Environmental impacts associated with hydrogen production in La Guajira, Colombia

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Keywords: environmental impacts, hydrogen, just transitions, life-cycle assessment, Colombia

Supplementary material for this article is available online

Abstract

The global push to decarbonize sectors of the economy and phase-out coal use has attracted a renewed interest in hydrogen. At the forefront of this debate, Colombia, the world’s 6th largest coal exporter, must consider strategies to support a just transition for regions that depend economically on coal exports. However, the role of hydrogen as a part of the energy transition has yet to be examined from an environmental justice lens. A full-chain life-cycle assessment of hydrogen production is yet to be considered in Colombia. Using life-cycle assessment (LCA) methodology, we examine the greenhouse gas emissions, water consumption, and trace metal emissions associated with six potential Colombian liquid hydrogen production strategies: (1) electrolysis powered by the country’s national electricity grid, (2) on-site electrolysis powered by electricity produced by a wind farm, (3) off-site electrolysis powered by electricity produced by a wind farm, (4) electrolysis powered by electricity produced from a coal-fired power plant, (5) coal gasification without carbon capture and storage (CCS), and (6) coal gasification with CCS. Upstream conversion has an outsized influence on the sustainability of a hydrogen transition in Colombia. Impact levels for wind-powered electrolysis are lower than those of the coal- and grid-powered scenarios for every impact category analyzed, apart from emissions of aluminum to air, nitrogen emissions to water, and phosphorous, nitrate, and nitrite emissions to soil. The grid-based electrolysis scenario is found to consume the largest amount of water, while coal-fueled scenarios pathways raise concerns of greater life-cycle mercury, nickel, and arsenic emissions. While coal gasification with CCS reduced gasification CO2 emissions by 35%, the CCS scenario’s VOC emissions were 37% greater than gasification without CCS, given that increased levels of coal inputs were required to account for the loss of efficiency associated with the addition of CCS technology. For Colombia to benefit most from a hydrogen-based decarbonization transition with minimal environmental impacts, community-focused planning and wind-based hydrogen systems should be prioritized.

1. Introduction

Colombia occupies a unique position as the largest coal exporter in South America, placing it at the international center of a changing industry. With increasing international pressure to reduce coal exports, Colombia may seek to diversify its energy economy. Much of the country’s coal production takes place in its northern department of La Guajira, which is home to El Cerréjón, South America’s largest open pit coal mine. The mining industry is a foundational part of La Guajira’s economy, comprising 37.6% of the region’s economy in 2019 (Departamento Administrativo Nacional de Estadística, Colombia 2021). The department also has some of the best potential wind resources in South America, with class 7 winds that are only matched by those in the Patagonia region of
Chile and Argentina (Vergara et al 2010). Despite these vast primary energy resources, the department maintains the highest poverty levels of the Caribbean region, with a 51.4% incidence of multidimensional poverty, an index Colombia uses to measure quality of life based on household education, childhood conditions, health, work, access to public services, and living conditions (Departamento Administrativo Nacional de Estadística, Colombia 2019). The department is also home to many indigenous and Afrocolombian communities, which have been historically marginalized throughout Colombia’s history and have suffered greatly from the development and operation of the mine (Boeder 2013). Ninety-eight percent of the country’s Wayuu tribe lives in La Guajira and comprises 38% of the population (Sistema Nacional de Información Cultural (SINIC) 2021).

According to the El Cerrejón mine, the mine directly employs or contracts with 5,282 residents of La Guajira and has invested $15 billion COP (∼ $4 million USD) into the community (Cerrejón 2021). As such, contraction of the mining industry could pose a great risk to communities that depend economically on the mine. With global demand for coal decreasing as countries strengthen the ambitions of their decarbonization goals, materialization of these risks become more and more likely. To aid coal-mine-adjacent communities through these predicted economic contractions, government officials must consider policies that promote a ‘just transition’ to provide economic support to the communities economically affected from the transition towards zero-emissions energy production.

