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Methodological Overview of Life Cycle Cost Analysis of Hydrogen Production

Bamidele Victor Ayodele *
Institute of Energy Policy and Research, Universiti Tenaga Nasional
Email: ayodelebv@gmail.com

Siti Indati Mustapa
Institute of Energy Policy and Research, Universiti Tenaga Nasional
Email: Indati@uniten.edu.my

Ozavize Freida Ayodele
UCSI University
Email: freida.ayodele@yahoo.ca

* *Corresponding Author*

Abstract
Purpose: The study presents an overview of the life cycle costs analysis of hydrogen production from various methods such as water electrolysis, natural gas steam reforming, and coal gasification.
Design/methodology/approach: The study employed a modified systematic literature review
Findings: The various studies reviewed show that the life cycle costs of production vary with the type of production process. Hydrogen production using off-grid electricity from wind turbines was found to have the highest life cycle costs of production of $24/Kg of hydrogen. While hydrogen production from natural gas steam reforming has the lowest life cycle production cost of $1/Kg of hydrogen.
Research limitations/implications: A holistic comparison of the life cycle costs analysis of the different hydrogen production processes might not be achievable due to the differences in the functional units of the production processes, system boundaries, material, and energy flow.
Practical implications: The application of life cycle costs analysis facilitates the real determination of profitability and enables the stakeholders to have holistic views of the costs at every stage which can help to identify any potential inefficiencies and overspending.
Originality/value: To the best of our knowledge, we present for the first time the comparative review of the life cycle cost analysis of hydrogen production by various methods.
Paper type: Literature review

Keywords: Hydrogen, Life cycle cost analysis, Water electrolysis, Natural gas steam reforming, Coal gasification

Introduction

The declining fossil energy resources and their environmental impact from their utilisation have propelled the quest for alternative, cleaner and sustainable energy sources (Ayodele, Abdullah, Alsaffar, Mustapa, & Saleh, 2020). Hydrogen has been projected as one of the important sustainable and renewable energy sources due to its numerous advantages over energy from fossil fuel (Bhandari, Trudewind, & Zapp, 2014). One of the key advantages of utilising hydrogen as an energy source is the tendency to combust without emission of carbon dioxide (Dutta, 2014). Moreover, it has a high energy density as well as a good energy carrier

(Nabgan et al., 2017). Hydrogen can be produced through several technological routes such as reforming of natural gas, reforming of biomass, and water electrolysis (Ayodele et al., 2020). Presently, the global hydrogen demand is being met by reforming of natural gas (IEA, 2019). Hydrogen production by water electrolysis has been projected as a more sustainable pathway for hydrogen production and could increase the share of global hydrogen production (Acar & Dincer, 2014). Besides, natural gas reforming and water electrolysis, other emerging technological routes for hydrogen production include gasification of biomass, dry reforming of natural gas, and photocatalytic glycerol reforming.

In order to consider energy economic calculations on the engineering system of hydrogen production from various technological routes, life cycle cost analysis must be employed. The life cycle cost analysis is a tool used to evaluate the total costs associated with design, development, operation, and maintenance of the life cycle of production system (Viktorsson, Heinonen, Skulason, & Unnthorsson, 2017). The cost elements usually considered during life cycle analysis of a system include the design costs, development costs, production costs, investment costs, operation/maintenance costs and disposal costs (Balaman, 2019). Since, there are emerging technological routes with great potentials for sustainable hydrogen production, the life cycle cost analysis of each of the technological routes that fulfilled similar performance requirements can be performed as a function of their initial costs as well as operating costs for the purpose of comparing the various processes in terms of the options that maximise net savings. Hence, this mini review focuses on a quick overview of literature on life cycle cost analysis of various hydrogen production alternatives. First, an overview of hydrogen production processes reviewed from the selected papers is presented. This is followed by an overview of the life cycle cost analysis of the various production processes. Subsequently, the literature was synthesised with a view to analysing the various trends in literature with suggested future research outlook. The distribution of the study locations of the life cycle cost analysis of the hydrogen production is depicted in Figure 1. Obviously, most of the study on the life cycle costs analysis of hydrogen production was conducted in China. This is because there are several hydrogen productions plants in China which range from medium to large scale. Other countries captured in the studies include Algeria, France, Germany, Iceland, Norway, South Korea, Turkey and USA.

