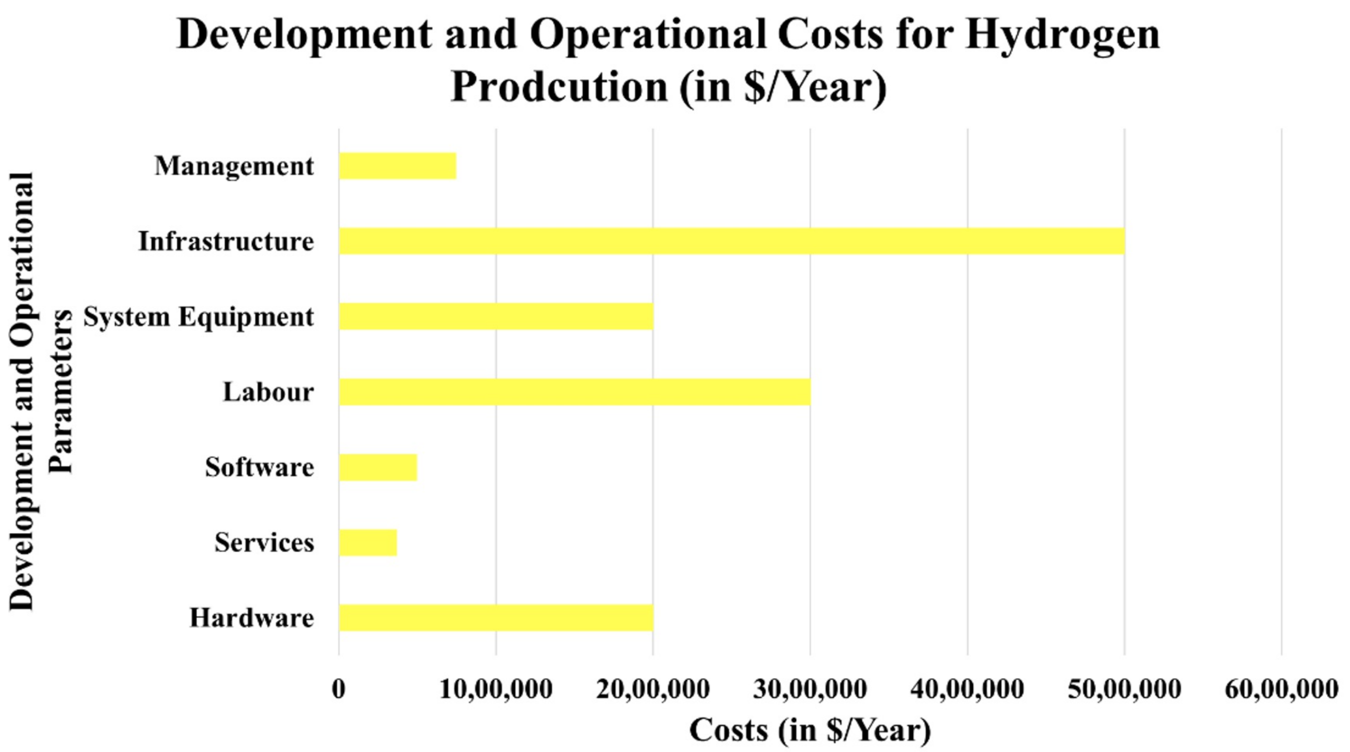


Figure 4. Operational and Development Cost Analysis of LCH Production (1 TPD Plant).

3.2. Benefits Analysis of Low-Carbon Hydrogen

The benefit analysis usually consists of tangible and intangible benefits, which help in the performance and effectiveness of a plant. Benefit analysis comprises more effective promotion campaigns, better industry-to-industry or industry-to-consumer retention, enhanced productivity, workflow efficiency, and high-quality and effective equipment. An approximation and estimation analysis of the benefit analysis for industrial low-carbon hydrogen plants is shown in **Figure 5**.