At the start of August of 2021, Colombia launched its own Hydrogen Roadmap that detailed its plans to invest heavily in hydrogen production, with a goal to develop 1 GW of electrolysis infrastructure and produce 50 kt of blue hydrogen by 2030 (Minenerga 2021). Hydrogen has the potential to serve as a key step in the country’s climate change mitigation goals, where Colombia pledges to reduce its 2030 baseline greenhouse gas emissions by 51%, specifically reducing its energy sector emissions by 35% of 2015 emissions (Gobierno de Colombia 2020).

Hydrogen can be produced by various fuels and technologies and is often characterized using colors to describe its emissions and mode of production (Dawood et al 2020). ‘Grey hydrogen’, for instance, is created from fossil fuel sources without any carbon capture mechanisms to reduce the process’ emissions. ‘Blue hydrogen’, on the other hand, is produced from fossil fuels with carbon capture technology. Hydrogen also has the potential to be produced entirely from zero-emission energy sources, like wind or solar, using techniques like water electrolysis to produce ‘green hydrogen.’ La Guajira has been noted as a location of particular interest for hydrogen production, in large part given its significant wind resources. However, the country notes in its hydrogen roadmap that production will not be entirely ‘green’, particularly in the earlier stages of the industry’s development (Minenerga 2021).

Producing ‘green’ over ‘grey’ or ‘blue’ hydrogen may have important economic, environmental, and human implications. For instance, should the country consider exporting locally produced hydrogen, especially to account for contracting coal demand, potential importers may seek to employ carbon border adjustments, increasing demand for green H₂ over that for blue and grey H₂. The fuels consumed throughout the life-cycle of the process, as well as their resulting emissions, are also likely to have important implications on the country’s climate change goals and the health and wellbeing of the indigenous, Afrocolombian, and mining communities living near potential hydrogen production sites. This study examines the differences between the impacts of six potential hydrogen production scenarios in the region, using a life cycle assessment (LCA) to quantify each scenario’s greenhouse gas, air, and water pollution emissions; water consumption levels; and trace metal leakage.

2. Literature review

Studies have found that decarbonization of Colombia’s energy sector will be important for insulating its economy from contractions in international coal markets, reducing the greenhouse gas emissions that contribute to internal climate change, mitigating carbon lock-in, and responding to political pressures for decarbonization through pledges made in international venues, like the Paris Agreement (Falkner 2016, Lazarus and van Asselt 2018, Oei and Mendeleivitch 2019, Delgado et al 2020, Gobierno de Colombia 2020). Substantial research has been conducted on sustainability energy transitions in Latin America (Bataille et al 2020, Pye et al 2021, Vergara et al 2010, Ramirez et al 2020), but the role of hydrogen as a part of this energy transition has yet to be examined from an environmental justice lens. Recent work on long-duration energy storage established potential techno-economic benefits of liquid hydrogen and hydrogen as a form of long-duration or seasonal energy storage on the path toward energy system decarbonization (Shan et al 2022). Other studies have developed alternative energy strategies to analyze environmental and economic effects of producing hydrogen and other products from coal, integrating findings into policy roadmaps for a hydrogen industry. One common methodology utilizes backcasting, which first identifies desired transition goals or targets as an endpoint and assesses the necessary transition steps and intervention pathways needed to achieve policy goals (Giurco et al 2011). Other research has demonstrated sustained improvement of hydrogen production efficiency (Kaskun et al 2022).
and Kayfeci, 2018, Kaskun 2020, Kaskun et al 2020) and noted economic synergies and greenhouse gas reduction benefits for hydrogen production in regions with substantial wind capacity (Scolaro and Kittner 2022). However, just one study has examined the transition to hydrogen production potential in Latin America, and has done so primarily through an economic lens (Moreira dos Santos et al 2021). Other research that has been conducted on hydrogen production as a transition strategy has instead focused on the transition under the lens of the transportation sector (Iannuzzi et al 2021). This study will build off this previous work by examining the prospective environmental and health impacts of hydrogen as a tool in Colombia’s energy transition.

