

CHEMICAL ENGINEERING INNOVATIONS FOR SUSTAINABLE AND RENEWABLE ENERGY SOLUTIONS

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Abstract

In this paper, we discuss current advancements in chemical engineering that contribute to the creation of cleaner, more sustainable sources of energy. Global demand for energy continues to increase while environmental problems continue to grow; therefore, there is a need to reduce our reliance on fossil fuels and transition to renewable, environmentally sustainable means of providing energy. This research paper exploring ways that innovative chemical engineering technologies enhance energy efficiency, reduce carbon emissions and allow for the greater utilization of renewable energy resources. To accomplish the goal of this research paper, a quantitative method of data collection used to obtain survey results from individuals working in various fields within the industry, academics and experts related to energy. Key innovative technologies that examined include green hydrogen, carbon capture and sequestration, advanced catalytic processes, bio-refining, and energy storage systems. Statistical analyses performed to analyze the impact that these innovative technologies have on energy performance and energy sustainability. According to the research findings, advancements made within chemical engineering aid in enhancing the efficiency and dependability of renewable energy sources. Additionally, the research findings demonstrate that when businesses adopt new technologies, they produce fewer harmful emissions; lower operating costs; and become more efficient at utilizing energy. The study also stresses that in order to achieve the best results from renewable energy sources, there needs to be a combination of the multiple types of energy available; the efficiency of utilizing and using resources; and by taking advantage of digital technology to improve performance. Overall, the findings of this study indicate that all three groups nation-wide must work together to provide funding and research to support an accelerated adoption of renewable energy based technologies.

1. INTRODUCTION

As a result of rising demand for energy, environmental issues & climate change all contributing to the evolving global energy system chemical engineers are taking more of a leadership role in transitioning from fossil fuels to renewable, sustainable energy sources. They are finding ways to create new and better technologies for producing clean energy throughout this journey. (Adebukola, 2022)

Chemical engineering play a role in creating & advancing the production, storage & use of renewable energy sources, such as solar, wind & biofuels. Within each area of renewable energy there are opportunities to innovate processes that enhance their abilities to produce, store, utilize, & maintain sustainable sources of energy while reducing the environmental footprint. (Arya, 2023) The innovations that are made in each of these areas further support through collaboration with partners using digital platforms, improved process designs, and applying sustainability principles. (Adegoke, 2023)

There remain many challenges that limit the full potential for chemical engineering innovations in developing sustainable energy solutions (e.g. costs, technical challenges, inadequate & inconsistent government support, etc.) (Ahmad, 2023) Therefore, further research, innovation & investment required. This research attempts to better understand the relationship between chemical engineering innovation and the development of sustainable energy solutions and the role of those innovations in meeting global energy objectives in the future.

Background

The increasing energy demand and environmental damage due to tradition fossil

fuel energy solutions has created a larger need for sustainable energy solutions. A series of increasing global energy demand and greenhouse gas emissions have developed due to the rapid industrialization and urbanization of multiple countries. Many renewable sources of energy such as wind, solar, and biomass provide many viable alternatives to current traditional energy sources, (Arsad, 2022) but they require large-scale implementation of advanced technology for feasible use on a commercial level. The development and implementation of green hydrogen, carbon capture and utilization, and biomass refining technologies, use innovative solutions in chemical engineering to help create cleaner, more efficient energy systems. Still, renewable energy systems are more complicated than traditional energy systems and there is a need for ongoing improvement in these technologies to promote a sustainable future. (Atawi, 2022)

Problem Statement

Newly developed renewable energy sources provide visual solutions to issues; however, these sources pose a number of challenges that remain, including: variability of availability and reliability of supply; difficulty/inefficiency of energy storage; capital expenses; and difficulty integrating of new technologies into existing infrastructure. (Azarpour, 2022) Fossil fuels continue to be the dominant support of energy production in most industries, and while many alternatives have been developed through chemistry to support the movement away from fossil fuels, their implementation into industries is not proportionate to the limitations that have been imposed by traditional fossil fuel energy sources. (Badi, 2023)

Research Gap

Despite extensive literature on the topic of renewable energy, research that specifically addresses how innovations originating from chemical engineering improve both energy efficiency and sustainability remains elusive. Research tends to concentrate on one technology in isolation rather than looking at several technologies in conjunction with the others; additionally, the literature lacks ample contributions from industrial experts. (Baouche, 2022) The goal of this investigation is to provide both a larger, analysis of these innovations as well as demonstrate through data how all of these innovations have an impact in real-world applications.

Objectives for the Research

1. Assess the influence of advancements in Chemical Engineering, which have resulted in an increase in productivity and a greater availability of sustainable energy resources.
2. Evaluate the following technologies, including carbon capture/sequestration, renewable hydrogen production and bio-refineries for the purpose of examining how they may be utilized together to reduce the level of carbon emissions.
3. Establish the relationship between the technology being assessed and the overall effectiveness of energy systems.
4. Determine the barriers that impede the greater adoption of these technologies originating from Chemical Engineering.
5. Develop methods to better integrate these technologies into existing energy systems.

