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An Analysis of Greenhouse Gas Emissions in Electrolysis for Certifying Clean Hydrogen

Yunji Kim †, Inhong Min †, Jieun Lee and Heena Yang *

Water Energy Research Center, Korea Water Resources Corporation, Daejeon 34045, Republic of Korea; appstar@kwater.or.kr (Y.K.); minin7312@kwater.or.kr (I.M.); jelee@kwater.or.kr (J.L.)
* Correspondence: heena.yang@kwater.or.kr; Tel.: +82-042-870-7676
† These authors contributed equally to this work.

Abstract: The drive for carbon neutrality has led to legislative measures targeting reduced greenhouse gas emissions across the transportation, construction, and industry sectors. Renewable energy sources, especially solar and wind power, play a pivotal role in this transition. However, their intermittent nature necessitates effective storage solutions. Green hydrogen and ammonia have gained attention for their potential to store renewable energy while producing minimal emissions. Despite their theoretical promise of zero greenhouse gas emissions during production, real-world emissions vary based on system configurations and lifecycle assessments, highlighting the need for detailed evaluations of their environmental impact. Therefore, in this study, calculations were performed for the actual amount of produced greenhouse gas emissions that are associated with the production of green hydrogen using electrolysis, from raw material extraction and processing to hydrogen production, with these assessed from well-to-gate emission estimates. Emissions were also evaluated based on various types of renewable energy sources in South Korea, as well as hydrogen production volumes, capacities, and types. Using these data, the following factors were examined in this study: carbon dioxide emissions from the manufacturing stage of electrolysis equipment production, the correlation between materials and carbon dioxide emissions, and process emissions. Current grades of clean hydrogen were verified, and the greenhouse gas reduction effects of green hydrogen were confirmed. These findings are significant against the backdrop of a country such as South Korea, where the proportion of renewable energy in total electricity production is very low at 5.51%. Based on the domestic greenhouse gas emission efficiency standard of 55 kWh/kgH_2, it was found that producing 1 kg of hydrogen emits 0.076 kg of carbon dioxide for hydropower, 0.283 kg for wind power, and 0.924 kg for solar power. The carbon dioxide emissions for AWE and PEM stacks were 8434 kg CO_2 and 3695 kg CO_2, respectively, demonstrating that an alkaline water electrolysis (AWE) system emits about 2.3 times more greenhouse gasses than a proton exchange membrane (PEM) system. This indicates that the total carbon dioxide emissions of green hydrogen are significantly influenced by the type of renewable energy and the type of electrolysis used.

Keywords: green hydrogen; greenhouse gas emissions; electrolysis; renewable energy; clean hydrogen certification

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1. Introduction

Increased awareness of global warming and climate change has strengthened global efforts to reduce greenhouse gas emissions overall. The use of fossil fuel-based energy sources has been identified as a major contributor to global warming, primarily through massive carbon dioxide emissions. As a response to this, the international community ratified the Paris Agreement in 2015 to reduce greenhouse gas emissions, aiming to limit the global average temperature increase to below 2 °C, ultimately striving for 1.5 °C. Furthermore, at the 2021 Glasgow Climate Conference, various initiatives were discussed to achieve net-zero emission targets. All of these efforts highlight the growth of the global movement to address the climate crisis and transition to a more sustainable energy future [1–7].

Eco-friendly energy technologies play a crucial role in replacing fossil fuels and reducing greenhouse gas emissions generated during energy production and consumption processes. Renewable energy sources such as solar, wind, and hydroelectric power emit far fewer greenhouse gasses compared to fossil fuels, making their advancement and deployment key to reducing emissions. Additionally, advancements in energy storage and smart grid technologies can complement the intermittent nature of renewable energy and maximize the efficiency of energy systems [8–15]. Clean hydrogen, particularly produced through electrolysis powered by renewable energies such as solar and wind power, is gaining attention as a promising solution due to its renewable and pollution-free characteristics. Both the development and widespread adoption of these clean energy technologies are essential for transitioning towards a more sustainable energy future and mitigating the impact of climate change. By leveraging the inherent environmental benefits of renewable energy sources and innovative storage solutions, the production and utilization of clean hydrogen can significantly contribute to the goal of achieving net-zero greenhouse gas emissions across various sectors of the economy [16–19].

As mentioned above, clean hydrogen is gaining attention as a promising solution to mitigate issues caused by dwindling fossil fuel resources, owing to its renewable nature and lack of polluting effects. While the production costs for clean hydrogen currently exceed those of fossil fuel-based hydrogen, they are becoming increasingly competitive due to declining prices of renewable energy and technological advancements. Further enhancement in economic feasibility can be achieved through large-scale production and infrastructure development. Clean hydrogen finds versatile applications in the transportation, industry, and power sectors, particularly in hydrogen fuel cell vehicles, steel and chemical processes, and energy storage and generation. Current clean hydrogen technologies are rapidly advancing, with active research and investments in countries such as Japan, Germany, and South Korea. As production costs decrease and infrastructure expands, clean hydrogen holds substantial potential to establish itself as a primary energy source [20–28].

