

Lifecycle Costs and Environmental Impacts of Emerging Clean Energy Systems: A Comparative Review of Green Hydrogen, Advanced Geothermal, and Solid-State Batteries

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Abstract:

This study analyzes the lifecycle costs and carbon emissions of three emerging clean energy technologies—green hydrogen, advanced geothermal, and solid-state batteries—based on published research findings and policy reports. Data were collected from multiple sources, including Google Scholar, Web of Science, CNKI, and regional government documents, and synthesized to enable a cross-technology comparison. The results indicate that comprehensive lifecycle cost data are still limited, as costs vary across regions and environments, and long-term expenditures such as decommissioning are rarely addressed. Similarly, inconsistencies in the methodologies used to calculate carbon emissions result in significant discrepancies, preventing a reliable comparison of environmental performance across technologies. Among the three systems, green hydrogen exhibits the highest lifecycle costs, suggesting that greater financial support may be required to improve its economic feasibility. In contrast, advanced geothermal and solid-state battery systems show relatively lower costs, though their reported emissions differ substantially due to regional variations in data sources. Overall, this review highlights the need for standardized methodologies and field-based assessments to ensure accurate and comparable evaluations of clean energy systems, thereby providing a more robust foundation for policy design and investment strategies.

Keywords: Advanced Geothermal Systems; Green Hydrogen, Solid-State Battery; Life Cycle Cost; Carbon Emissions, Electrolyzer.

1. Introduction

Clean energy refers to technological systems designed for the efficient and environmentally sustainable development and utilization of energy resources, with the primary objectives of reducing environmental pollution and greenhouse gas emissions. As an essential pathway toward sustainable development, clean energy encompasses solar, wind, hydro, geothermal, biomass, and hydrogen energy. In recent years, China has implemented a comprehensive policy framework to support clean energy development, with specialized government agencies established to oversee and promote related initiatives. These measures have generated measurable social and environmental benefits. For example, in 2016, China's annual biogas production reached 15.8 billion cubic meters, displacing 25 million tons of standard coal consumption and reducing annual CO₂ emissions by more than 60 million tons [1]. Despite such progress, the deployment of clean energy continues to face barriers. High initial investment costs for equipment, installation, and infrastructure remain a central obstacle. Renewable energy sources such as solar and wind also suffer from intermittency, which necessitates additional storage systems and further escalates overall costs. Moreover, insufficient policy support persists, as governments allocate substantially greater subsidies to fossil fuels like coal compared with clean energy [2]. Geographic factors have also led to uneven resource distribution in countries such as China, resulting in regional imbalances, while overcapacity in traditional fossil fuel power plants has caused significant curtailment of renewable power generation [3].

Most existing studies examining clean energy focus on the lifecycle cost or emissions of a single technology in isolation. Such analyses provide valuable insights but fail to capture broader trade-offs across different systems. Very few studies adopt a comparative perspective that integrates both economic and environmental dimensions, leaving a critical gap in the literature. Without such comparisons, policymakers and investors lack a robust evidence base for determining which clean energy technologies should be prioritized in terms of subsidies, research funding, and long-term development strategies.

This study addresses this gap by comparing the lifecycle costs and carbon emissions of three emerging clean energy systems: green hydrogen, advanced geothermal, and solid-state batteries. By integrating data from academic literature and policy reports, the analysis aims to provide a cross-technology perspective that informs both investment decisions and policy design. The findings are expected to contribute in two ways: first, by filling the research gap in comparative evaluations of clean energy technologies,

and second, by offering a reference point for governments seeking to design effective subsidy policies. The remainder of this paper is organized as follows: the first section outlines the background, current status, and challenges of clean energy development; the second section presents lifecycle cost and emissions data for the three technologies, supported by comparative tables; and the final section discusses their advantages, limitations, and implications, concluding with recommendations for future research.