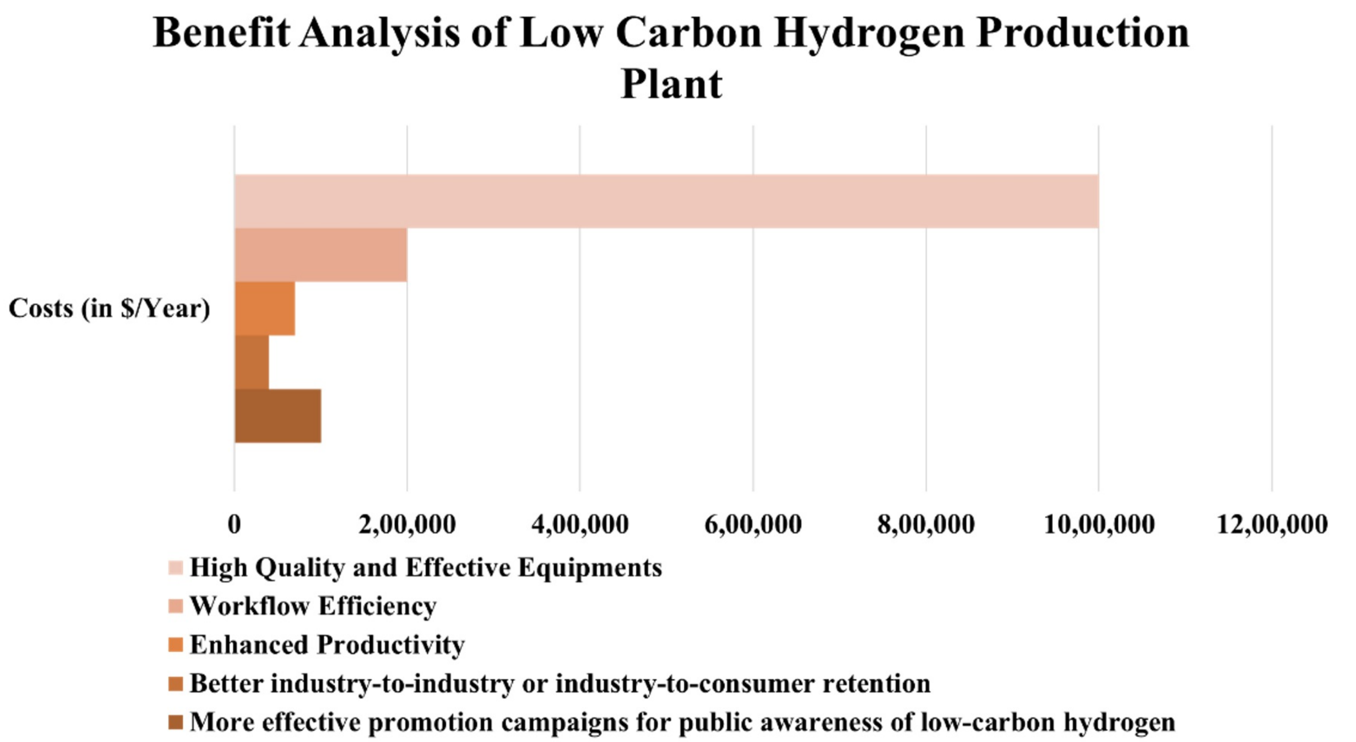


Figure 5. Benefit Analysis of LCH Production (1 TPD Plant) in USD/ Year. (i.e. it has been estimated that high-quality and effective equipment costs approximately 1 million USD per year)

3.3. Overall Cost–Benefit Analysis of Low-Carbon Hydrogen

Once the operational, development, and benefit–cost analyses are performed based on the approximation and estimation of the low-carbon hydrogen production plant, it is essential to compare the analyses to obtain the benefit–cost ratio for the final cost–benefit analysis. **Table 1** shows the cost–benefit analysis of low-carbon hydrogen and national government subsidies.

Table 1. Step-by-Step Overall Cost–Benefit Analysis of Low-Carbon Hydrogen for 1 TPD Production for 30 years.