One viable method to produce high-quality hydrogen is water electrolysis, which can be powered by intermittent renewable energy sources such as solar, wind, and hydroelectric power. Water electrolysis is categorized into two main technologies: alkaline electrolysis, a mature technology developed over a century, and proton exchange membrane (PEM) electrolysis, which is noted for high levels of efficiency and a compact design. Recent advancements in anion exchange membrane technology have further improved the potential for large-scale and cost-effective hydrogen production through alkaline water electrolysis. Additionally, PEM electrolysis is also gaining attention for its high level of efficiency and compact design advantages [29–35]. By operating these water electrolysis systems with renewable energy sources, total greenhouse gas emissions associated with hydrogen production can be significantly reduced, resulting in a feasible solution for transitioning to a low-carbon economy [36–44]. Nonetheless, green hydrogen production using renewable energy faces several limitations. Firstly, there is a lack of analysis regarding the indirect greenhouse gas emissions inherent in the electricity generated from renewable sources. Even though renewable energy sources are clean, failing to account for the indirect greenhouse gas emissions generated during their production processes prevents an accurate assessment of the true environmental benefits of green hydrogen [45–50]. Secondly, the scope of greenhouse gas emission calculations is not clearly defined. Comprehensive analysis is required for emissions generated throughout the entire process, from raw material extraction to production (well-to-gate), transportation (well-to-port), and final use (well-to-wheel) [51–55]. Thirdly, a precise calculation of greenhouse gas emission factors is essential, and this would involve the application of emission coefficients specific to each energy source and technology to ensure accuracy in emission calculations [56–60]. Moreover, current electrolysis technologies still face challenges such as high levels of power consumption and cost issues. Specifically, the costs and environmental regulations associated with rare metals such as iridium and platinum, as well as membrane materials such as fluorine, which are essential components of the membrane electrode assembly (MEA) in electrolysis, pose significant hurdles. To overcome these challenges, global efforts are underway to reduce the use of rare metals and to explore various fundamental materials, such as porous metal–organic frameworks (MOFs) [61–65]. The infrastructure development necessary for the production, storage, transportation, and utilization of green hydrogen is still in its initial stages, requiring substantial investment. Calculation methods for greenhouse gas emissions serve as crucial tools for evaluating the environmental impact of green hydrogen production. Typically, the life cycle assessment (LCA) methodology quantifies greenhouse gas emissions at each stage of hydrogen production, encompassing raw material extraction, energy supply, hydrogen production, storage and transportation, and final use stages. Currently, most of the studies on greenhouse gas emissions are divided into two main approaches: LCA (life cycle assessment) analysis and methods that define their own assessment scope. These studies predominantly analyze the greenhouse gas reduction effects of new materials and technologies in sectors known for high emissions, such as the construction, transportation, and steel industries. While there is extensive research on the greenhouse gas emissions and reduction effects of using hydrogen as a fuel, including hydrogen transport and co-firing power generation with hydrogen produced from fossil fuels, additional research is needed on the production stage, including the raw materials produced for electrolysis systems. Comprehensive greenhouse gas calculations apply energy consumption and emission factors specific to renewable energy usage and electrolysis system efficiency. This approach is essential for objectively evaluating the actual greenhouse gas reduction effects of green hydrogen [66–71]. Thus, in order to fully replace fossil fuels with hydrogen as a primary energy source, it is essential to develop necessary technologies and simultaneously assess the actual greenhouse gas reduction effects of hydrogen through a life cycle assessment (LCA) analysis. Bareiß et al. [42] calculated the carbon emissions of hydrogen produced using a PEM system within Germany's integrated power grid and the projected energy grid scenarios for 2050. They found that as the use of renewable energy increased, carbon emissions decreased by approximately 60%. Krishnan et al. [47] evaluated the environmental impacts of design improvements in AWE and PEM systems using power supplied by the Netherlands' integrated power grid and offshore wind power. Zhao et al. [51] conducted an environmental impact analysis using primary data on raw materials for electrolysis stacks. However, these studies only focused on the greenhouse gas emissions of electrolysis stacks, without considering the overall lifecycle of hydrogen, including the balance of plant (BOP) components and power consumption for hydrogen production. This comprehensive analysis, therefore, remains necessary [72–74].

This study presents a comprehensive analysis of greenhouse gas emissions per kilogram of hydrogen produced using renewable energy-driven electrolysis. This analysis was conducted by tracking emissions from the extraction and processing of raw materials to the final hydrogen production stage. In previous LCA studies on hydrogen production using electrolysis systems, greenhouse gas emissions were calculated using projected values for the latest technologies. By contrast, this study presents a definition of the scope and impact of greenhouse gas emissions from hydrogen production by considering factors such as the raw materials needed for electrolysis systems, energy requirements, and necessary processing steps. Furthermore, this study was conducted via analyses and research using actual data. Aligning with recent carbon emission standards for clean hydrogen in South Korea, the aim behind this study was to clearly elucidate the environmental advantages of green hydrogen production using renewable energy sources and provide objective evidence to support the establishment of a viable hydrogen economy. Furthermore, in this study, effective strategies for greenhouse gas reduction were explored, including improving the efficiency of electrolysis technology and maximizing the utilization of renewable energy throughout the production process.