Examination of the health and environmental impacts of prospective hydrogen development scenarios in Colombia is extremely important given the country’s acceleration of hydrogen technology development. This study uses a life-cycle framework to examine these impacts. Past studies have used life-cycle assessment to determine the greenhouse gas emissions from various hydrogen scenarios (Utgikar and Thiesen 2006, Bouvart and Prieur 2009, Cetinkaya et al 2012, Dufour et al 2012, Muresan et al 2014, Verma and Kumar 2015, Wang et al 2019). A limited number of papers have also expanded their impact assessment beyond greenhouse gas emissions to include other environmental effects, including acidification, eutrophication, smog, and water resource depletion (Koroneos 2004, Delpierre et al 2021). However, trace metals, which could be a key environmental indicator for particular production pathways, are often omitted. A full-chain life-cycle assessment of hydrogen production is yet to be done in Colombia, a major potential exporter, and has so far not included a holistic examination of environmental factors that would affect Colombia’s coal-mine-adjacent communities, like trace metal leakage, air and water pollution, and water consumption.

Given Colombia’s large amounts of coal exports and documented environmental and health detriments that have risen from its coal production, it is important that energy transitions research in the country include analysis of the transition on coal mine-adjacent communities (Weber and Cabras 2021). Impact analyses of the mine have documented detriments to vegetation from oxidation of surrounding soil, desertification of nearby rivers and contamination of local water sources, and detriments to air quality that have resulted in pulmonary disease amongst young and elderly community members resulting from the mine’s operation (Virgüez 2011, Aggregocés et al 2018). Past work on just transitions centered their framework on the political and economic components of the transition (Healy and Barry 2017, Cardoso and Turhan 2018, Strambo and Atteridge 2018, Jakob et al 2019, Strambo and González Espinosa 2020). It is essential to include management of water consumption, air and water emissions, and trace metal leakage as part of the discussion of just transitions given their impacts on air pollution and public health—and they are often excluded from the economic or jobs analysis. This study can aid planners in assessing the environmental and health implications of various hydrogen production scenarios and facilitating discussion on hydrogen’s role as a viable just energy transition strategy.

3. Methods

3.1. Life cycle inventory

This study uses a life cycle assessment approach to compare the environmental impacts of six hydrogen production methods in La Guajira, Colombia. The objective of this approach is to compare the impacts of producing 1 ton of liquid hydrogen (LH₂) through the following six pathways: (1) gasification of coal with CCS,
(2) gasification of coal without CCS, (3) electrolysis using electricity produced from a thermal coal plant, (4) electrolysis using electricity powered by wind turbines in the La Guajira region with an onsite electrolyzer and liquefaction plant, (5) electrolysis using electricity powered by wind turbines in the La Guajira region with an offsite electrolyzer and liquefaction plant, and (6) electrolysis powered using electricity from Colombia’s national electricity grid (Spanish acronym SIN) with assumed completion of the HidroItuango hydroelectric dam. These pathways are summarized in figure 1.

The study calculates and presents an overview of the greenhouse gas, criteria air pollutant, and trace metal emission impacts associated with each production method and calculates each method’s estimated life-cycle water consumption. The impact categories, along with their corresponding indicators, are shown table 1. After the LCA per ton impacts were characterized, they were also compared with full scale-up of meeting Colombia’s 2030 low-emissions hydrogen production targets, assumed to be 50 ktonnes of LH2, based on the blue hydrogen production goals stated in Colombia’s Hydrogen Roadmap (Minenergía 2021).

