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Circular Economy Assessment of Viable for Fuels for Mobility

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Abstract

The continuous rise in greenhouse gas (GHG) emissions and the potential lithium scarcity imposed by the increase in battery electric vehicles is escalating the need for alternative sustainable transportation options. There is a lack of holistic environmental assessments, considering the array of trade-offs between these technologies. In this work, we utilize a Circular Economy assessment framework, MICRON, to analyze and identify sustainable transportation fuel options based on five principal metrics: Waste, Energy, Emissions, Water, and Procurement. Based on this analysis, among Hydrogen (H_2) production technologies, H_2 from wind electrolysis is the most sustainable, resulting in a score of 0.63 for overall circularity. Among methanol production technologies, methanol produced by Biogas is the most sustainable, with a circularity score of 0.52.

Keywords: energy carriers, circular economy, circularity index, sustainability index

1. Introduction

The transportation sector is primarily dominated by internal combustion engine (ICE) vehicles, which rely on gasoline as their primary fuel source, contributing significantly to GHG emissions. The rest of the vehicles are mainly battery electric vehicles (BEVs), the largest consumers of lithium. Lakhani N, et al. (2023) predicted that by 2040, the global demand for lithium is predicted to rise over 40 times, leading to environmental and social instability. The escalating threats of climate change and resource depletion emphasize the urgent need for transitioning to more efficient and sustainable transportation fuels.

Methanol stands out as a prominent alternative in today's market to reduce global emissions in the transportation sector. Its production from captured carbon dioxide (CO_2) helps counterbalance the CO_2 emissions during vehicle use. Additionally, methanol burns cleaner than gasoline when used in internal combustion engines and offers flexibility in blending with other fuels across various air-fuel ratios. Hydrogen (H_2), another promising energy carrier, is gaining traction, particularly in public transportation buses. Due to its zero emissions at its point of use in fuel cell vehicles (FCVs) and its high energy efficiency, H_2 is a promising alternative for the near future. Ammonia also holds potential as a transportation fuel. Its ability to store hydrogen in greater quantities than other fuels addresses a significant challenge faced by hydrogen due to its low density. This feature positions ammonia as a viable candidate in the evolving fuel mix for the transportation sector. However, the sustainability of these fuels for transportation is highly contingent on their production processes. Some production pathways may generate more waste and emissions, and they often consume significant resources (energy, water, and other natural materials). For that reason, a holistic metric that considers these factors when assessing technologies is fundamental to determining their viability as transportation fuels.

Despite various efforts to assess the viability of these energy carriers, including life cycle assessments (Bouillass et al., 2021), life cycle inventory, and social life cycle assessments (Ahmed et al., 2023), a comprehensive, unified framework for their environmental comparison is still lacking. Circular economy (CE) represents a sustainability assessment tool that enables the assessment of different technologies to determine the most circular technology among them. In this work, a CE assessment is conducted to assess holistically the sustainability of different production methods for these low-carbon fuels.

2. Methodology

Determining the most circular vehicle technology would require a comprehensive revaluation of its use and disposal, along with the fuel production process. As the first step, this work contemplates a cradle-to-gate scope, as shown in Figure 1, for the fuel synthesis of some of the most promising fuels: renewable gasoline, hydrogen, methanol, and ammonia. All the emissions, along with an array of other CE metrics, are evaluated for the stages of feedstock extraction, transportation, and production of the fuel.