2. Materials and Methods

The Clean Hydrogen Certification System evaluates and certifies the environmental impacts of hydrogen throughout its entire lifecycle, from production to utilization. Its primary goal is to minimize the environmental footprint of hydrogen and promote sustainable energy transition.

Key aspects of the Clean Hydrogen Certification System include the following:

- Establishment of Evaluation Criteria: Evaluation criteria for clean hydrogen certification are primarily focused on greenhouse gas emissions generated during the hydrogen production process and are used to assess the environmental efficiency of hydrogen produced using various energy sources.
- Classification of Energy Sources: This system distinguishes between hydrogen produced using renewable energy sources (such as solar, wind, and hydroelectric power) and fossil fuels (like coal and natural gas). Hydrogen produced from renewable sources generally exhibits lower greenhouse gas emissions and can achieve higher certification grades.
- Evaluation of Production Processes: This aspect involves the evaluation of all greenhouse gas emissions produced during the hydrogen production process, including raw material extraction, electricity consumption, electrolysis processes, compression, and storage.
- Compression and Storage Processes: The environmental impacts of hydrogen compression and storage are also evaluated. High-pressure compression systems can induce additional greenhouse gas emissions, making the development of technologies to minimize these impacts crucial.
- Certification and Grading: Based on the evaluations above, hydrogen is classified into different grades, typically ranging from Grade 1 to Grade 4. These grades reflect the type and efficiency of energy sources used, with higher grades indicating greater environmental sustainability.
- Global Market Application: South Korea's Clean Hydrogen Certification System was developed in alignment with internationally recognized standards to maintain competitiveness in the global market and foster growth in the hydrogen economy. As a result, the Clean Hydrogen Certification System can be used to strengthen the sustainability of the hydrogen economy and play a significant role in addressing climate change challenges.

In this study, to analyze the carbon dioxide emissions of a green hydrogen production system utilizing 100% renewable energy, two assumptions were established, as follows:

(1) All energy required within the emission calculation scope is supplied by renewable energy generation, excluding fuel used for transportation.
(2) Within the emission calculation scope, the raw material extraction and processing stages only include the components necessary for electrolysis system production (out-housing, balance of plant, stack).

Under these conditions, the aim of this study was to provide a detailed analysis of the carbon dioxide emissions associated with green hydrogen production.

2.1. Scope of Greenhouse Gas Emission Calculation

For an accurate assessment of greenhouse gas emissions, establishing a comprehensive scope that covers the entire production process is essential. Therefore, the process in its entirety, from production to utilization, was meticulously examined in this study and delineated into three primary scopes. Firstly, the well-to-gate (WTG) scope encompasses all phases from raw material extraction to the finalization of hydrogen production, quantifying all direct and indirect greenhouse gas emissions generated during these operations. Secondly, the well-to-port (WTP) scope includes greenhouse gas emissions arising from hydrogen production, storage, and transportation phases, taking into account emission variations depending on the mode of transport. Thirdly, the well-to-wheel (WTW) scope spans across all stages until hydrogen reaches the end user, incorporating both WTG and WTP processes. Furthermore, it assesses greenhouse gas emissions occurring at the ultimate stage of hydrogen utilization [75].

Detailed factors and boundaries governing greenhouse gas emission calculations across the hydrogen lifecycle are illustrated in Figure 1 [76].

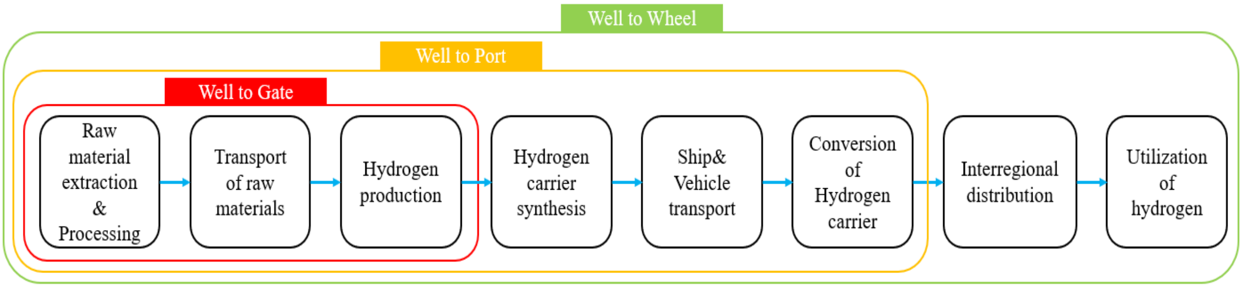

Figure 1. Boundaries governing greenhouse gas emission calculations of hydrogen [72].