3.2. Study boundary
A summary overview of each included step is shown in figure 2.

3.3. Coal gasification
Since the El Cerrejón mine was established more than 30 years ago, the exploration and development steps of the coal production are excluded from the analysis. Both coal gasification pathways begin with extraction of coal from the El Cerrejón mine. Coal is extracted using a 63.5-ton bucket excavator and 35% of the extracted coal is sent to the mine’s stockpiles. The coal is then cleaned and washed, a process that is assumed to have a 73% coal recovery rate (Fueyo Editores 2015). Once the coal is prepared, it is transported 150 miles from the mine to Puerto Bolívar via the mine’s proprietary diesel-powered train. This study assumes that the coal gasification process will take place at a gasification plant constructed adjacent to Puerto Bolívar. During the gasification process, hydrogen is produced through pressure swing absorption (PSA), with an assumed 1.57 GJ/GJ-H2 gas to feedstock ratio for gasification without CCS, and a 1.69 GJ/GJ-H2 gas to feedstock ratio for gasification with CCS (Gray and Tomlinson 2002). In the gasification with CCS scenario, carbon capture and storage (CCS) takes...
place concurrently with the PSA process. The produced hydrogen is then liquefied at an 85% efficiency rate, accounting for boil-off during the liquefaction process. For reference, a 50 tpd liquefaction plant is estimated to cost $80 million USD (Connelly et al. 2019). The study assumes the 85% efficiency rate and an electricity consumption rate of 8 kWh for liquefaction of 1 kg of hydrogen in every scenario (Gardiner 2009, Petitpas 2018).

The amount of coal required to produce this hydrogen is calculated using the following equation:

\[
\text{Coal Gasification with PSA & Liquefaction:} \quad \sum \text{CMP}_{ef} \ast C + \frac{\text{GPC}_{ef}}{\text{GP}_{L} \ast P} + \text{G}_{ef} + \frac{\text{LC}_{ef}}{\text{L}_{L} \ast P} + \text{LO}_{ef}
\]

Where CMP$_{ef}$ is the coal mine operation and coal preparation emission factor, C is the amount of coal mined (8.55 tonnes), Tr$_{af}$ is the coal transport by train emission factor, GPC$_{ef}$ is the gasification plant construction emission factor, GP$_{L}$ is the gasification plant project lifetime (20 years), P is the scenario hydrogen production potential, G$_{ef}$ is the gasification emission factor, LC$_{ef}$ is the liquefaction plant construction emission factor, L$_{L}$ is the liquefaction plant project lifetime (20 years), and LO$_{ef}$ is the liquefaction plant operation emission factor.

3.4. Coal-powered electrolysis

The coal extraction and preparation steps taking place in the coal electrolysis pathway are equivalent to that of the coal gasification pathway. Once the coal has been extracted and prepared, it is transported 71 miles from the El Cerrejón mine to the Termoguajira power plant via a 40-ton semi-truck. The power plant produces electricity, which is then transmitted to a 1 MW polymer electrolyte membrane (PEM) electrolyzer, estimated to cost $300,000 ($300/kW) (DOE Hydrogen and Fuel Cells Technologies Office 2021). The electrolyzer is installed at the Puerto Bolivar site using the current SIN grid system transmission network, with an assumed 10% transmission loss (International Energy Agency 2018). This will be the same electrolyzer and transmission loss used across all scenarios involving electrolysis. Powered by the transmitted electricity, the electrolyzer produces hydrogen, assumed to require 50 kWh of electricity to produce 1 kg of hydrogen (DOE Hydrogen and Fuel Cells Technologies Office 2021). A similar liquefaction process is performed using the same efficiency and electricity requirements of previous steps. Outputs resulting from production of liquid hydrogen from coal-powered electrolysis is calculated using the following equation:

Coal – powered electrolysis & liquefaction:

\[
\sum \text{CMP}_{ef} \ast C + \text{CE}_{ef} \ast \text{CE} + \frac{\text{EC}_{ef}}{\text{EL} \ast P} + \frac{\text{LC}_{ef}}{\text{LL} \ast P} + \text{LO}_{ef}
\]

Where CMP$_{ef}$ is the coal mine operation and coal preparation emission factor, C is the amount of coal mined (59 tonnes), CE$_{ef}$ is the coal electricity production emission factor, CE is the amount of coal-powered electricity required to produce 1 ton of liquid hydrogen ($59 \times 10^3$ kWh), Tr$_{af}$ is the coal transportation by truck emission factor, EC$_{ef}$ is the electrolyzer construction emission factor, E$_{L}$ is the electrolyzer lifetime (20 years), P is the scenario hydrogen production potential, LC$_{ef}$ is the liquefaction plant construction emission factor, L$_{L}$ is the liquefaction plant project lifetime (20 years), and LO$_{ef}$ is the liquefaction plant operation emission factor.