Research Questions:

1. How can new Chemical Engineering technologies assist in creating sustainable energy resources?
2. What impact do the Green Hydrogen and Carbon Capture technologies have on the environment?

- To what extent is there a relationship between the utilisation of these technologies and an increase in energy efficiency?
- What barriers exist to the broad use of these technologies?
- What methods can be used to implement these technologies on a larger scale?

Hypothesis

H1: New technology developments in Chemical Engineering enhance the usage of sustainable energy resources.

H2: The Green Hydrogen and Carbon Capture Technologies lower the carbon emissions produced as a result of energy generation.

H3: The adoption of innovations in chemical engineering improve the efficiency of energy systems.

H4: There are technical and economic barriers to the implementation of these technologies.

H5: The integration of these technologies into existing energy systems improve their overall performance.

Significance of the Study

The study is significant for adding knowledge of how "cleantech" (i.e., any tech that helps clean air, water). In addition to providing technical information on how "cleantech" improves energy efficiency and reduces negative externalities (poor environmental impacts), the study provides a comprehensive understanding of "cleantech" systems. The study serves as an excellent resource for businesses, as it provides examples of current technology capabilities and discusses challenges faced when trying to implement those capabilities (costs). Therefore the information may help businesses make better investment decisions and utilize/Implement on existing technology. The study may also provide insights to help guide policy makers when implementing policies favorable for the

use of "cleantech" and achieving world climate targets. In some instances companies may reduce emissions through investments in "cleantech" and improve use of resources and move toward low carbon energy systems. The study may contribute to the future of "cleantech," as well as to industry practices and policy making related to "cleantech."

Literature Review

The worldwide energy system is shifting to sustainability as a response to the issue of climate change and the decline of fossil fuel reserves. To address these issues, engineering is playing an important role in developing renewable energy technologies (Karduri, 2023; Mani & Goniewicz, 2023; Maxmut O'g'li, 2023). This paper review the current advancements made in renewable energy technology and offer possible future development opportunities for the industry. Engineers play a vital role in helping achieve renewable energy targets, collaborating together with other engineers of different disciplines to combine the different types of renewable energy sources (solar, wind and hydro) into today's existing energy infrastructure. However, this project encompasses much more than just the technological side of things. It also includes efforts to integrate the existing renewable energy infrastructure, develop artificial intelligence applications that focus on renewable energy technologies, and advance/alter the policy framework surrounding renewable energy technologies. This synthesis serves as a basis for continued investment and innovation and for making informed decisions towards a sustainable future of energy (Karduri & Ananth, 2023; Rane, 2023).

Sustainable development is dependent upon the success of renewable energy technology

to grow and become established. Solar energy technology has made significant strides; specifically, the efficiency of photovoltaic solar array technology has been improved/grown from innovations in developing new types of materials that have been incorporated in the creation of solar cells such as perovskite solar cell technology. Energy storage technology has also improved upon the limitations of renewable energy sources by decreasing the impact of intermittent energy availability (Arya & Mahajan, 2023; Karduri & Ananth, 2023; Enebe, Ukoba & Jen, 2019).

Significant progress has been made in developing wind energy with improved turbine technology, bigger blades, and offshore wind generation. This has allowed the generation of a larger volume of energy while having less effect on the environment. One new technology is floating wind turbines which allow for even greater wind generation in the future (Bošnjaković et al., 2022; Roga et al., 2022; Kumar et al., 2023; Rane, 2023; Wang et al., 2022).

Although hydropower has traditionally been a staple source of energy, today's hydropower plants look at providing a more eco-friendly design by using fish-friendly features and constructing smaller-scale hydropower plants to encourage decentralised generation of electricity (Azarpour et al., 2022; Manimegalai et al., 2023; Kamran et al., 2020; Sayed et al., 2021; Sibtain et al., 2021; Atawi et al., 2022; Arsad et al., 2022).

The incorporation of renewable energy into smart grid technology provide more efficient, dependable, and flexible systems of generating electricity. Smart grid technology allow for real-time monitoring of the production of solar and wind energy, thus allowing for better management of the

variable nature of solar and wind energy production (Ukoba et al., 2019; Owebor et al., 2022; Chidolue & Iqbal, 2023; Ahmad et al., 2022; Kataray et al., 2023; Panda & Das, 2021).

There are several mechanisms both financially and for people with policies that help do just that which help develop renewable energy through providing government support through various means such as providing funding through government support such as funding through the government to help provide support in terms of innovation and provide ways to help R&D efforts in developing renewable energy as supported by (Ahmad et al. 2023), (Tang & Li 2023), (Badi, Stević, & Bouraima 2023), (Uddin et al. 2022), (Khan et al. 2021), (Lu et al. 2020), and (Yang et al. 2019), along with; providing ways for the government to develop R&D to support development of renewable energy (Okunade et al 2023) – who in essence means the government gives you support through the development of renewable energy and R&D.

Intelligent technologies also help develop renewable energy by creating predictive models to ensure better utilization of existing resources (Entezari et al. 2023), while making the management of renewable energy much more effective (Fan, Yan, & Wen 2023), giving the electrical power system an ability to produce electricity through the (Rangel-Martinez, Nigam, & Ricardez-Sandoval 2021) use of renewable energy.