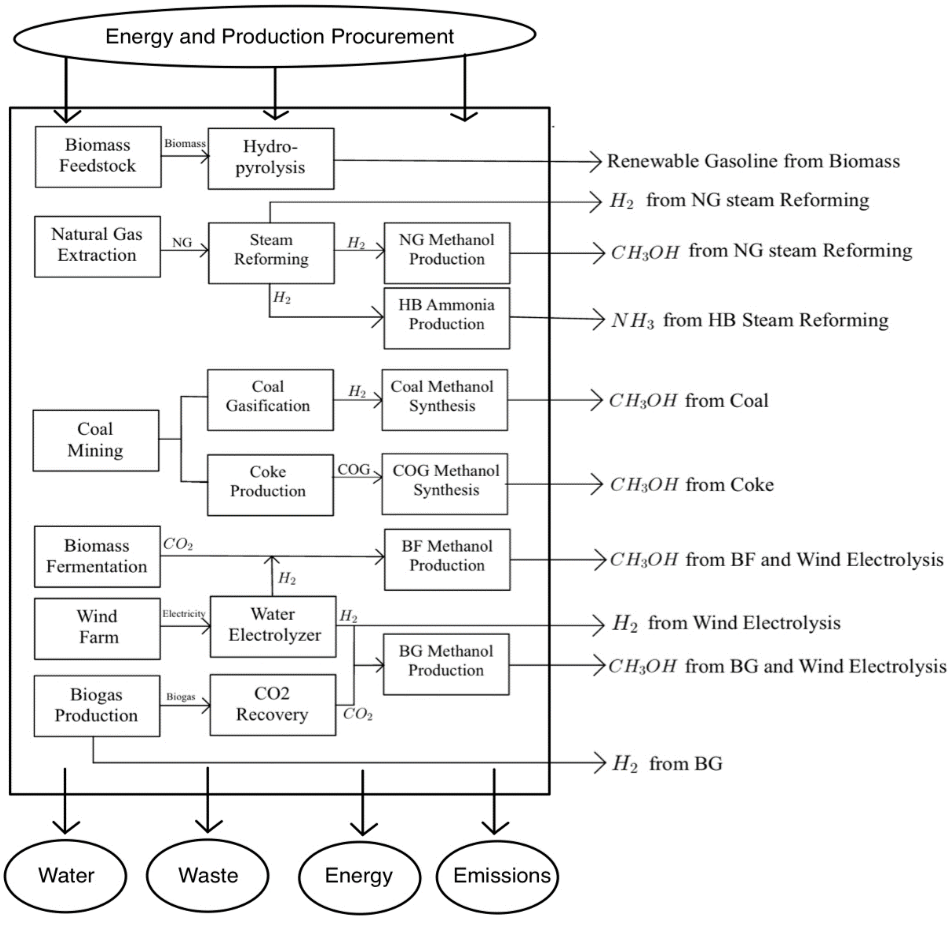


Figure 1. Circularity Assessment Scope: A cradle-to-gate analysis of different fuel production pathways

Baratsas et al, (2022) proposed a CE assessment tool to evaluate the circularity of companies. The CE impact scores range from 0 to 1, where zero represents linear operations and 1, circular operations. The calculator was designed based on the five circular economy goals identified. The goals encompass: i) minimizing waste and pollutants, ii) decreasing the utilization of natural resources, iii) boosting the proportion of renewable resources, iv) lowering emissions, and v) increasing the durability of products. Therefore, the impact principal categories of waste, water, procurement, energy, and emissions were defined according to the CE goals. These principal categories are scored based on metrics derived from GRI standards (standards commonly used in sustainability reports) and LCA.

In the present work, this calculator is adapted to analyze the production of fuels for powertrains with the final intention of determining the most circular transportation fuel. A table with the metrics utilized in the current study is presented in **Table 1**. A weight is assigned to the metric of each indicator so a score for each category can be computed. An overall index can be obtained from the linear average of the different categories.

Table 1. Principal indicators and metrics of the circular economy calculator.

Principal Category	Metric
Waste	**1a.** % Hazardous Waste over Total Waste Generated
	1b. % Diverted Waste over Total Generated Waste
	1c. Waste generated [kg] / kg of fuel produced
Water	**2.** Total volume of water recycled and reused as a percentage of the total water withdrawal [%]
	2b. % of water consumed per water withdrawn
	2c. Water consumed per kg of fuel produced
Procurement	**3.** % of renewable material
Energy	**4a.** % of Renewable over Total Energy Consumed
	4b. Total Energy Consumed per kg of fuel produced [MJ]
GHG Emissions	**5a.** Net Total Emissions per kg of fuel produced [$kgCO_2e$/ kg]
	5b. NO_x, SO_x etc. over kg of fuel produced [kg/kg]

3. Discussion and Results

Given the established scope, the manufacturing of the fuel and production of the inputs are studied. The Overall “Circularity” Index, along with the sub-indices is calculated here for the considered fuels and available data on production technologies. An extensive literature review was carried out to collect the data needed for the calculator indicators, and a normalized value from 0 to 1 was calculated for each metric, as shown in Table 2.