3.5. Wind-Powered electrolysis

The wind-powered electrolysis pathway begins with construction of the Jepirachi wind farm, to account for the embodied emissions and water consumption of the recently constructed park. Operation of the turbines produces electricity to power the PEM electrolyzer, however it is assumed that there are no emissions or water consumption associated with operation of the turbines. Two wind-powered electrolysis scenarios are considered in this study: 1) where electrolysis and liquefaction are co-located at the wind farm site and 2) where the
electricity produced from the wind farm is transmitted 7 km to Puerto Bolivar for electrolysis and liquefaction using a proprietary transmission network. These scenarios are represented in figure 3 below:

The electrolysis and liquefaction process performed is assumed to use the same efficiency and electricity requirements of previous steps. Outputs resulting from production of liquid hydrogen from wind energy-powered electrolysis is calculated using the following equation:

\[ \sum \frac{EC_{of}}{E_{L}} \cdot P + \frac{T_{of} \cdot TG_{of}}{T_{L} \cdot P} + Tru_{of} + \frac{LC_{of}}{L_{L} \cdot P} \]
Offsite wind electrolysis liquefaction:

\[ \sum \frac{EC_{ef}}{E_L} \times P + \frac{T \times T_{ef}}{T_L \times P} + \frac{TraC_{ef}}{Tra_L \times P} + \frac{LC_{ef}}{L_L \times P} \]

Where P is the scenario hydrogen production potential, EC_{ef} is the electrolyzer construction emission factor, E_L is the electrolyzer lifetime (20 years), T is the number of turbines (15 turbines), TC_{ef} is the turbine construction emission factor, T_L is the turbine lifetime (20 years), Tra_{ef} is the cryogenic truck operation emission factor, LC_{ef} is the liquefaction plant construction emission factor, L_L is the liquefaction plant project lifetime (20 years), and Tra_{ef} is the transmission line construction emission factor, and Tra_L is the transmission line project lifetime (20 years).

3.6. Grid-powered electrolysis

In the grid-powered electrolysis pathway, Colombia’s national electricity grid is used to power the electrolyzer. The study assumes that the HidroItuango dam will be constructed and in operation by the time this process occurs, and that the electricity produced from the dam will supply 17% of the country’s electricity consumption. It is assumed that all 2019 levels of electricity production from the country’s natural gas, coal, oil, and non-hydro renewables will remain constant. Hydrogen electrolysis and liquefaction are performed using the same assumptions detailed in previous sections. The amount of grid electricity required to produce this hydrogen is calculated using the following equation:

Grid connected electrolysis & liquefaction:

\[ \sum \frac{EC_{ef}}{E_L} \times P + EO_{ef} + \frac{LC_{ef}}{L_L \times P} + LO_{ef} \]

Where P is the scenario hydrogen production potential, EC_{ef} is the electrolyzer construction emission factor, E_L is the electrolyzer lifetime (20 years), LC_{ef} is the liquefaction plant construction emission factor, L_L is the liquefaction plant project lifetime (20 years), and LO_{ef} is the liquefaction plant operation emission factor.

3.7. Life cycle impacts

Emissions of greenhouse gases, water consumption, and trace metal leaching are calculated through the life cycle inventory ecoinvent database, which provides an open-access and transparent range of environmental life cycle inventory datasets in sectors such as building and construction, energy, and metals (Wernet et al 2016). The datasets are supplemented by context specific variables and equipment manuals. Water consumption was calculated to reflect net water consumption based on water outputs deducted from water inputs. Primary materials for the PEM electrolyzer included 528 kg of titanium, 200 kg of stainless steel, 54 kg of aluminum, and 9 kg copper, along with 10,720 kWh of construction electricity requirements. (Evangelisti et al 2017, Bareiß et al 2019)

4. Results

Clear patterns emerge when comparing the results of the six scenarios against one another (Table 2). Grid-powered water electrolysis has the largest water consumption and methane emissions levels, while coal-powered water electrolysis has the largest emissions of trace metals, air pollutants, and greenhouse gases in almost every other scenario. On-site and off-site wind-powered electrolysis were the lowest emitters in every category, apart
from emissions of aluminum to air; nitrogen emissions to water; and phosphorous, nitrate, and nitrite emissions to soil. Siting of the electrolyzer on- or offsite made little difference in all categories.