The emission calculations for each scope are as follows.

For the WTG scope, emissions are calculated by summing emissions from raw material extraction, energy supply, and the electrolysis process.

$$E_{feedstock\ supply} + E_{energy\ supply} + E_{input\ materials} + E_{hydrogen\ production} + E_{compression} \quad (1)$$

For the WTP scope, emissions are calculated by adding emissions generated during storage and transportation to the well-to-gate emissions.

$$E_{systhesis} + E_{transportation} + E_{conversion} \quad (2)$$

For the WTW scope, emissions are calculated by including emissions generated at the final consumption stage to the well-to-gate and well-to-port emissions.

$$E_{distribution} + E_{CCS\ process} + E_{utilization} \quad (3)$$

To calculate the full lifecycle of hydrogen, a E_{WTW} (well-to-wheel) approach is typically applied, which includes E_{WTG} (well-to-gate) and E_{WTP} (Well-to-Plant) values, along with hydrogen transportation, CO_2 capture, and hydrogen utilization. These equations define the scope and boundaries for calculating carbon emissions from hydrogen production, storage, and utilization. Depending on how carbon emissions are calculated and which processes and systems are included in the assessment, additional detailed factors can be incorporated.

For example, calculating carbon emissions using the WTW (well-to-wheel) method can be performed to assess the entire lifecycle of hydrogen. However, for a more detailed calculation, carbon emissions from disposal and recycling processes can also be included. This ensures a comprehensive evaluation of the total carbon footprint of hydrogen throughout its lifecycle.

2.2. Clean Hydrogen Certification Standard

The increasing global focus on achieving carbon neutrality and fulfilling nationally determined contributions (NDCs) has brought the role of clean hydrogen to the forefront of global energy-related discussions. As countries grapple with the challenges of decarbonization, especially in energy-intensive sectors, they have actively been developing frameworks and support mechanisms to promote the production and use of clean hydrogen, tailored to their specific national conditions. One of the key initiatives in this domain is led by the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE). In 2021, the IPHE released methodologies for calculating greenhouse gas emissions to facilitate the certification of clean hydrogen. These methodologies cover essential components, such as how emissions are calculated, frameworks for implementation, and systems for tracking and managing certifications. The aim of this initiative is to establish standardized procedures that can be universally recognized, ensuring transparency and reliability in the process of certifying clean hydrogen across different countries. Complementing the IPHE's efforts, the International Energy Agency (IEA) has been instrumental in assessing and guiding the development of global certification schemes. In 2023, the IEA reported on the diverse designs of certification schemes adopted by various countries, emphasizing the need for these schemes to be adaptable to national contexts and recognizing the unique challenges and opportunities each country faces in integrating clean hydrogen into their energy systems. In the United States, the Inflation Reduction Act (IRA) introduced comprehensive standards for certifying clean hydrogen. These include specific emission benchmarks (measured in kilograms of CO_2 equivalent per kilogram of hydrogen produced) and a grading system based on emission levels. This framework aims to incentivize the production of hydrogen with lower greenhouse gas emissions, thereby supporting the transition to cleaner energy sources. Similarly, the United Kingdom has aligned its certification standards closely with those of the United States but has introduced distinct criteria to encourage the production of clean hydrogen within its own energy landscape. This approach reflects a nuanced strategy to harmonize global objectives with domestic priorities. Within the European Union (EU), the Renewable Energy Directive (RED II) plays a pivotal role in defining certification standards for hydrogen production. This directive takes into account the temporal and spatial relationships between hydrogen production and renewable energy generation. This holistic approach ensures that hydrogen certified under RED II effectively contributes to the EU's renewable energy targets while minimizing environmental impacts. Turning to Asia, Japan has been proactive in establishing certification standards for both clean hydrogen and ammonia. At the 2023 Hydrogen Strategy Conference, organized by Japan's Hydrogen Association and Clean Ammonia Association, these standards were introduced to promote the adoption of clean hydrogen technologies in the region. Japan's initiatives underscore its commitment to fostering a sustainable hydrogen economy, aligning with global efforts to mitigate climate change.

Therefore, the evolution of clean hydrogen certification schemes reflects a concerted global effort to accelerate the transition towards sustainable energy systems. The trends in these schemes, with their detailed descriptions as compiled in Table 1 [77–81], provide a comprehensive overview of how different countries are designing and implementing frameworks to support the deployment of clean hydrogen technologies amidst the imperative of climate-based action.

Table 1. Design criteria for certifying clean hydrogen.

