iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 Issue: VI Month of publication: June 2025

DOI: https://doi.org/10.22214/ijraset.2025.72749

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Advancement of Greenhouse Gas Incorporating the Sustainable Systems-Thinking Scheme by Employing Profitable Hydrogen Production

Sk Insaruddin[1], Prof. Abhijit Mangaraj[2]
[1]MTech Environmental Engineering, College: GIFT Autonomous, Bhubaneswar, Odisha, India
[2]Civil & Environmental Engineering, College: GIFT Autonomous, Bhubaneswar, Odisha, India

Abstract: With an emphasis on the incorporation of cost-effective hydrogen generation technologies, this dissertation explores the control of greenhouse gas emissions from the perspective of a sustainable systems-thinking scheme. There is an urgent need for long-term, creative solutions to reduce emissions of greenhouse gases as the world struggles to cope with the worst effects of climate change. By conducting a thorough literature analysis, this study delves into the state of greenhouse gas management techniques and highlights the power of systems-thinking ideas to develop long-term, all-encompassing plans.

Underlying this research are the theoretical frameworks of systems-thinking and the function of hydrogen in renewable energy infrastructures. A thorough evaluation of several technologies for producing hydrogen, considering their efficiency, cost, and influence on the environment, is a part of the study approach. Finding solutions that are both financially feasible and effective in lowering emissions of greenhouse gases is the goal.

This dissertation explores the creation and evaluation of efficient methods for producing hydrogen, with an eye toward their potential incorporation into larger sustainable systems. Case studies provide valuable insights into real-world issues by demonstrating how techniques might be used in practice. Findings are critically examined in the results and comments section, which offers implications for sustainable systems development and greenhouse gas management.

This study adds to the continuing conversation about long-term strategies for managing greenhouse gas emissions by presenting a systems-level plan based on efficient hydrogen generation. Policymakers, businesses, and academics may use the offered suggestions as a road map to a more sustainable future by adopting policies that are both ecologically responsible and financially feasible.

Keywords: Electrolysis, Emission, Greenhouse, Hydrogen, Renewable Energy, Sustainable.

I. INTRODUCTION

Our approach to the management of greenhouse gases (GHG) has been forced to undergo a paradigm shift because of the growing significance of the danger posed by climate change. To solve this essential, the purpose of this research is to investigate the possibility of incorporating a sustainable systems-thinking scheme with the usage of technologies that are cost-effective for producing hydrogen. This study was motivated by the rising knowledge of the interconnection of environmental, economic, and social systems, which highlights the need of developing solutions that are both comprehensive and sustainable in order to address climate change. In response to the growing danger posed by climate change, which is exemplified by the widespread influence of greenhouse gas (GHG) emissions on the climate of the Earth, there has been a widespread need for immediate and efficient steps to mitigate the effects of climate change. The deficiencies of conventional methods to greenhouse gas management, which often fail to adequately address the whole complexity of the problem, highlight the critical nature of this call for action. These techniques tend to ignore the complex web of interactions that exist within natural and human systems, which are a contributing factor to the ongoing deterioration of the environment. Considering these constraints, there is a rising recognition of the need of a paradigm shift toward solutions that are more holistic and integrated. It is in this setting that systems thinking emerges as a strong theoretical framework, giving a holistic viewpoint that takes into consideration the interdependencies and feedback loops that are inherent in the vast fabric of environmental and social systems.