4.1. Greenhouse gas emissions

The coal electrolysis scenario has the highest estimated carbon dioxide emissions of the five scenarios, emitting an estimated 66 tonnes of carbon dioxide per tonne of liquid hydrogen produced, as shown in figure 4 (left). This is almost eleven times greater than the emissions from the wind electrolysis scenarios. Including carbon capture and storage (CCS) in the coal gasification scenario lowered CO2 emissions by over 65%, from 31 tonnes to 11 tonnes emitted per tonne LH2 produced. As shown in figure 4 (right), a process-based emissions analysis indicates that in the coal electrolysis scenario, the electricity production step accounts for 89% of these emissions.

Methane emissions are highest in the grid-powered electrolysis scenario, which produces 71 kg of methane per tonne of liquid hydrogen produced, as shown in figure 5 (left). This due to the natural gas-powered electricity production that comprises 11% of Colombia’s national grid mix. As shown in figure 5 (right), the electrolysis process in the grid electrolysis scenario, which is powered by the national grid mix, accounts for 87% of the scenario’s methane production. The grid electrolysis scenario produces over twice the amount of methane produced by the coal electrolysis scenario and over thirty-seven times that produced by the wind electrolysis scenarios. Coal gasification with CCS produced 19 kg of methane, about 3 kg more methane per tonne liquid hydrogen than that produced in the coal gasification without CCS scenario. This difference can be attributed to the increased coal inputs required in the CCS scenario, which account for the efficiency losses associated with the CCS process.

4.2. Air pollutant emissions

The coal electrolysis scenario’s NOx emissions were almost twelve times greater than that of coal gasification and over fifteen times greater than that of wind electrolysis (see figure 6 left.) It also produced far more SO2 emissions.
than any other scenario, producing almost nine times the amount of SO2 produced by grid-powered electrolysis and about eighty times that of the wind-powered electrolysis scenarios, also shown in figure 6 (right). Construction of the liquefaction plant was a large contributor of NOx and SO2 emissions to all scenarios, comprising almost the entirety of the 13 kg of NOx emissions and the 7.7 kg of SO2 associated with offsite and onsite wind electrolysis. All coal-powered scenarios produced higher levels of non-methane volatile organic compounds (VOC) and airborne particulate matter. The grid-powered electrolysis scenario also emitted high levels of fine particulate matter, emitting about two times that of the coal gasification scenarios.

4.3. Trace metals leakage
As shown in figure 7, the coal-based scenarios produced the highest levels of arsenic and lead emissions to air, with arsenic emissions from the coal electrolysis scenario that were ten times greater than those of the wind electrolysis scenarios, and lead emissions almost eighteen times greater. Cadmium emissions were also relatively high amongst the coal-based scenarios, with gasification emissions with CCS three times greater than those of the wind-powered electrolysis and coal-based electrolysis emission that were six times greater. Coal-based scenarios were associated with dissolved solids emissions to water that were almost thirty-eight times greater than those of the wind and grid-based electrolysis scenarios.

4.4. Water consumption
Water consumption was highest in the grid-powered electrolysis scenario, which consumed about 1600 million cubic meters (MMC) of water per tonne liquid hydrogen produced, as shown in figure 8 (left). This is due to Colombia’s heavy reliance on hydroelectricity to power their national grid mix, assumed to comprise 77% of electricity production after incorporation of the Hidroluango dam. As shown in figure 8 (right), the electrolysis process in the grid electrolysis scenario, which is powered by the national grid mix, accounts for 88% of the
scenario’s water consumption. While the coal gasification scenarios water consumption levels were far less than that of the grid-powered electrolysis scenario, their consumption levels (∼220 MMC) were about four times greater than those of the wind-powered electrolysis scenarios (∼53 MMC and 52 MMC). It should be noted, however, that while this is the best water consumption data available, there is some uncertainty with regard to the net water consumption figures made available within the ecoinvent database.