Country	System Boundary	Emission Benchmark ($kgCO_2eq/kgH_2$)	Purity, Pressure	Support Budget
USA	Well-to-gate	4	99%, 3 MPa	USD 13 Billion
EU	Well-to-Wheel	3.4	99%, 3 MPa	USD 560 Million
UK	Well-to-Gate	2.4	99%, 3 MPa	USD 10 Million
Japan	Well-to-Gate	3.4		USD 44 Billion

In response to global developments, South Korea has recognized the importance of establishing standards for clean hydrogen, announcing the Clean Hydrogen Certification Guidelines in 2023. This initiative is aimed at ensuring the timely implementation of certification systems within national agendas and related frameworks, such as clean hydrogen development bidding markets. According to the guidelines unveiled, the assessment scope for greenhouse gas emissions of clean hydrogen is defined using the well-to-gate approach. Under this framework, hydrogen is categorized into Grade 4 if it emits 4 $kgCO_2eq$ or less per 1 kg of hydrogen, excluding emissions from ships. The emission levels for clean hydrogen corresponding to each grade are specified in detail in Table 2 [82–86]. This classification system not only underscores South Korea's commitment to align with international standards but also aims to foster a robust market for clean hydrogen, ensuring transparency and environmental accountability in hydrogen production and utilization. These guidelines were designed to support the broader goal of achieving carbon neutrality and meeting the nation's climate targets effectively

Table 2. Clean Hydrogen Certification Guidelines ($kgCO_2eq/kgH_2$) in South Korea.

Grade	1	2	3	4
CO_2 Emission	0~0.1	0.1~1	1~2	2~4

2.3. CO_2 Emission Factor

When estimating greenhouse gas emissions, the inclusion of emission factors is crucial. In this study, these are explained by dividing them into generation and consumption stages, based on greenhouse gas emission factors for electricity. During the electricity generation stage, emission factors are calculated separately for fossil fuel-based and renewable-energy-based generation. For fossil fuel generation, direct emissions resulting from the combustion of coal, natural gas, petroleum, etc., to produce electricity are quantified. For renewable energy generation, indirect emissions occurring during the construction and maintenance of power plants are considered. During the electricity consumption stage, indirect emissions occurring during the use of electricity are calculated. For both alkaline water electrolysis (AWE) and proton exchange membrane (PEM) electrolysis systems, indirect emissions due to electricity consumption are estimated. For PEM systems, emissions are also calculated considering additional system efficiency differences beyond electricity consumption.

$$\text{Greenhouse Gas Emissions} = \text{Emission Factor} \times \text{Energy Consumption} \tag{4}$$

The methodology for calculating greenhouse gas emissions in green hydrogen production involves a comprehensive approach across various stages. In the initial phase of electricity production, emissions are computed based on the energy mix used, with a focus on renewable sources such as wind or solar power, which primarily incur emissions during facility construction and maintenance rather than direct fuel combustion. During electricity consumption for hydrogen production, indirect emissions are calculated by multiplying electricity consumption and specific greenhouse gas emission factors, accounting for upstream emissions in the electricity supply chain. For hydrogen production via electrolysis powered by renewables, Scope 3 indirect emissions are considered, encompassing upstream activities such as raw material extraction, processing, and transportation related to electrolysis [83]. Emissions from transporting raw materials to and from production facilities are also included to provide a complete emissions profile. Finally, at the usage stage, emissions are assessed based on specific factors depending on how hydrogen is used, offering insights into its overall environmental impact throughout its lifecycle. The aim behind using this methodological approach is to obtain a detailed analysis of greenhouse gas emissions associated with green hydrogen production, supporting informed decision making towards sustainable energy solutions.

3. Results and Discussion

3.1. Electricity Grid Rate and CO_2 of Renewable Energy in South Korea

In this study, greenhouse gas emissions from green hydrogen production using actual renewable energy sources (hydropower, wind power, tidal power, and solar power) were calculated and compared. In the past, hydrogen energy lacked economic viability, but it has now reached a point where indirect economic benefits are being secured as environmental costs increase, such as those of greenhouse gas regulations. In this study, the potential of hydrogen energy as the most important means of energy transition was explored, with this reflecting the current situation. An analysis of South Korea's electricity production shows that the proportion of renewable energy is as follows: hydropower—1.17%, wind power—0.55%, and solar power—3.79%. The CO_2 emissions associated with these sources have increased in the order of hydropower, wind power, tidal power, and solar power, as depicted in Figure 2. While fossil fuels still dominate as the primary sources of electricity supply, the share of renewable energy is gradually increasing. This trend indicates that the expansion of renewable energy sources is essential for a sustainable electricity supply.

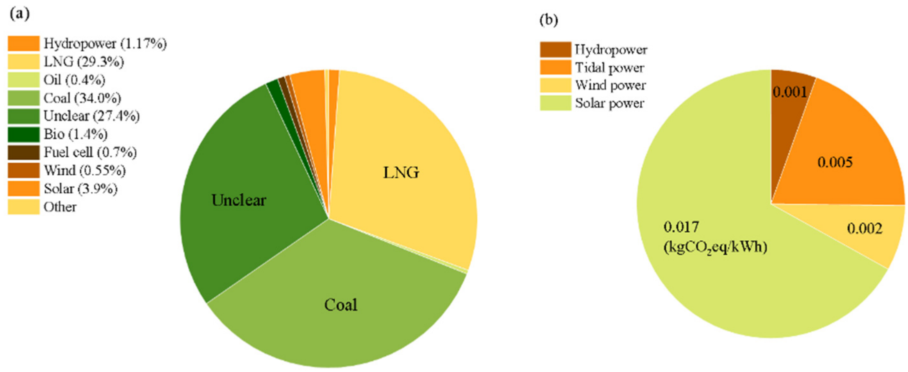

Figure 2. (**a**) Power grid composition and (**b**) greenhouse gas emissions according to renewable energy sources in South Korea ($kgCO_2eq/kWh$).