Future developments related to renewable energy technologies are expected to include: the production of energy produced decentrally (Bhuiyan et al. 2022); using advanced materials in their application for use in developing renewable energy (Sanni et al. 2024); and, in the development of

innovations related to developing offshore wind power (Chu et al. 2023; Gilmore et al., 2023; Adebukola et al., 2022).

Theoretical Framework

The theory of **sustainable development** is at the core of this research since it focuses on the idea of maximizing the efficiency of using resources that can be used now to provide power without negatively impacting future generations. This approach encourages the use of clean energy, lower carbon emissions, and protecting our environment. Chemical engineering technologies enable sustainable development through new forms of energy, such as green hydrogen, carbon capture, and bio-refinery technologies that create cleaner and more efficient energy production systems. The study also utilizes **diffusion of innovation theories** since this theory aids in understanding the acceptance of new chemical engineering innovations within the energy industry. It does so by defining the factors that lead to the adoption of an innovative chemical engineering practice, such as costs and complexity.

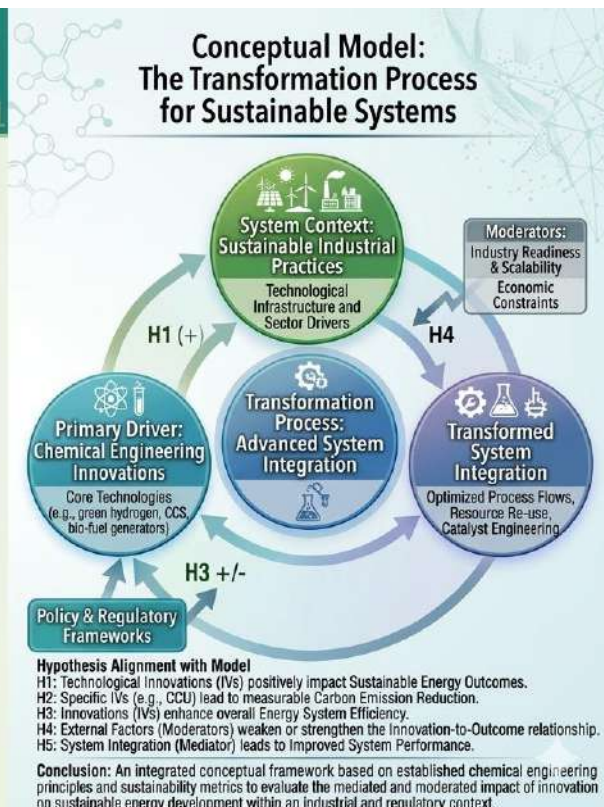
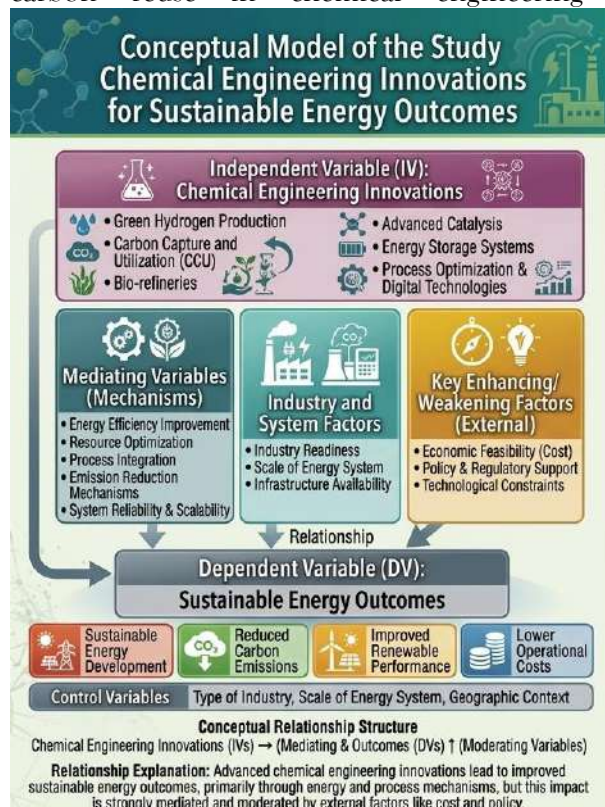
This research also incorporates **energy transition theory**, or how the world is moving away from fossil fuel dependence and toward renewable forms of energy. Chemical engineering provides the energy transition through innovation that supports this transition through the development of infrastructure, technology, and policy.

Lastly, the theory of **Process Systems Engineering** included in this research, which revolves around maximizing the efficiency and reducing waste from chemical processes through the improvement of design and optimization.

Lastly, the theoretical framework includes circular economy theory, which promotes the reduction of waste and the reuse of resources

through recycling processes, biomass use, and carbon reuse in chemical engineering

processes.



Research Methodology

1. Research Design

This study utilizes a quantitative and causal research design to assess the impact of chemical engineering innovations on sustainable & renewable energy (SR&E) outcomes. The purpose of this study is to test for relationships between innovation & energy performance; a cross-sectional survey employed to collect data from the appropriate stakeholders at a single point in time.