Table 2. Circularity metric values and literature review for each technology.

	Waste			Water			Proc.	Energy		GHG Emissions	
Technology	**1a**	**1b**	**1c**	**2a**	**2b**	**2c**	**3**	**4a**	**4b**	**5a**	**5b**
H_2 from Elec. Wind (Mann et al. , 2004)	1.00	1.00	0.00	0.36	0.00	0.75	0.0	1.00	0.00	1.00	0.92
H_2 Biogas (Hajjaji et al., 2016)	1.00	1.00	0.97	0.00	0.00	0.79	1.0	0.40	0.88	0.00	1.00
H_2 from NG SMR (Spath et al., 2001)	1.00	0.00	0.98	0.00	0.00	0.47	0.0	0.01	0.00	0.00	0.00
Methanol by NG (Li et al., 2018)	0.00	1.00	1.00	0.00	0.00	0.69	0.31	0.02	0.66	0.72	0.91
Methanol by Ethanol fermentation (Demirel, 2016)	1.00	0.00	0.94	0.00	0.00	0.00	0.0	0.33	0.66	0.85	0.94
Methanol by BG using H_2 wind Elec. (Eggemann et al., 2020)	1.00	1.00	0.00	0.00	0.01	0.00	0.57	0.11	0.60	1.10	0.92
Methanol by Coal (Li et al., 2018)	0.14	0.14	0.98	0.00	0.00	0.72	0.89	0.02	0.55	0.58	0.98
Methanol by Coke (Li et al., 2018)	0.96	1.00	0.59	0.09	0.00	0.70	0.63	0.01	0.45	0.64	0.59
Renewable Gasoline (Zupko, 2019)	0.95	0.95	0.96	0.00	0.00	0.00	1.0	0.00	0.29	0.45	0.77
NH_3 by HB with H_2 SMR, US grid (Biçer et al., 2017)	1.00	0.00	0.98	0.89	0.06	0.93	0.0	0.13	0.59	0.43	0.00

Figure 2 presents the sub-index circularity scores for each evaluated technology. Among the methanol production methods, methanol derived from coke demonstrates the highest waste recycling rate, achieving a perfect score in the waste sub-index. This efficiency significantly offsets its emissions, positioning it as the methanol technology with the highest circularity. Excluding hydrogen produced via wind electrolysis, the remaining hydrogen production methods utilizing the same type of energy: the U.S. energy mix. Nevertheless, biogas production stands out due to its superior efficiency, leading to higher circular sub-index values in three out of four categories and trailing closely in the fourth. Despite its renewable production, gasoline production remains a predominantly linear technology. The overall circularity indices for these technologies are further illustrated in **Figure 3**.