Moreover, the increase in renewable energy has contributed to a reduction in greenhouse gas emissions in South Korea. This reduction occurs because renewable energy sources produce electricity with lower or negligible CO_2 emissions compared to fossil fuels. As the share of renewables in the energy mix grows, overall greenhouse gas emissions from the electricity sector decrease. This shift underscores the importance of transitioning to renewable energy sources in order to mitigate climate change and achieve sustainable energy goals.

3.2. CO_2 Emissions According to Electrolysis Feedstock Materials

CO_2 emissions were calculated for electrolysis feedstock materials, assuming a capacity of 100 kW for both AWE and PEM systems. In both cases, outdoor housing exhibited the highest CO_2 emissions, followed by BOP (balance of plant) and then stack components, in descending order. Of particular significance is the fact that in the case of AWE systems, CO_2 emissions from the stack were more than twice those of PEM systems, with values of 8434 $kgCO_2$ and 3695 $kgCO_2$, respectively. This difference underscores the significant impact of metal processing, particularly the quantities of carbon steel and stainless steel, on CO_2 emissions. A comparison of CO_2 emissions is illustrated in Figure 3, with emission values specific to materials and processes sourced from Table 3. Operating conditions for electrolysis equipment are generally assumed to be 60 °C for AWE (alkaline water electrolysis) systems and 80 °C for PEM (proton exchange membrane) systems, with the operating pressure being below 5 bar rather than at high pressure. The raw materials used in the electrolysis system were the actual materials employed in its fabrication.

These findings highlight the importance of considering the environmental impact throughout the entire lifecycle of electrolysis systems. The production and assembly phases, especially involving metal-intensive components such as carbon steel and stainless steel, substantially contribute to the overall CO_2 footprint. Therefore, this necessitates strategies for optimizing material usage, improving manufacturing efficiencies, and exploring alternative materials with lower rates of environmental impact. Comprehensive lifecycle assessments, encompassing not only manufacturing but also transportation and end-of-life disposal, are crucial for accurately evaluating and mitigating the environmental consequences of green hydrogen production technologies.

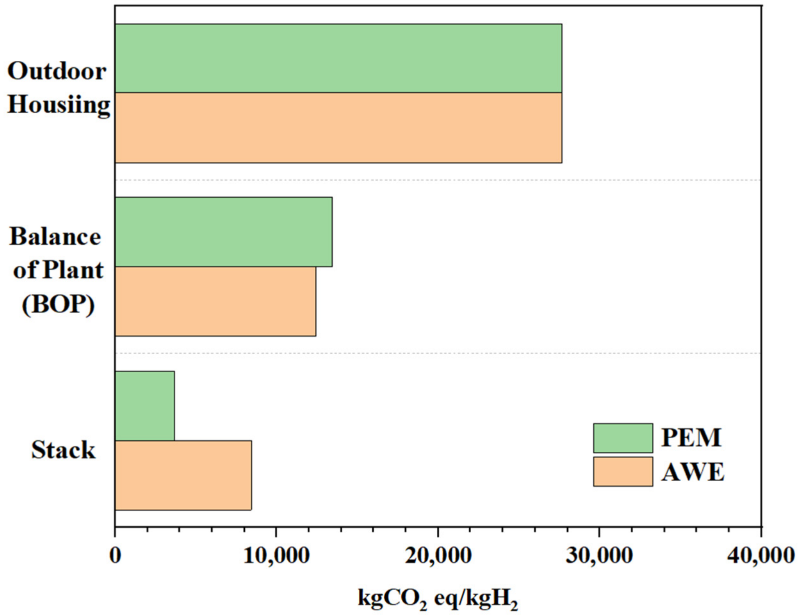

Figure 3. CO_2 emissions of materials according to electrolysis types.

Table 3. The amount of CO_2 emission produced of raw materials based on electrolysis components (kg).