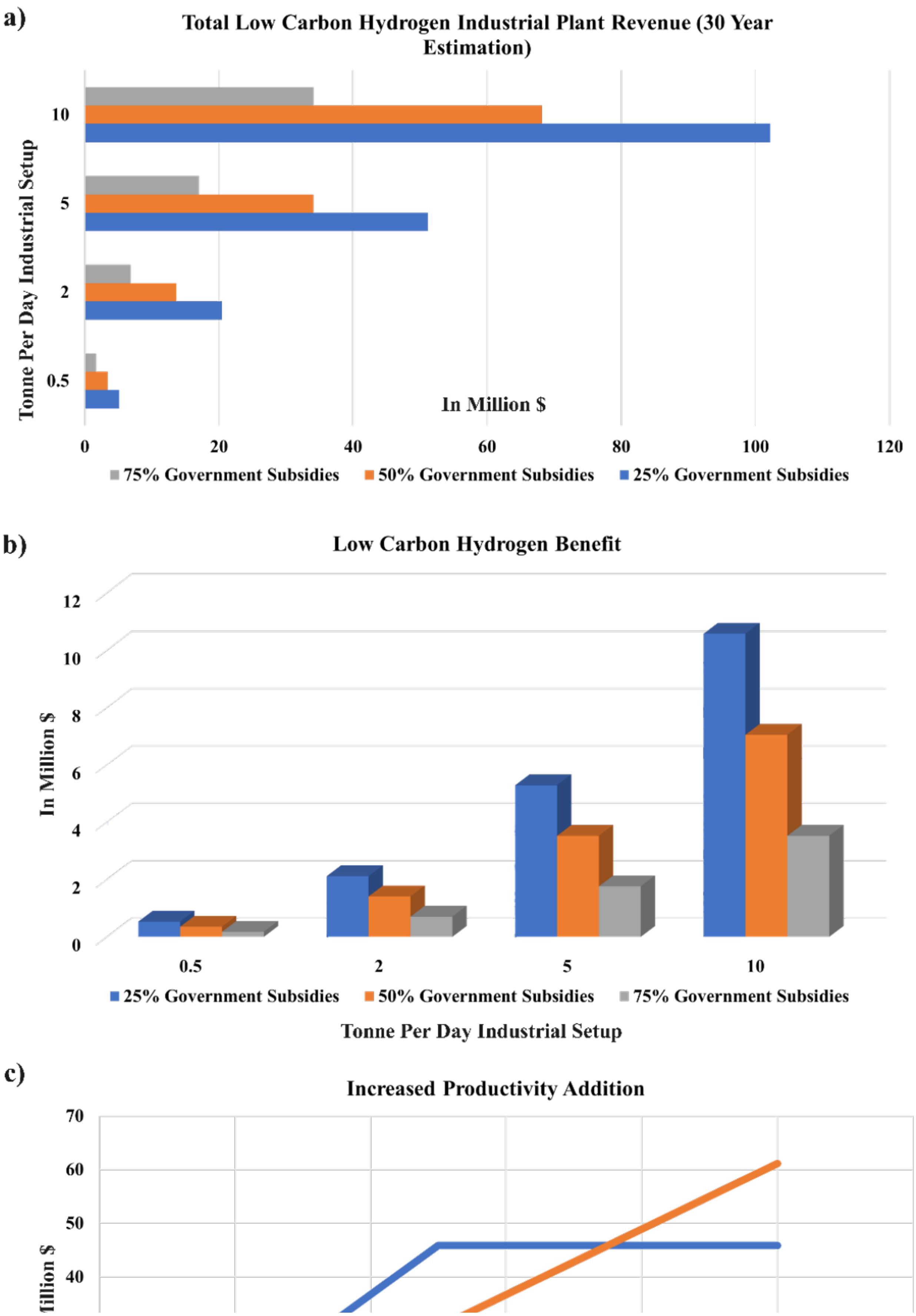
National Government Subsidies	25%	50%	75%
Total Low Carbon Hydrogen Industrial Plant-Revenue	10.224 (in million $)	6.81625 (in million $)	3.408 (in million $)
LCH Benefit	1.0575 (in million $)	0.705 (in million $)	.3525 (in million $)
Increased Productivity Addition	9.1665 (in million $)	6.11125 (in million $)	3.05 (in million $)
Net-Cost Benefit	8.72	8.66	8.65

Based on the overall cost–benefit analysis, the final net cost–benefit ratios for 25%, 50% and 75% were 8.72, 8.66 and 8.65, respectively. The primary significance of the net cost–benefit analysis ratio is the determination of quantitative measures such as the incorporation of intangibles, net present values, and benefit–cost analysis. A positive net cost–benefit ratio signifies that the industrial production plant showcased here has the potential to be economically beneficial and should be considered for implementation. Similarly, a negative net cost–benefit ratio signifies that the industrial production plant could not be financially viable. Hence, the results above show that a 1 tonne per day low-carbon hydrogen production plant would be economically feasible and could be implemented for profitable, sustainable, affordable low-carbon hydrogen production.