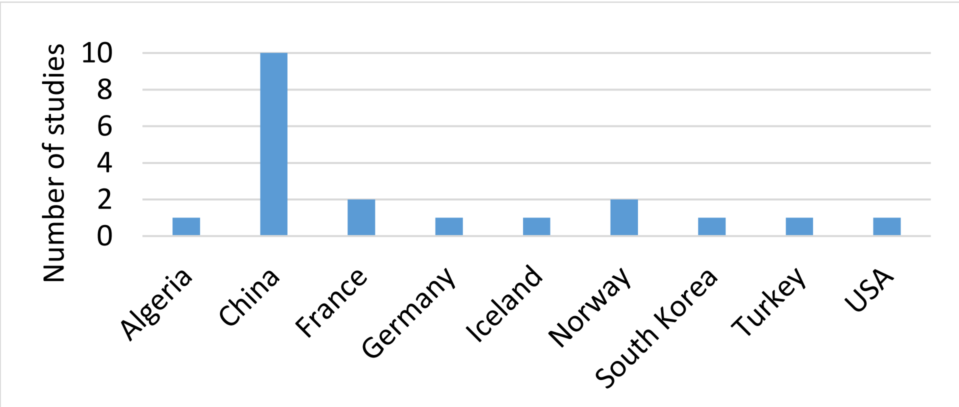

Figure 1: Distribution of the Studies

Overview of the Hydrogen Production Process

In this section, a brief overview of the three selected hydrogen production processes that were investigated for life cycle cost analysis was presented. About 45% of global hydrogen demand is produced from steam reforming of natural gas. Based on the work of Lee, Yoo, Cha, Lim, & Hur (2009), the stages involved in hydrogen production by natural gas steam reforming includes extraction and liquefaction, transportation, gasification, reforming process, compression and storage as well as utilisation. Often time, the extraction and liquefaction of the natural gas are carried in a different location as reported by Lee et al. (2009) and then transported to LNG ports where it is then gasified and then utilised to produce hydrogen by reforming process. The produced hydrogen undergoes series of compression and subsequently stored for further utilisation in hydrogen fuel cell vehicles. The electrolysis method is an electrochemical reaction that utilised electricity and water for hydrogen production. The stages in the electrolysis method include water extraction, water purification, transportation through pipeline to the electrolyser for the hydrogen production and the subsequent compression and storage. Most often, electricity generated from windmill or from domestic grid is usually employed for the water electrolysis. The hydrogen produced by water electrolysis is typically utilised in fuel cell vehicles. Hydrogen can also be produced from biomass gasification or reforming. The stages involved in the production process include biomass production, biomass reforming or gasification and the subsequent compression of the hydrogen for fuel cell vehicles and other applications.

Overview of Life Cycle Cost Analysis of Hydrogen Production from Various Processes

The life cycle cost analysis of various hydrogen production processes has been reported in literature. Yao, Jia, & Mao (2010) presented a framework for hydrogen energy life cycle cost analysis as shown in Figure 2. According to Yao et al. (2010), there are five stages in developing the life cycle cost analysis of hydrogen production. The first stage involves the confirmation of the different phases and range of hydrogen energy life cycle. The different phases include hydrogen production, hydrogen storage, and hydrogen application. The second stage involves the identification of the costs associated with the different phases and itemises the analysis. The third stage involve the setting up of cost breaking structure of the hydrogen energy life cycle. The fourth stage involves the selection of suitable model for the cost estimate of each of the phases involve in the hydrogen energy life cycle. The final stage involves the detailed analysis of the different relationship between each of the cost elements of the life cycle model.