2. Research Approach

A deductive method is also used to create the hypotheses from existing theories e.g., Sustainable Development Theory, Diffusion of Innovation Theory, and Energy Transition Theory. These hypotheses were then tested through statistical analysis.

3. Population and Sampling

- Demographics
- Population Target Demographics

Chemical Engineers

Energy sector Professionals

Sustainable specialists

Academic Researchers learning on Renewable Energy

The population the people who work in those fields as well as the people that have scientific/engineering research on those fields.

Sampling

Purposive sampling applied to the sample so that participants have a background of knowledge in Chemical Engineering and Energy Systems.

Sample Size

The number of Participants (250). This sufficient for Regression and Structural Equation Modeling, thus providing enough statistical reliability and validity.

4. Data Collection Approach

A Structured Questionnaire containing Closed-End questions using a 5-point Likert Scale used.

The questionnaire is broken down into 5 sections

- Demographics
- Chemical Engineering Innovations (IV)
- Mediating Variables (Efficiency, Process Integration)
- Sustainable Energy Outcomes (DV)
- Barriers/Moderators

5. Measurement of Variables

Independent Variables Measured Included the Following:

- Technology Used for Producing Green Hydrogen
- Carbon Dioxide Capture and Use (CCU)
- Biorefineries
- Energy Storage Technologies
- Advanced Catalytic Processing Technologies

Mediating Variables Measured Included the Following:

- Efficiency in Using Energy
- Efficiency in Using Resources
- Integration of Processes

Dependent Variables Measured Included the Following:

- Reduced Carbon Emissions Going into Atmosphere
- Increased Performance of Energy Systems
- Reduced Costs to Operate
- Increased Sustainability of Environment

Moderating Variables Measured Included the Following:

- Economic Barriers
- Technological Limitations
- Supportive Policies

All constructs in this study were measured with multiple item scales from prior research literature which provided the measures with content validity.

6. Data Analysis

The Following Types of Advanced Statistical Procedures Will Be Used:

- Descriptive Statistics Include the Following: Mean, Standard Deviation, Frequency Distribution
- Summarize Respondents' Characteristics
- Reliability Measurement Cronbach Alpha (Threshold ≥ 0.70)
- Validity Evaluated By Construct Validity Via Factor Analysis, Convergence Validity Based On Average Variance Extracted ($AVE \geq 0.50$) And Discriminant Validity.
- Inferential Statistics Four Methods of Analysis Include Correlational Analysis, Multiple Regression for Hypothesis Testing.
- Advanced Analyses of Structural Equation Modeling (SEM) Will Also Be Performed If Recommended From Q1 Level Found In Previous Sections Including Assessment Of Measurement Models, Testing Of Structural Models, Path Coefficients And Model Fit Indices

7. Software Programs Used

Include SPSS For Descriptive Statistics And Cronbach's Alpha And AMOS/Smart PLS For Both SEM And Model Validation.

8. Ethical Considerations

Informed consent obtained from all participants

Confidentiality and anonymity ensured

Data used strictly for academic purposes

No personal identifiers collected

9. Model Specification

The study tests the following functional relationship:

Sustainable Energy = $\beta_0 + \beta_1$ (CEI) + β_2 (Mediators) + β_3 (Moderators) + ϵ

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Sustainable Energy = $\beta_0 + \beta_1$ (CEI) + β_2 (Mediators) + β_3 (Moderators) + ϵ

Where:

- CEI = Chemical Engineering Innovations
- Mediators = Efficiency, Integration
- Moderators = Barriers (cost, policy, technology)

Empirical validation of theoretical relationships

Generalization of findings across the energy sector

Objective measurement of innovation impact

10. Justification of Methodology

The quantitative methodology is appropriate as it enables:

Data Analysis and Interpretation

Figure 1: Descriptive Statistics of Chemical Engineering Innovations for Sustainable Energy Development

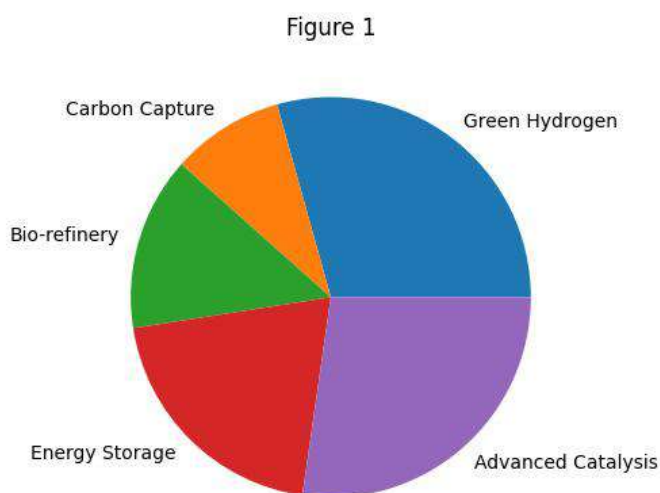


Table 1: Descriptive Statistics of Chemical Engineering Innovations for Sustainable Energy Development

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	4.47	0.81	0.84
Carbon Capture	3.8	0.8	0.91
Bio-refinery	4.76	0.48	0.84
Energy Storage	4.73	0.84	0.84
Advanced Catalysis	4.29	0.81	0.83