4. Variability in Industrial Scale Ups through Cost–Benefit Analysis

The calculations described above were explicitly performed for 1 tonne per day. In contrast, for industrialists who target different technical readiness levels (TRLs), consumer readiness levels (CRLs), social readiness levels (SRLs) and tonne-per-day technological setups, it becomes challenging to calculate the economic aspects of the production plant. This situation could be determined as the “Industrial Scale Variability”. The significant research gap in the current financial analysis of hydrogen production is the apathy of the different combinations and variations that industries demand. **Figure 6** critically examines the overall cost–benefit analysis for various tonne-per-day setups, precisely following the maximum TRL, SRL and CRL values.

For the industrial variability, the main parameters used to calculate the overall cost–benefit analysis, including the total low carbon hydrogen industrial plant revenue, low carbon hydrogen benefit and increased productivity addition, were segregated into 0.5 TPD, 2 TPD, 5 TPD and 10 TPD plant setups. With the help of this segregation, the values were calculated. The industrial demand ranging from 0.5 TPD to 10 TPD specifically for hydrogen production scale-up industrial plants could be examined, and the CBA was calculated by the infographics mentioned in **Figure 6**. Through such economic analysis, a thorough industrial plant can also be demonstrated, which could be used for upscaling of the current research. The proposed industrial hydrogen production plant is shown in **Figure 7.**



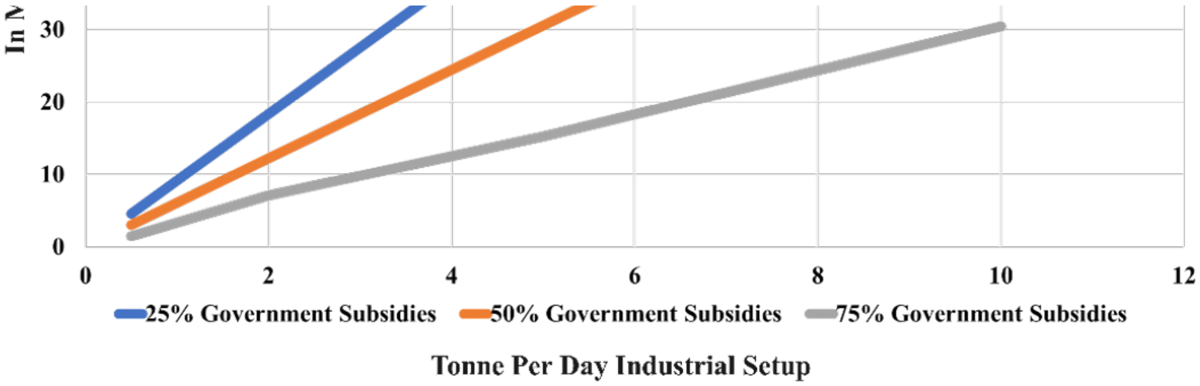


Figure 6. Industrial Variability of Hydrogen Scale-Up Production Plants.

Hydrogen generation, hydrogen storage, and appropriate hydrogen fuel require a combined integrated system. Many integrated systems have been proposed in recent years, but they need to consider sustainability or be more affordable and efficient. The integrated system presented in **Figure 7** is entirely novel and, in theoretical calculations, has proven to be sustainable, affordable and efficient. For hydrogen storage, catalytic dehydrogenation of $LiAlH_4$ is used for hydrogen storage, which has been proposed to involve three different processes: i) balloon primary storage (BPS), ii) fixed storage (FS) (5-25 bar) and iii) main hydrogen storage (MHS) (detachable). Disachable hydrogen storage and direct hydrogen generation work together with the help of artificial intelligence (AI) and Internet of Things (IoT) tools. They are then connected to several devices, such as vehicles, electricity, and purification tools, for adequate hydrogen fuel. Such a method is still theoretical and would require thorough practical experimentation. This model is explicitly constructed in accordance with CBA, which is described above, and a process diagrammatic overview of the hydrogen production plant is provided.