2. Results

2.1 Presentation of key findings

2.1.1 Green Hydrogen System Cost Analysis

The core component of a green hydrogen system is the electrolyzer stack, which refers to an integrated system formed by interconnecting multiple electrolyzer cells in specific configurations, primarily designed for large-scale water electrolysis for hydrogen production or other electrochemical processes. The main electrolyzer types include alkaline water electrolyzers (AWE), proton exchange membrane electrolyzers (PEMWE), and solid oxide electrolysis cells (SOEC).

Green hydrogen continues to face economic challenges, primarily due to the high capital expenditure associated with electrolyzers and their periodic replacement costs. As shown in the lifecycle cost comparison, the total projected investment in green hydrogen systems is estimated between \$197.78 billion and \$679.2 billion, the highest among the three systems. Although global electrolyzer capacity is expected to increase significantly by 2030, the leveled cost of hydrogen remains higher than geothermal or battery systems.

The electrolyzer's capital expenditure (CAPEX) constitutes the largest portion of costs, accounting for 55% of the total, with unit costs ranging between \$500–1,400 per kilowatt [4]. By 2025, the total installed cost for alkaline water electrolysis (AWE) systems—including equipment, land, and installation—is projected to average \$800 per kilowatt [5–7].

Operational and maintenance (O&M) expenses also contribute significantly. Fixed O&M costs are estimated between \$20–40 per kilowatt annually, covering items such as labor and monitoring [5–9]. The primary variable cost comes from stack replacement, which occurs every 9–11 years and represents approximately 35% of the initial CAPEX, amounting to about \$175–490 per kilowatt [4]. Additionally, decommissioning and site restoration after decades of operation incur costs; 2023 figures indicate

these studies approximately \$100 per kilowatt [10-13].

Looking ahead, global electrolyzer capacity is anticipated to grow substantially. By 2030, installed capacity is forecast to reach between 124 million and 240 million kilowatts [14-16]. As a result, the total estimated investment in electrolyzers is projected to range from \$197.78 billion to \$679.2 billion.

On the environmental front, green hydrogen remains a minor segment within hydrogen production. According to International Energy Agency (IEA) data from 2021, the output of low-carbon hydrogen was below 1,000,000,000 kg kilograms globally [17]. As shown in Table 1, which indicating a relatively low environmental impact despite high costs.

2.1.2 Advanced Geothermal System Cost Structure

Advanced Geothermal Systems use technological innovation and engineering optimization to break through the constraints of traditional geothermal development, which enabling more efficient, flexible, and cost-effective utilization of geothermal energy.

Well drilling and completion constitute the major cost component in advanced geothermal systems, with significant upfront investment requirements. Although fixed operational expenses and the levelized cost of electricity remain relatively low, system performance and energy consumption vary considerably based on design and scale. As illustrated in the lifecycle cost comparison chart, the total investment for Advanced Geothermal Systems ranges between \$36.15 billion and \$97.62 billion, reflecting its substantial upfront capital requirements. Geothermal systems are characterized by long lifespans and low emissions, Table 1 indicates that its carbon emissions are significantly lower than other systems, at only 11,199 kg, highlighting its environmental advantage.

Well drilling and completion represent the largest cost component in advanced geothermal systems, constituting approximately 50% of the total CAPEX. These initial investments are estimated to range between \$1,870 and \$5,050 per kilowatt [18]. The utilization of Enhanced Geothermal Systems (EGS) further elevates costs, potentially reaching up to \$8,700 per kilowatt [19].

Fixed operational expenses scale with the size of the power plant. For instance, a 5 MW facility incurs annual fixed costs ranging from \$100,000 to \$400,000 [10]. The levelized cost of electricity, excluding fuel, remains relatively low, typically between \$0.01 and \$0.03 per kilowatt-hour [11].

Energy consumption varies significantly based on system design, scale, and operational conditions. For example, the geothermal system at the Indian Bowl buildings consumes 54,310 kWh annually, resulting in operational costs

between approximately \$543 and \$1,629 per year [12]. Wellfields generally have a lifespan of around 30 years, though specific decommissioning cost data are not yet available [12].