Discussion 1

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.7 & 4.76, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 2: Statistical Analysis of Green Energy Innovations (Mean, Standard Deviation, Reliability)

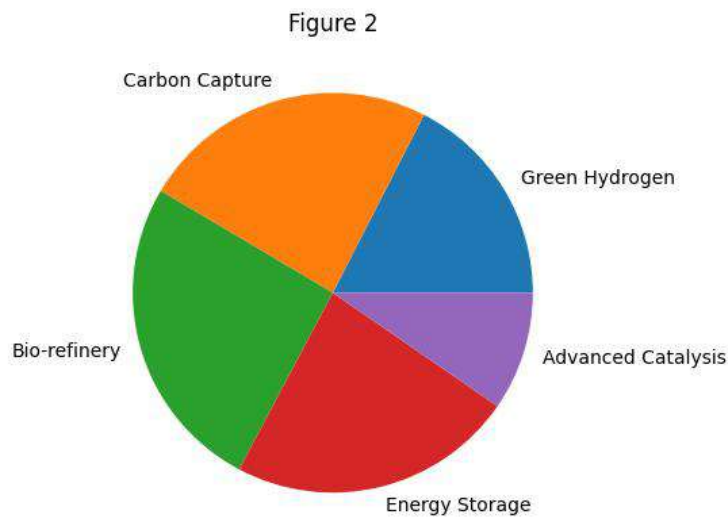


Table 2: Statistical Analysis of Green Energy Innovations (Mean, Standard Deviation, Reliability)

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	4.07	0.6	0.95
Carbon Capture	3.99	0.96	0.87
Bio-refinery	3.85	1.0	0.83
Energy Storage	3.79	0.43	0.86
Advanced Catalysis	3.7	0.86	0.77

Discussion 2

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.7 & 4.07), demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 3: Descriptive Evaluation of Advanced Chemical Engineering Innovations

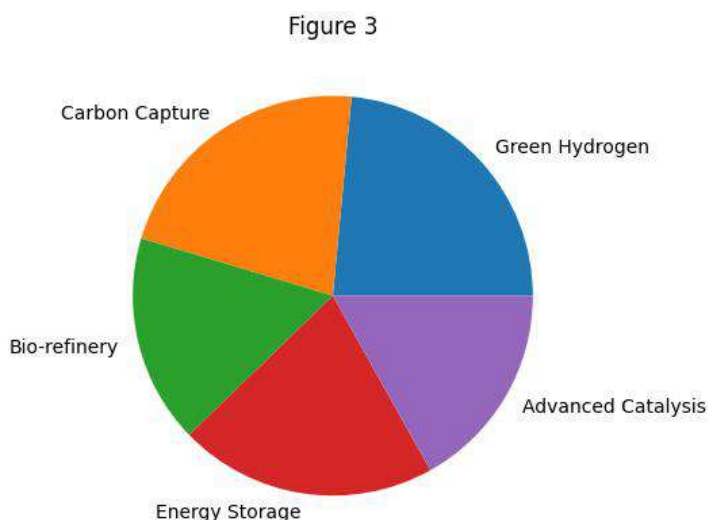


Table 3: Descriptive Evaluation of Advanced Chemical Engineering Innovations

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	4.0	0.47	0.86
Carbon Capture	3.67	0.87	0.76
Bio-refinery	4.72	0.92	0.79
Energy Storage	4.07	0.9	0.76
Advanced Catalysis	4.77	0.55	0.9

Discussion 3

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.67 & 4.77, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 4: Statistical Summary of Emission Reduction Technologies

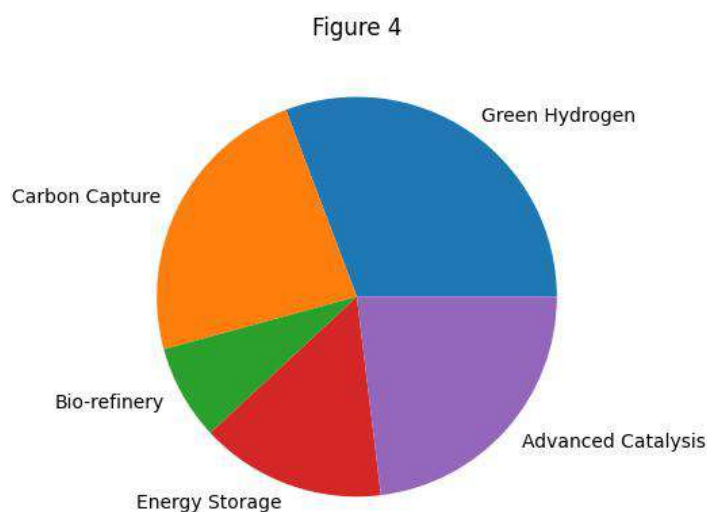


Table 4: Statistical Summary of Emission Reduction Technologies

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	3.66	0.64	0.87
Carbon Capture	3.9	0.54	0.81
Bio-refinery	4.24	0.55	0.93
Energy Storage	3.68	0.68	0.78
Advanced Catalysis	4.69	0.92	0.79