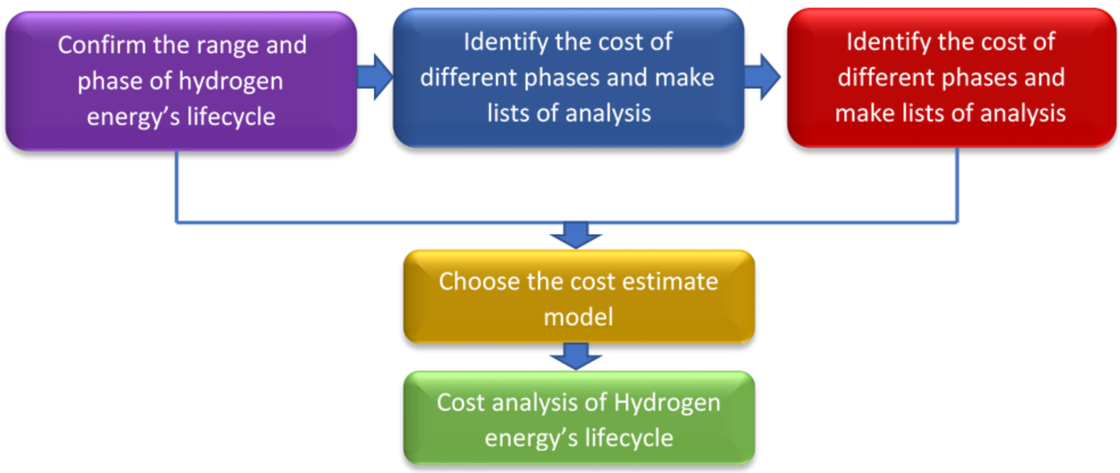

Figure 2: Hydrogen Energy Life Cycle Cost Analysis Framework (Yao et al., 2010)

The life cycle cost analysis of the different hydrogen production processes is summarised in Table 1. The hydrogen production processes investigated include water electrolysis using different strategies such as grid-connected electricity, off-grid connected electricity, electricity generated from wind turbines, electricity generated from solar PV, coal gasification, natural gas steam reforming and liquefaction process. In most of the studies, the period of analyses for the life cycle cost analyses ranges from 10-30 years. Hydrogen life cycle costs such as the cost of hydrogen production, the investment cost, the operation, and maintenance costs were considered in most of the studies. As shown in Figure 3, the life cycle production cost of hydrogen varies with the type of production process. Amongst the life cycle costs analysis of the different processes, hydrogen production by water electrolysis using electricity generated from wind turbines was found to have the highest production costs of 24 $/kg-hydrogen. The high cost of production could be attributed to the off-grid electricity from the wind turbine. On the contrary, the same electrolysis process with electricity sources from wind turbines, solar photovoltaic cell and domestic grid-connected were found to have lower costs of hydrogen production. The type of electricity source used for hydrogen production by water electrolysis play significant role in the life cycle cost analysis. Other hydrogen production process such as coal gasification, natural gas steam reforming was found to have a lower production cost of hydrogen.

Table 1: Summary of Literature on LCCA Related to the Various Hydrogen Production Method

Production method	$/kg-hydrogen	Analysis Period	Life cycle cost considered			Reference
			Cost of hydrogen production	Investment cost	Operational and maintenance cost	
Water electrolysis	0.97	25 years	√	√	√	Li, Chen, Liu, & Wang (2017)
Wind-water electrolysis (grid connected)	3.36	25 years	√	×	×	Greiner, KorpÅs, & Holen (2007)
Wind-water electrolysis (off-grid)	7.44	25 years	√	×	×	Greiner et al. (2007)
Wind-water electrolysis (grid connected)	13.2	25 years	√	×	×	Greiner et al. (2007)
Wind-water electrolysis (off-grid)	24.00	25 years	√	×	×	Greiner et al. (2007)
Wind-water electrolysis	1.21	20 years	√	√	√	Douak & Settou (2015)
PV-water electrolysis	4.67	30 years	√	×	√	Mason & Zweibel (2007)
Water electrolysis using electricity	1.13	10 years	√	√	√	He, Sun, Xu, & Lv (2017)