Component	Materials	AWE	PEM
Stack	Carbon steel	822	6
	Stainless steel	1656	993
	Aluminum	244	1
	Transition metals	144	74
	Polypropylene	10	6
	Thermoplastics	240	10
	Polyvinylchloride	26	-
	etc.	4	71
BOP (Balance of Plant)	Carbon steel	1452	1648
	Carbon steel sheet	497	626
	Stainless steel	753	796
	Aluminum	509	526
	Transition metals	772	894
	Polypropylene	39	14
	Polyester	49	1
	Thermoplastics	157	164
	Polyvinylchloride	20	13
	Ceramic	63	63
	Silica	108	65
	Acrylonitrile butadiene styrene	92	-
	Thermoplastics	157	-
	etc.	34	52
Outdoor Housing	Carbon steel	11,040	11,040
	Carbon steel sheet	19	19
	Stainless steel	195	195
	Transition metals	241	241
	Thermoplastics	34	34
	Fluorescent lamps	85	85
	Exterior paint	330	330
	etc.	39	9

The amount of CO_2 emitted during the transportation of electrolysis feedstock materials varies depending on the mode of transport. Air transport emits approximately 0.001 $kgCO_2$ eq/kg*km, while shipping emits about 0.00005 $kgCO_2$ eq/kg*km. For domestic transportation by truck, the emission rate is approximately 0.0002 $kgCO_2$ eq/kg*km, resulting in air transport having the highest CO_2 emission rate per km. Nevertheless, shipping and truck transportation are the most commonly used methods in practice due to their cost-effectiveness and logistical feasibility. When considering a 100 kW electrolysis setup, the contribution of CO_2 emissions from shipping was found to be less than 10% when calculated based on the distance traveled. For instance, using Daejeon, a central city in South Korea, as a reference point, CO_2 emissions from the transportation of materials via trucks were observed to remain within a range of 5% at maximum, as indicated in Table 4 of this study.

Table 4. Amounts of CO_2 emission from domestic material transport in South Korea.

Region	Distance (km)	GHG Emissions ($kgCO_2eq$)	
		AWE	PEM
Seoul	161	638	579
Wonju	167	661	600
Cheongju	46	182	165
Daejeon	30	119	108
Jeonju	84	333	302
Gwangju	168	665	604
Daegu	153	606	550
Busan	260	1030	935

Therefore, in the calculation of CO_2 emissions associated with electrolysis feedstock production and transportation, a margin of error of up to 2–5% was considered to account for uncertainties in material production and transportation processes. This approach ensures a more comprehensive assessment of the environmental impact of electrolysis feedstock supply chains.

3.3. CO_2 Emissions during Hydrogen Production Process

The calculation scope for green hydrogen in South Korea simply includes the hydrogen production process, thereby facilitating a straightforward estimation of CO_2 emissions and classification according to energy sources and their efficiencies.

This comprehensive analysis is depicted in Figure 4. As shown in the figure, the graph shifts to the left with the increase in electrolysis system efficiency, indicating that higher efficiency of the electrolysis system results in a lower CO_2 emission rate. The formula for calculating the hydrogen production efficiency of the electrolysis system is as follows:

$$\text{Efficiency of electrolysis}(\%) = \frac{39.4\ \text{kWh}\ \times \text{Hydrogen production}\left(\frac{\text{kg}}{\text{h}}\right)}{\text{Capacity of electrolysis}(\text{kWh})} \times 100 \quad (5)$$

Notably, due to the comparatively high level of CO_2 emissions associated with solar power generation, the production of green hydrogen from solar sources typically remains classified as Grade 2, even when efforts are made to enhance electrolysis efficiency. By contrast, hydroelectric power retains its Grade 1 classification, even if its efficiency decreases slightly over time. Meanwhile, tidal power exhibits varying grades depending on its operational efficiency. Therefore, hydroelectric power is currently considered the most favorable energy source for green hydrogen production in South Korea. It is worth noting that South Korea has established an electrolysis efficiency standard of 55 kWh/kgH_2 for such evaluations, and this standard serves as a crucial reference point in assessing the environmental impacts and feasibility of green hydrogen production from renewable energy sources within the country.

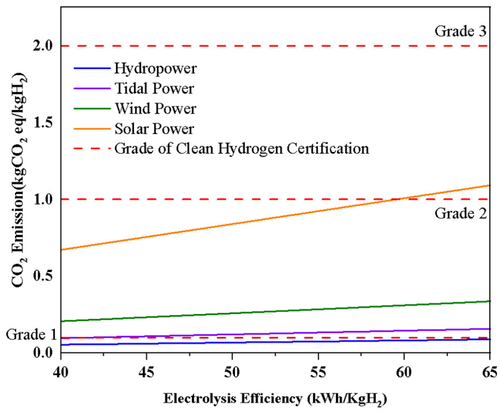

Figure 4. CO_2 emissions associated with different renewable energy sources based on their respective electrolysis efficiencies.