Global geothermal power generation capacity is projected to reach 19.33 million kW by 2025 [18]. Accordingly, the total estimated investment required ranges from \$36.15 billion to \$97.62 billion.

In terms of environmental performance, advanced geothermal systems exhibit low emissions. Geothermal heat pumps, for example, are projected to produce approximately 11,199 kg of CO₂ emissions in 2025 [18].

2.1.3 Solid-State Battery Energy Storage Cost Analysis

Solid-State Battery Energy Storage refers to battery technology that replaces traditional liquid or gel electrolytes with solid-state electrolytes, storing electrical energy and releasing it when needed. Its core feature is using solid materials (such as oxides, sulfides, or polymers) as ion-conducting media, enabling energy storage solutions with higher energy density, improved safety, and longer lifespan.

Solid-state battery technology faces relatively low total cost. The lifecycle cost comparison chart shows that solid-state battery storage requires an estimated total cost between approximately \$11.58 billion and \$14.16 billion, the lowest among the three systems. Despite potential advantages in reducing carbon emissions compared to conventional lithium-ion batteries, as presented in Table 1, its carbon emissions range from 2,319,700 kg to 2,699,979 kg, the overall cost structure remains substantial, influenced by efficiency losses and maintenance expenses.

The CAPEX for solid-state batteries, represented by Li-NMC technology, involves significant initial investment. Installation costs in 2020 averaged between \$352 and \$487 per kWh [14].

Operational and maintenance costs consist of both fixed and variable components. Fixed O&M expenses range from \$3.72 to \$4.55 per kW-year, while variable costs reach approximately \$521.5 per kWh [14]. An additional efficiency loss cost of about \$0.005 per kWh is incurred due to the system's 85% round-trip efficiency [14].

End-of-life management also contributes to the total cost. Decommissioning, which includes recycling and disposal processes, is estimated at \$50 to \$80 per kWh, though partial cost recovery is achieved through material recycling [14].

A 2023 report documented an annual energy consumption of 2,374 kWh for operational control, alongside a total annual energy throughput of 343,334 kWh, resulting in a combined total of 345,708 kWh. [15] The corresponding total cost is projected between approximately \$11.58 bil-

lion and \$14.16 billion.

Regarding environmental performance, while no direct emissions data are currently available for solid-state batteries, studies suggest they may reduce carbon emissions by 29% to 39% compared to conventional lithium-ion batteries [19]. Using the reference value of 11 kg CO₂/kWh for traditional lithium-ion batteries [19], solid-state battery emissions are estimated to range from 6.71 to 7.81 kg CO₂/kWh. Based on an annual energy consumption of 345,708 kWh, the total carbon emissions would therefore

lie between 2,319,700 kg and 2,699,979 kg.

2.2 draw a chart

Lifecycle cost comparison across different clean energy technologies is illustrated in Fig. 1. This chart integrates published cost data for green hydrogen, advanced geothermal, and solid-state battery systems, highlighting relative investment requirements and operational expenditures.