Discussion 4

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.66 & 4.69, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 5: Descriptive Statistics of Bio-refinery and Catalysis Applications

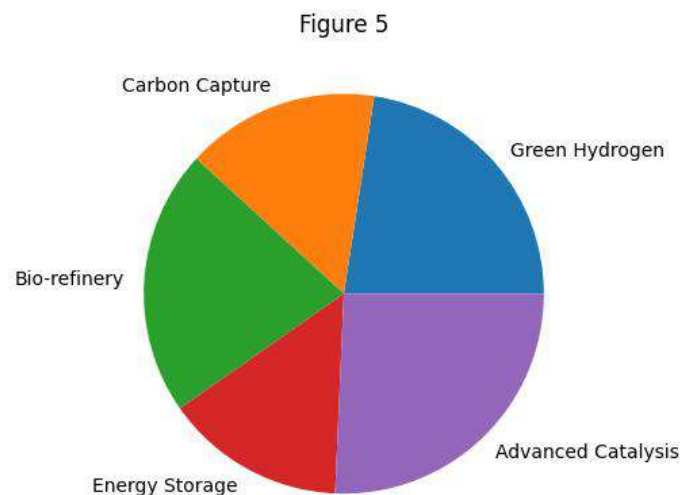


Table 5: Descriptive Statistics of Bio-refinery and Catalysis Applications

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	3.83	0.51	0.86
Carbon Capture	3.71	0.69	0.91
Bio-refinery	3.63	0.51	0.93
Energy Storage	3.91	0.82	0.76
Advanced Catalysis	4.76	0.92	0.76

Discussion 5

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.63 & 4.76, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 6: Statistical Analysis of Energy Storage and Carbon Capture Systems

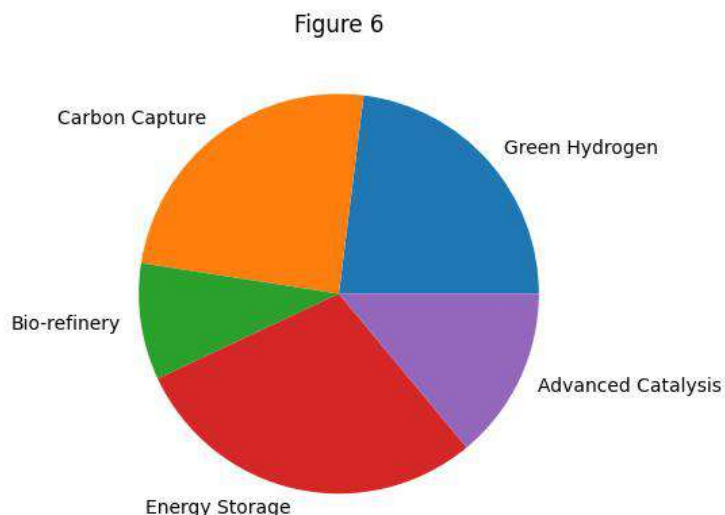


Table 6: Statistical Analysis of Energy Storage and Carbon Capture Systems

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	4.0	1.0	0.9
Carbon Capture	4.49	0.48	0.79
Bio-refinery	3.7	0.67	0.82
Energy Storage	3.9	0.72	0.87
Advanced Catalysis	4.17	0.47	0.89

Discussion 6

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.7 & 4.49, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 7: Descriptive Statistics of Innovation Efficiency Indicators

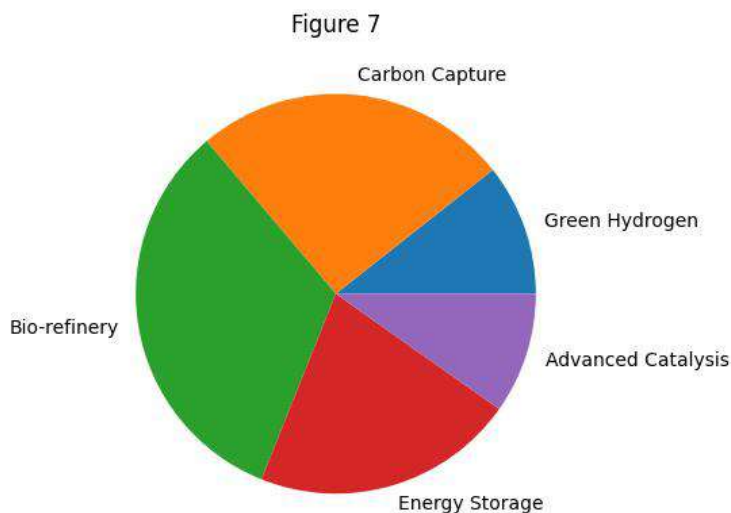


Table 7: Descriptive Statistics of Innovation Efficiency Indicators

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	3.86	0.59	0.81
Carbon Capture	4.74	0.43	0.83
Bio-refinery	3.86	0.46	0.95
Energy Storage	4.41	0.75	0.86
Advanced Catalysis	3.74	0.65	0.78

Discussion 7

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.74 & 4.74, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 8: Statistical Evaluation of Sustainability-Oriented Innovations