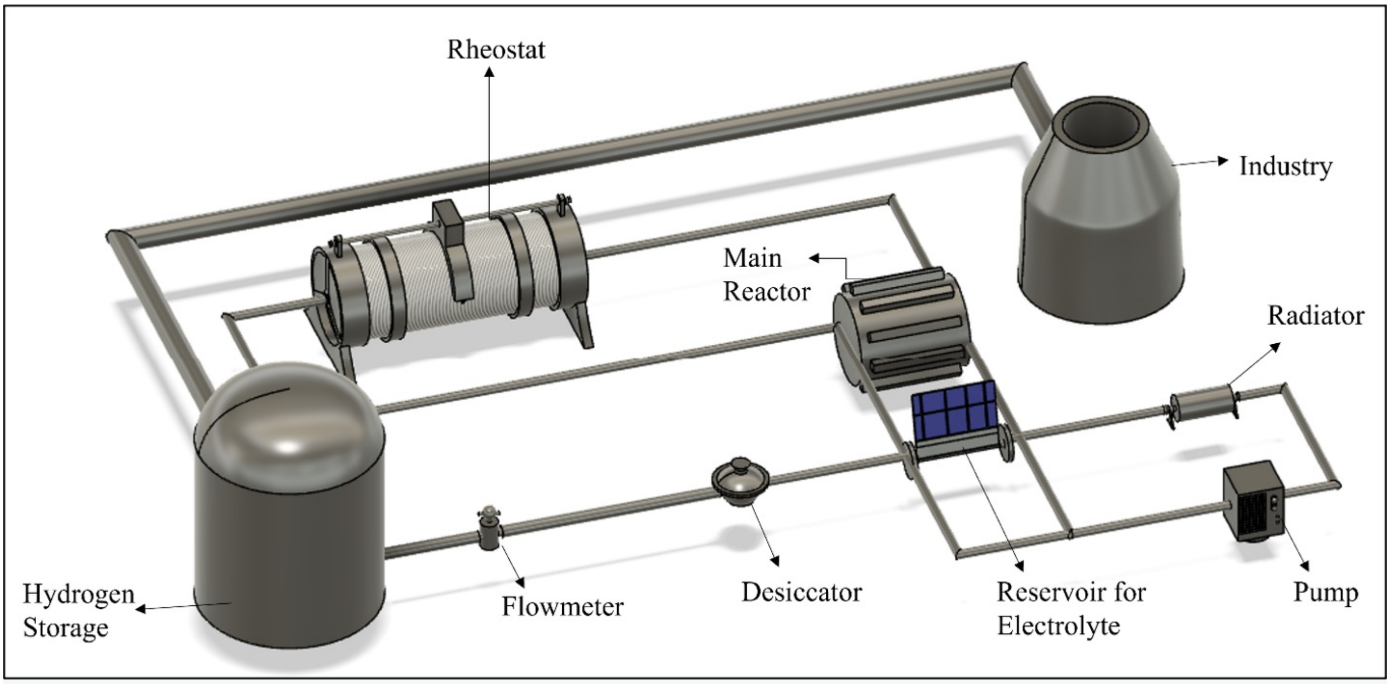


Figure 7. Industrial scale-up hydrogen production plant from 0.5 TPD to 10 TPD.

5. Conclusions

A thorough cost–benefit analysis was conducted through operational and development costs, benefit costs and overall CBA analysis for a 1 TPD hydrogen production plant. Several conclusions were drawn from our hypothesis. A thorough economic analysis of the current renewable energy sources is essential for commercializing modern renewables for industrial scaled-up production plants. A positive net cost–benefit analysis ratio was portrayed during the analysis (+8.72, +8.66 and +8.65 for 25%, 50% and 75% of the national government subsidies, respectively), which showed that the economy of the 1 TPD hydrogen production plant is not only economically viable but also sustainable and affordable for both industries and consumers. From the future perspectives of modern renewables, the use of hydrogen energy is booming. It should rapidly become commercially viable in the coming years, for which industries should conduct thorough sustainable and economic analyses for industrial plants to reach a free-flow globalized low-carbon hydrogen economy. The industrial scale variability for industrial plants ranging from 0.5 TPD to 10 TPD was also examined by calculating various parameters necessary for CBA, and a proposed scaled-up hydrogen plant was also determined. Such analysis is extremely important for industrialists currently producing hydrogen, and with the help of various national government subsidies, they can produce affordable, efficient and sustainable low-carbon hydrogen.

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