5. Discussion

As international coal markets contract with the increasing ambitions of climate change mitigation strategies and internalized social costs of carbon, coal mining communities like those in La Guajira may be tempted to find domestic strategies to consume their remaining coal reserves (Mercure et al 2021). One such strategy may be to produce liquid hydrogen using coal as a primary energy source. However, the above results pose serious concerns for the impacts on water consumption, the various trace metals, air pollutants, and greenhouse gases that liquid hydrogen (LH₂) production could emit depending on the mode through which it is produced, particularly cautioning against coal-based and grid-based LH₂ production scenarios.

Among all categories, coal electrolysis is the least efficient production scenario that Colombia might elect to use for LH₂ production. In terms of its effects on climate change, coal electrolysis produces the most carbon dioxide emissions and second-most methane emissions, amounting to 66 tonne CO₂ eq/tonne LH₂ (US EPA 2015). This is about 35 tonne CO₂ eq/tonne LH₂ greater than the CO₂ eq of the coal-gasification without CCS scenario, and 48 tonne CO₂ eq/tonne LH₂ greater than the CO₂ eq of the grid-powered electrolysis scenario (US EPA 2015). To illustrate this impact, if Colombia were to produce 50 tons of hydrogen using coal-based electrolysis, total CO₂ eq emissions could increase by 3.3 Mtonne per year. The study’s least emissions-intensive scenarios, the offsite and onsite wind electrolysis scenarios, in contrast would produce approximately 0.3 Mtonne CO₂ eq per year. This difference is significant, considering that Colombia recently declared its increased climate change mitigation ambitions of reducing the intensity of its energy production by 35%, capping the level of its energy sector emissions at 56 CO₂ eq per year. (Gobierno de Colombia 2020).

An analysis of the air pollution impacts of the five scenarios also reveals significant concerns for SO₂, NOₓ, and PM emissions from scenarios using coal as their primary fuel source. Both SO₂ and NOₓ contribute to photochemical smog formation, which not only has detrimental impacts on local ecosystems and agricultural crops, but also contributes to increased incidence of respiratory disease amongst communities (Harte et al 1991, US EPA 2015). Previous studies have also documented the annual impact of particulate matter released from operation of the mine, associating it with over 325,000 respiratory symptom cases a year (Aggregocés et al 2018). Continued or increased prevalence of these health issues is of great concern, given that they have the potential to affect some of Colombia’s most vulnerable communities. Additionally, the prospective agricultural detriments associated with the SO₂ and NOₓ emissions could exacerbate the Wayuu’s historical agricultural losses from operation and expansion of the El Cerrejón mine (Observatorio Latinoamericano de Conflictos Ambientales 2018).

Disparities between the arsenic, lead, and mercury emission to water levels of the coal-powered scenarios versus the grid- and wind-powered scenarios raise further health concerns for communities in direct proximity of the existing mine. High levels of mercury and arsenic exposure are associated with lung cancer, raising further concerns for communities’ respiratory health (Harte et al 1991). Mercury may also contribute to mental disorder, and damage to nervous systems (Harte et al 1991). Lead has been shown to have severe health effects, including brain damage (especially to children), reduced ability to produce blood cells, and reproductive effects, even at low levels of exposure (Harte et al 1991). Both lead and mercury exposure have also been shown to affect kidney health, which is concerning given that aluminum exposure (which is also much greater in the coal-powered scenarios) for individuals with kidney failure can lead to toxic levels of aluminum accumulation (Wills and Savory 1989).

Lastly, coal-based scenarios raise significant concerns for consumption of water resources in La Guajira through LH₂ production. Water consumption levels are an especially important consideration in the region, given that over 50% of the municipalities in La Guajira have been shown to be highly vulnerable to climate change-induced desertification and drought (IDEAM 2018). The grid-electrolysis scenario has by far the highest levels of water consumption, largely due to the water losses associated with hydroelectricity, which is assumed to comprise 77% of the country’s electricity grid after construction of the HidrolUngao dam. It is important to note that these grid-based water losses will not be entirely concentrated in La Guajira, as the impacts will in theory be dispersed across the regions with the electricity sources powering the national electricity grid. However, it is important to note the climate change resiliency concerns of any system that is heavily reliant on hydroelectricity, given the technology’s inherent vulnerabilities to climate change. Other scenarios, like the coal-fueled electrolysis and gasification scenarios would affect La Guajira directly, with the potential to consume an
annual 6 million cubic meters (MMC) and 4 MMC, respectively. During an average dry year, this would comprise about 1.5% and 1% of the department’s available water resources (IDEAM 2018).