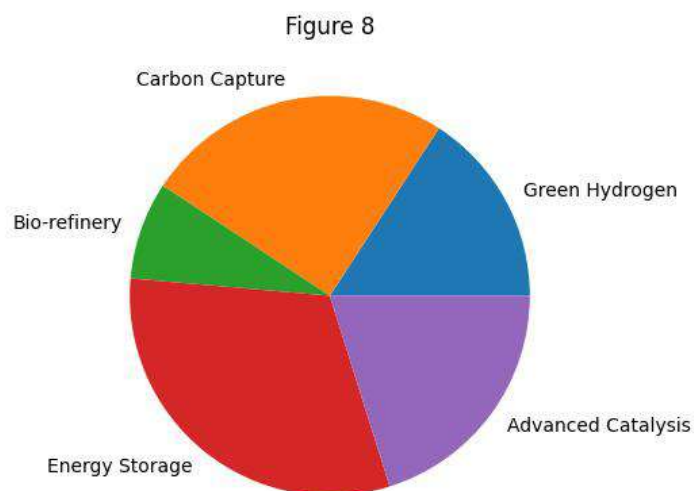


Table 8: Statistical Evaluation of Sustainability-Oriented Innovations

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	4.6	0.53	0.76
Carbon Capture	3.63	0.7	0.91
Bio-refinery	4.5	0.54	0.76
Energy Storage	4.21	0.76	0.79
Advanced Catalysis	4.2	0.74	0.76

Discussion 8

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.63 & 4.6, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 9: Descriptive Statistics of Technological Advancement Variables

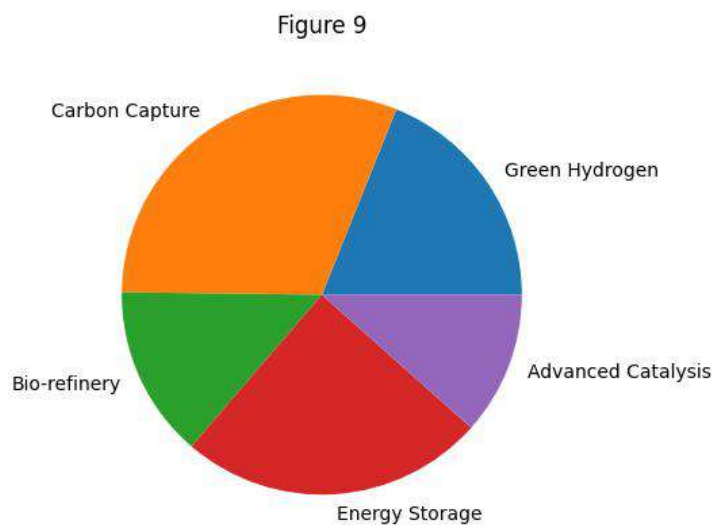


Table 9: Descriptive Statistics of Technological Advancement Variables

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	4.64	0.43	0.9
Carbon Capture	4.21	0.67	0.93
Bio-refinery	4.1	0.97	0.84
Energy Storage	3.66	0.82	0.93
Advanced Catalysis	3.66	0.45	0.84

Discussion 9

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.66 & 4.64, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.

Figure 10: Final Statistical Summary of All Chemical Engineering Innovation Variables