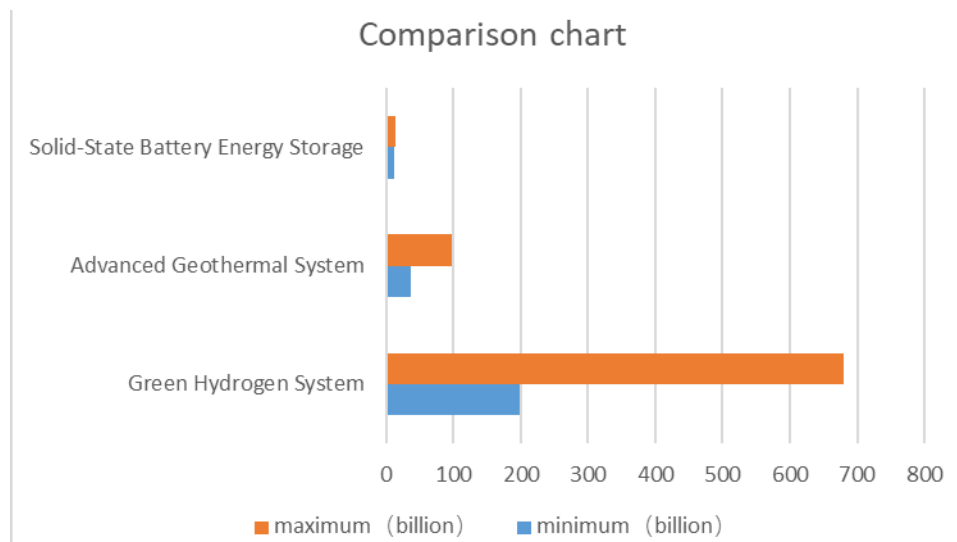


Fig. 1 Comparison chart of life cycle costs of various systems

From the figure, it can be seen that the cost of solid-state battery energy storage is relatively low. The cost is determined by the annual energy consumption of these systems, and solid-state batteries themselves can perform energy conversion, so the annual energy consumption is relatively low. In addition, this study cannot guarantee that all costs can be calculated, and some scattered costs may not have been studied.

A summary of carbon emissions associated with each clean energy technology is presented in Table 1. This table provides a direct comparison of reported values for green hydrogen, advanced geothermal, and solid-state battery systems, enabling an assessment of their relative environmental impacts.

Table 1. Data table of carbon emissions of various systems

Name of system	value(kg)
Green Hydrogen System	less than 1,000,000,000
Advanced Geothermal System	11,199
Solid-State Battery Energy Storage	2,319,700–2,699,979

From the above data chart, it can be seen that the carbon emissions of advanced geothermal systems are relatively

low, as geothermal systems are only frequently used in some regions during the summer and winter. The other two systems can be used throughout the year. The carbon emissions of the green hydrogen system are relatively high. However, the data source for this study on the green hydrogen system is global, while the other two are emissions from a specific region. Due to the different comparison ranges, some data may appear disproportionately large.

3. Conclusion

The results of this study reveal a clear trade-off among the three clean energy technologies. Solid-state batteries demonstrate relatively low upfront costs but are associated with higher lifecycle carbon emissions, reflecting efficiency losses and limited large-scale deployment experience. Advanced geothermal systems, in contrast, require substantial capital investment, primarily due to drilling and infrastructure costs, yet exhibit consistently low carbon emissions and long lifespans. Green hydrogen systems remain the most expensive option, largely driven by the high capital costs of electrolyzers and operational requirements; however, they hold the greatest potential

for decarbonization if coupled with low-carbon electricity inputs. Together, these findings underscore the complex balance between economic feasibility and environmental performance across different clean energy systems.

Compared with existing research, which often evaluates the lifecycle cost or emissions of a single technology in isolation, this study expands the scope by integrating a comparative analysis of green hydrogen, advanced geothermal, and solid-state batteries. Previous work, such as studies focusing exclusively on energy storage, provided valuable insights but lacked a cross-technology perspective. By situating these three systems within the same analytical framework, this study addresses a critical gap and offers a more comprehensive view of their relative trade-offs. Nevertheless, limitations remain. Lifecycle cost data are incomplete, with components such as decommissioning expenses and long-term material degradation rarely documented. Furthermore, available data are inconsistent across years and regions, leading to variations in cost and emission metrics that hinder systematic comparison. These limitations highlight the need for standardized methodologies and long-term tracking studies to ensure accuracy and comparability.

The findings carry several implications for both policy-makers and researchers. Governments seeking to accelerate clean energy deployment may consider targeted subsidies for green hydrogen to reduce its production costs and improve competitiveness, while promoting solid-state battery development could enhance economic feasibility in the absence of large-scale hydrogen adoption. From a research perspective, long-term field studies are essential to monitor operational performance and end-of-life costs, and the creation of an open-access global database for clean energy lifecycle inventories would significantly improve data reliability. Future research should also conduct comparative analyses across diverse policy contexts, regional conditions, and climate scenarios to better capture external influences. Such efforts will provide a stronger evidence base for strategic decision-making and sustainable investment in clean energy systems.

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