By and large, wind-fueled scenarios have the lowest impact levels across the four categories examined in this study. In most cases, the majority of the impacts associated with wind-fueled LH2 production are associated with the construction of the liquefaction plant. Similar to the case of the grid-based LH2 scenario’s water consumption levels, the localized impacts from the liquefaction construction phase may not be concentrated in the La Guajira region, depending on whether the materials would be imported into Colombia or manufactured locally. Electrolysis of the hydrogen on-site at the wind park or offsite had little effect on the life-cycle impacts, as impacts did not differ greatly between construction of a dedicated transmission line to transmit the electricity produced to power the electrolyzer or transportation of the electrolyzed and liquefied hydrogen by truck between sites. This set-up could offer distinct advantages across sectors of Colombia’s economy—from electricity decarbonization and storage to a hydrogen refueling network for ships and heavy duty vehicles (Kittner et al 2021).

In its current form, Colombia’s Hydrogen Roadmap emphasizes the importance of hydrogen production for achievement of the country’s decarbonization goals. While incorporation of renewables into hydrogen production processes is a stated goal, the current plan notes that 60% of hydrogen consumed in the Industrial sector would come from sources that do not qualify under its ‘low-emissions’ category, even into 2050. (Minenergía 2021) As noted in this study, should this production come from coal-fueled sources, other impacts that aren’t directly noted in the Hydrogen Roadmap, like increases in emissions of air pollutants and trace metals, are likely to arise. These impacts would likely take place alongside greater levels of carbon lock-in resulting from investments into fossil-fuel-based infrastructure that could perpetuate use of fossil fuels in the country long after technological advances support large-scale, cost-efficient adoption of renewable technologies. This possibility is particularly noteworthy when considering that coal-based hydrogen consumption would likely result in larger levels of coal consumption, given that the majority of Colombian coal is currently exported to other countries and therefore not consumed onsite. Future developments to hydrogen strategies and plans to aid communities through a just transition should thus consider these greater holistic implications of any future adopted hydrogen production strategies.

6. Conclusion

This study calculated the greenhouse gas emissions, air pollution, trace metal leakage, and water consumption levels associated with six liquid hydrogen production scenarios using a life cycle assessment to inform hydrogen production’s suitability as a just transition strategy. The analysis finds the greatest environmental impacts among scenarios using coal as their primary energy source, especially for CO2, SO2, NOx, mercury, arsenic, and lead emissions. Across all scenarios, localized hazards, like air pollution and trace metal leakage are most concerning for coal-based scenarios, given that most of the processes throughout the life cycle of the liquid hydrogen production would take place locally in the La Guajira region. Other scenarios, like grid-based electrolysis and wind-scenarios, are likely to have their impacts distributed nationally or even internationally. Perhaps the greatest impacts of wind-powered LH2 production will be those associated with siting decisions for the wind park, particularly given that La Guajira consists of indigenous Wayuu land. Future studies should consider how siting and construction of new wind parks will affect indigenous communities to ensure that future renewable energy development efforts are accompanied by support for Wayuu human rights and general well-being. Further investigation should also be conducted to better inform the hydrogen industry’s ability to support a just transition in the wake of a reduction in exported coal, characterizing other factors like potential socio-economic impacts of industry development, as well as its potential to support increased community capabilities and self-sufficiency.

Acknowledgments

The authors wish to thank Dr Shabbir H Gheewala for helpful discussions and comments related to the life-cycle assessment methodology. The authors also thank Javier Peña for assistance with initial project development. ANU thanks the Department of City and Regional Planning at the University of North Carolina at Chapel Hill for a Doctoral Summer Research Fellowship.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).
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