Figure 2. Circularity indicator metrics for each technology

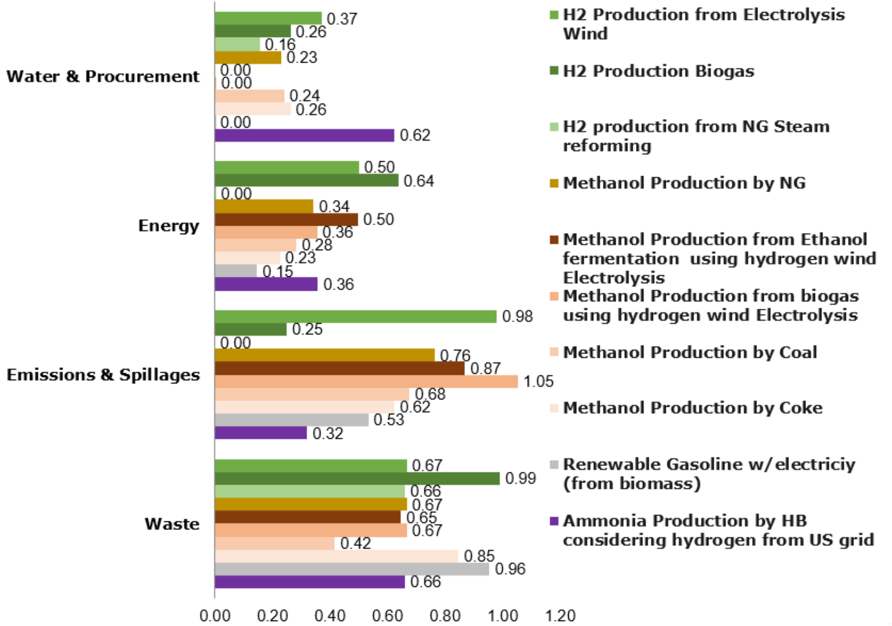
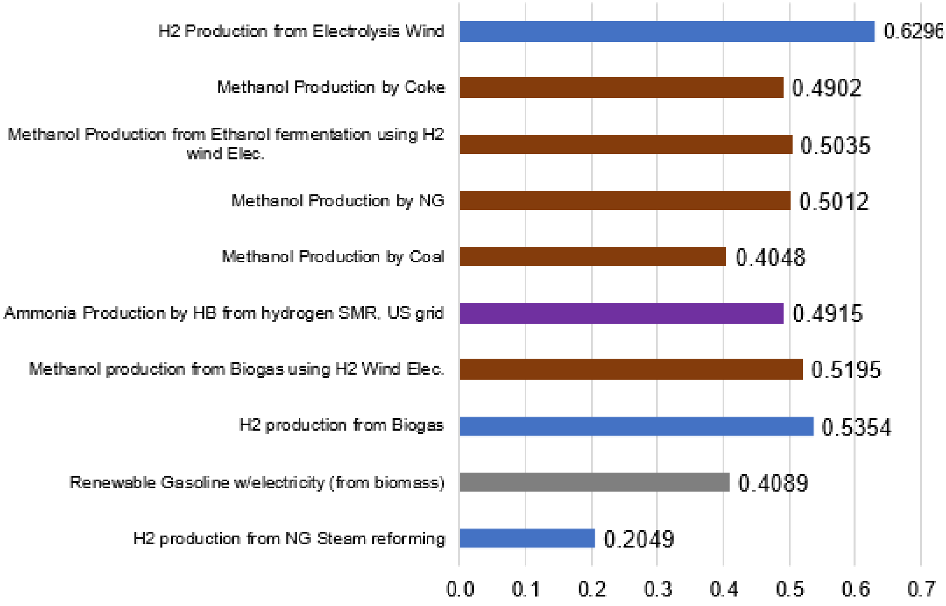


Figure 3. Overall circularity for all the considered production pathways ranked by most circular most linear.



4. Conclusions

This study successfully leveraged the MICRON CE framework to quantify the circularity indices of various fuel production technologies. Our findings revealed that hydrogen generated through wind electrolysis emerged as the leading circular technology, while methanol production via biogas outperformed in terms of circularity for methanol technologies. These insights underscore the need for a strategic shift towards these more circular technologies in order to meet greenhouse emission reduction goals sustainably. In addition, the current trajectory of renewable methanol production, characterized by its linearity, raises concerns over its feasibility in the short to medium term without substantial advancements. While the assessments conducted were thorough, the breadth and depth of the analysis could be further strengthened with additional data on a wider range of ammonia and hydrogen production technologies. Future research endeavors will aim to enhance the framework by integrating considerations for fuel transportation and storage, as well as their usage in FCVs, thereby providing a more comprehensive view of the vehicle's life cycle and supporting the drive towards a sustainable energy economy.

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