When considering the entire green hydrogen production process in actuality, the emission levels vary significantly. Firstly, in this study, raw materials were incorporated based on electrolysis configuration parameters and their subsequent transportation methods. Assuming a 100-kW electrolysis capacity, an additional 5% was included to account for electrolysis system transportation. It is important to note that electrolysis manufacturing is a one-time process, typically with a lifespan of 40,000 to 45,000 h. Currently, most green hydrogen certification schemes do not encompass emissions from compression and transportation processes; because hydrogen is primarily used in its compressed form, emissions from high-pressure compression must also be taken into consideration. Therefore, emissions were segmented into detailed categories for different compression levels in this study, as follows: 80 bar, 400 bar, and 700 bar. The overall system configuration is illustrated in Figure 5. Carbon emissions from the hydrogen compression process do not include the raw materials used in compression equipment such as storage tanks. Instead, calculations are focused on carbon emissions resulting from the power consumption required by the compression system. Nevertheless, it is important to highlight that even just the CO_2 emissions from the electrolysis system manufacturing process exceed the Grade 1 range for green hydrogen. Hydrogen refueling stations commonly compress hydrogen to 700 bar for storage and usage. This compression process constitutes a significant portion of CO_2 emissions, underscoring the urgent need for research and development in hydrogen storage and transportation technologies. In summary, a comprehensive lifecycle assessment reveals substantial disparities between the CO_2 emissions involved and those typically addressed by international green hydrogen certification standards.

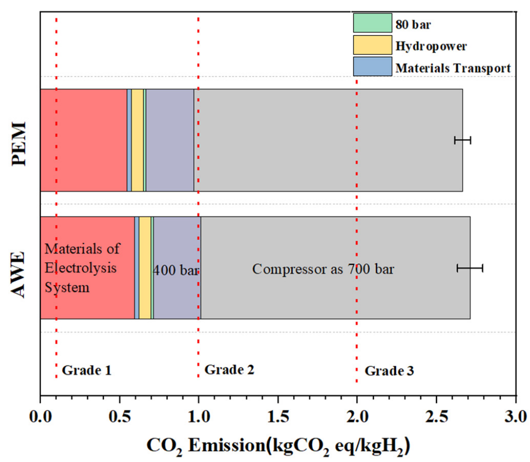

Figure 5. CO_2 emissions from electrolysis system configuration to compression.

4. Conclusions

In conclusion, this study provides a comprehensive assessment of green hydrogen's role within South Korea's energy landscape, focusing on its production from renewable energy sources such as hydropower, wind power, tidal power, and solar power. Historically, the utilization of green hydrogen has faced economic challenges, but recent advancements have positioned it to yield indirect economic benefits amid rising environmental costs, including stringent greenhouse gas regulations. This analysis underscores the pivotal role of hydrogen energy as a cornerstone of energy transition, reflecting current dynamics and potential future directions. Examining South Korea's electricity generation mix reveals a notable increase in the proportion of renewable energy sources, albeit from a relatively low base. Specifically, hydropower constitutes 1.17%, wind power constitutes 0.55%, and solar power constitutes 3.79% of the total energy mix. Despite their varying contributions, all renewable sources exhibit lower greenhouse gas emissions compared to traditional fossil fuels. Thus, this shift toward renewables is crucial for reducing overall greenhouse gas emissions from the electricity sector, emphasizing the necessity of expanding renewable energy capacities for a sustainable electricity supply. Evaluations of CO_2 emissions associated with electrolysis feedstock materials can provide critical insights into the environmental impacts of green hydrogen production—notably, that manufacturing and transporting electrolysis components contribute significantly to overall emissions. Another highlight of this study includes the finding that electrolysis systems, especially during their fabrication phase, emit substantial CO_2, with higher emissions associated with materials such as carbon steel and stainless steel. These findings challenge current green hydrogen certification schemes, which often do not comprehensively account for emissions from manufacturing and transportation processes. Furthermore, this study introduces a nuanced understanding of CO_2 emissions during the hydrogen production process itself via categorization of renewable energy sources based on their respective CO_2 emissions, revealing that solar power, despite its environmental benefits, may still fall into Grade 2 classification due to higher emissions associated with its lifecycle stages. By contrast, hydropower retains a Grade 1 classification, indicating its superior environmental performance and suitability as a primary energy source for green hydrogen production within South Korea. The establishment of an electrolysis efficiency standard at 55 kWh/kgH_2 serves as a pivotal benchmark for evaluating and improving the environmental performance of green hydrogen production. This standard guides efforts to enhance efficiency and reduce CO_2 emissions throughout the hydrogen value chain, ensuring alignment with sustainability goals and regulatory frameworks. Moreover, this study highlights the critical role of hydrogen compression in overall emissions. The compression process, particularly at high pressures such as 700 bar, significantly contributes to CO_2 emissions associated with hydrogen storage and transportation. Addressing these emissions necessitates innovative approaches and technologies to minimize environmental impacts and optimize energy efficiency in hydrogen utilization.

In summary, this comprehensive analysis underscores the importance of holistic lifecycle assessments in evaluating the environmental impacts of green hydrogen production, emphasizing the need for integrated approaches that encompass all stages of hydrogen production, from renewable energy generation to electrolysis manufacturing and hydrogen compression. By bridging these gaps and aligning with international standards, South Korea can foster a robust green hydrogen economy that decisively contributes to global efforts towards sustainable energy transition and climate change mitigation. Moving forward, continued research and development in hydrogen storage, transportation technologies, and efficiency improvements across the entire value chain will be essential to maximize the environmental benefits of green hydrogen and accelerate its adoption as a cornerstone of clean energy systems worldwide.

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