from wind farm						
Hydrogen from Chlor-alkaline plant	1.90	10 years	√	√	√	He et al. (2017)
Water electrolysis	10.30	20 years	√	√	√	Viktorsson et al. (2017)
Coal gasification	1.22	n.r	×	√	√	Yao et al. (2010)
Natural Gas steam reforming	1.00	n.r	×	√	√	Yao et al. (2010)
Water electrolysis	1.78	n.r	×	√	√	Yao et al. (2010)
Liquifaction process	1.44	20 years	√	√	√	Yilmaz (2019)
Electrolysis of Water	n.r	20 years	√	√	√	Fang (2019)

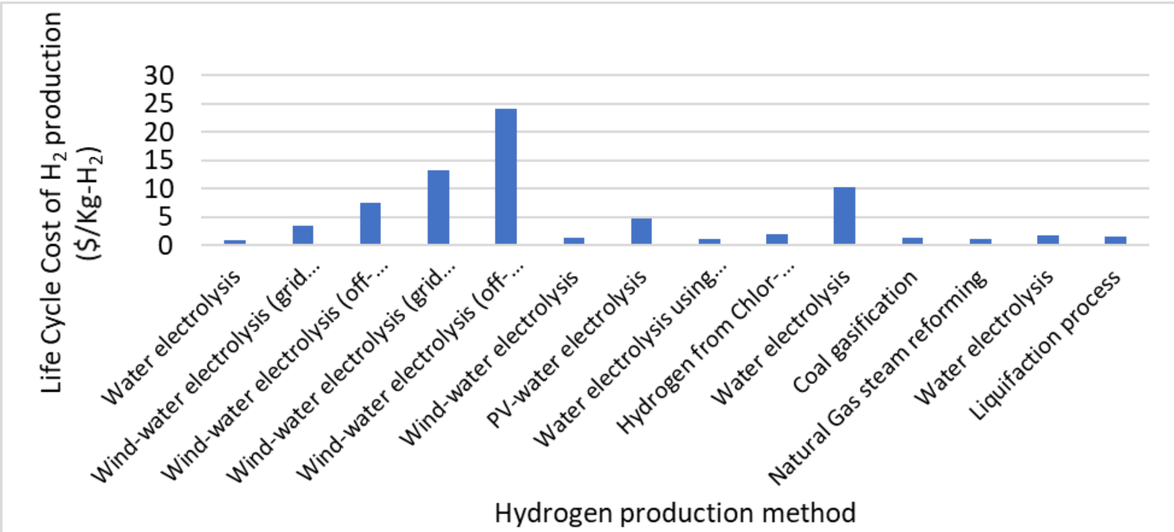

Figure 3: Life Cycle Cost of Hydrogen Production Obtained Using Different Methods

Conclusion and Future Research Outlook

The life cycle cost analysis of the different routes for hydrogen production based on selected reviewed papers has been presented. The study revealed that despite the common end-product from the various processes reported is hydrogen, there were variations in the life cycle costs analysis of each of the production processes. It can be inferred from this study that the life cycle costs analysis of any production process is strongly depended on the material and energy compositions of such production process.

Theoretical Implications

This study presents for the first time the comparative review of the life cycle cost analysis of hydrogen production by various methods.

Practical and Social Implications

The application of life cycle costs analysis facilitates the real determination of profitability and enables the stakeholders to have holistic views of the costs at every stage which can help to identify any potential inefficiencies and overspending.

Limitations and Suggestion for Future Research

A holistic comparison of the life cycle costs analysis of the different hydrogen production processes might not be achievable due to the differences in the functional units of the production processes, system boundaries, material, and energy flow. It is worthwhile to state that most of the studies employed common cost elements in the life cycle costs analysis. Based on the life cycle costs analysis of the different hydrogen production, the production costs seem to be competitive in the long term.

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