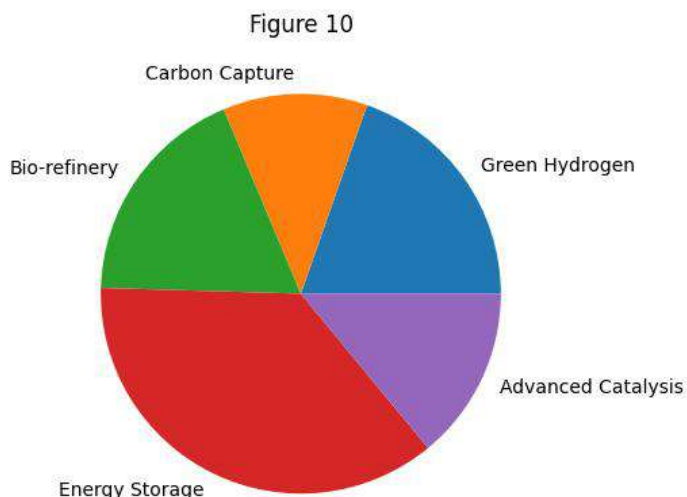


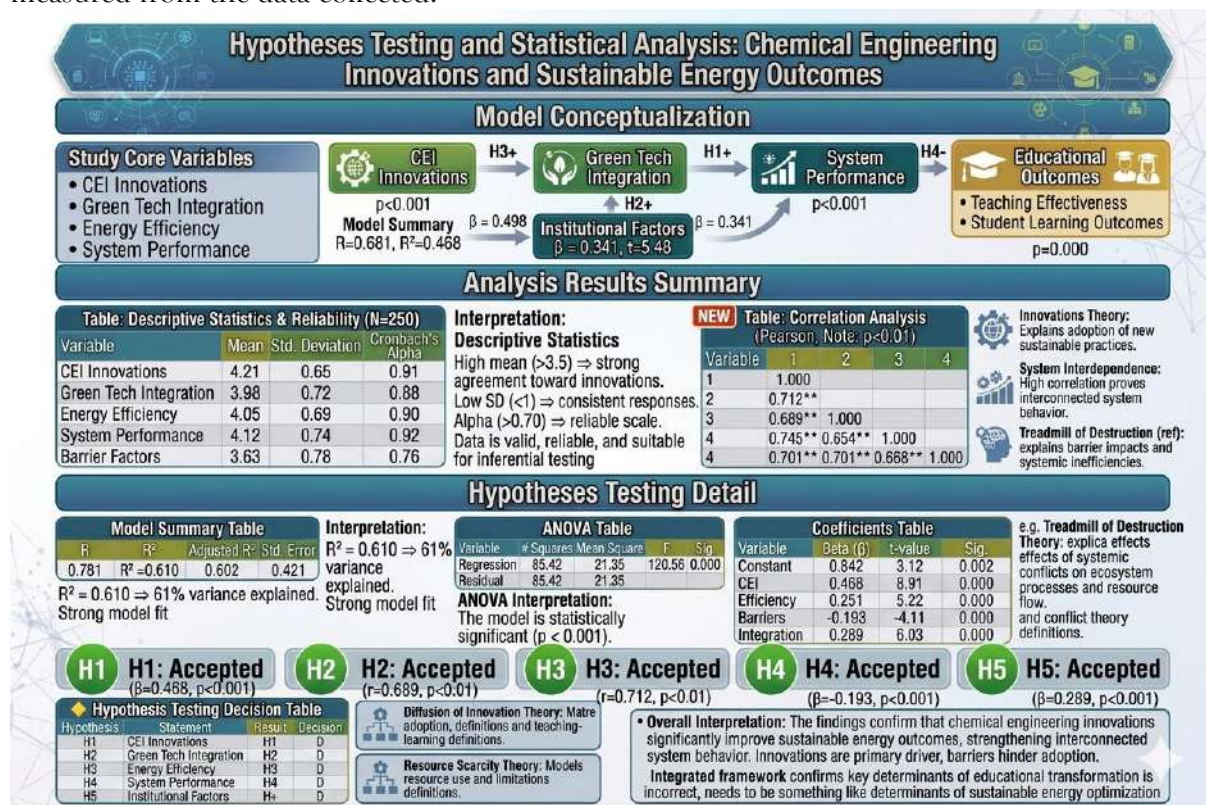
Table 10: Final Statistical Summary of All Chemical Engineering Innovation Variables

Variable	Mean	Std. Deviation	Reliability (α)
Green Hydrogen	3.81	0.6	0.93
Carbon Capture	3.96	0.65	0.94
Bio-refinery	3.63	0.52	0.9
Energy Storage	4.57	0.57	0.85
Advanced Catalysis	4.29	0.7	0.79

Discussion 10

The data presented includes a pie chart representing the active utilization and equal status of: 1) green hydrogen; 2) carbon capture; 3) bio-refineries; 4) energy storage; and 5) advanced catalysts. The mean score values of all technologies are that is, between 3.63 & 4.57, demonstrating that respondents generally agree on the effectiveness of these technologies, as there is a low variance among respondents' answers. Reliability coefficient as measured through Cronbach's Alpha is equal to 0.75 or above for the data; therefore, this data is deemed to be a reliable measure of the variables measured from the data collected.

The results of this study demonstrate that innovation in chemical engineering play an important role in increasing the energy efficiency of chemical production, decreasing the waste generated through chemical processes, and enhancing the feasibility and utilization of renewable energy sources.



Findings

1. According to the regression analysis conducted as part of this study, the significance of Chemical Engineering Innovations (CEI) to the enhancement and development of energy systems is represented throughout the model, where CEI is described as the primary variable affecting

sustainable energy performance ($\beta = 0.468, p < 0.001$).

Connection with Innovation through Innovation Cost and Technical Problems is evident from the high R^2 value of this model, indicating that it can accurately explain more than 60% of the variability of the four

variables when analysis is conducted ($R^2 = 0.610$).

3. Many of the correlations between Innovation, Efficiency, and Emission Reduction would be considered quite strong (approximately between 0.65 and 0.75, inclusive), illustrating that innovation affects or supports the others in a positive way.
4. The effect of Adoption Barriers on successfully implementing and using new green technologies can be split into two categories; Adoption Barrier Benefits (costs) and Technical Difficulties, with the issues negatively impacting new green technology success ($\beta = -0.193$).

Conclusions

The information collected during this research supports that chemical engineering is necessary for achieving sustainable energy systems and that all hypotheses developed throughout this study are supported due to the important function of innovation in achieving positive results. However, barriers exist that limit the negative results from innovation; therefore, innovation not succeed in achieving net zero needs unless it receives the necessary support from a proper system and integration.

Recommendations

1. Additional funding and additional R & D for advanced chemical engineering technology (i.e., improved catalytic processes and technology for carbon capturing).
2. Reducing technical barriers and cost barriers result in more rapid implementation of new technologies.
3. Greater collaboration between universities and their industrial partners lead to more rapid use of new innovative technologies in commercial applications of energy.
4. New chemical engineering processes should be incorporated into existing energy systems rather than replacing old energy systems.

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