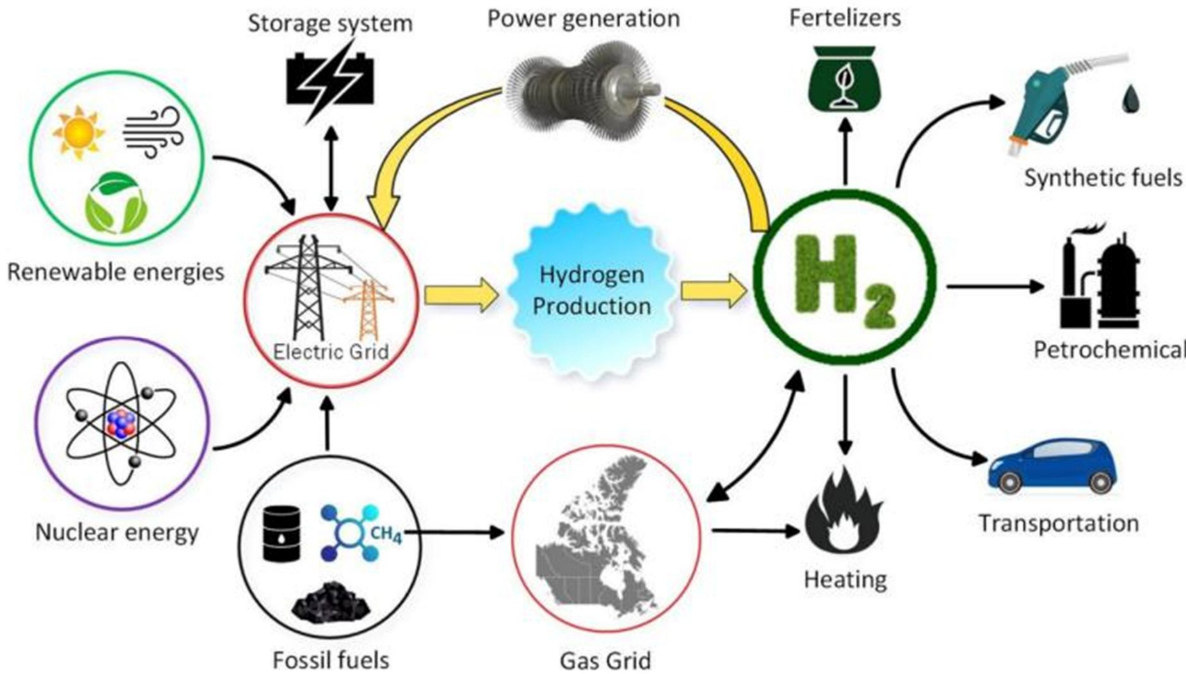


Figure 1.1:Hydrogen production

The traditional dependence on fossil fuels for the generation of energy is a significant contributor to the significant amounts of greenhouse gas emissions that are now being produced. This dependence not only makes the climate situation worse, but it also brings to light a systemic challenge that is already present in the energy systems that are now in place. For this reason, sustainable systems thinking becomes an absolute need to handle the environmental repercussions of energy production while also taking into consideration the wider socioeconomic effects. This method recognizes the necessity for a synergistic link between environmental sustainability and economic viability, and its goal is to understand and maximize the numerous connections that exist between the many components of the systems.

Figure 1.2: Greenhouse gas using the sustainable systems-thinking

The investigation of alternative energy sources that not only reduce the amount of damage done to the environment but also have the potential to be profitable is an essential component of the paradigm of sustainable systems thinking. As a result of the inherent features that it has as a clean and diverse energy carrier, hydrogen has emerged as a viable contender in the search for solutions that are sustainable in terms of energy. Hydrogen is a powerful fuel that can decouple the production of energy from greenhouse gas emissions, therefore offering a route towards a future energy system that is low in carbon emissions.

The incorporation of hydrogen into the energy landscape, on the other hand, is not without its difficulties. To evaluate the practicability and scalability of hydrogen generation systems, one of the most important factors to consider is how cost-effective they are. The larger objective of developing sustainable energy systems is inextricably linked to the economic sustainability of hydrogen generation via the production of hydrogen. Therefore, to bridge the gap between environmental sustainability and economic viability, it is vital to have a complete grasp of the cost dynamics of the various techniques of producing hydrogen.

In addition to the environmental imperative, the realization of the interdependence of environmental, economic, and social systems is a driving force behind the pursuit of alternative energy sources, notably hydrogen. Both factors contribute to the urge to investigate these sources. Within the framework of this discussion, sustainable systems thinking transforms into a guiding philosophy that places an emphasis on the need of taking an integrated and comprehensive approach to the resolution of issues. By using this framework, the study endeavours to decipher the complexities of greenhouse gas management and energy transition, while also recognizing the fluid and linked character of the difficulties that are now being faced.

Figure 1.3: Greenhouse

Within the context of this networked environment, the dissertation intends to investigate the possibility of combining a cost-effective hydrogen generation technology with a sustainable systems-thinking scheme. The investigation is being carried out using a multidisciplinary approach that incorporates elements from the fields of environmental science, engineering, economics, and systems theory. The project seeks to provide not just theoretical insights but also practical techniques for lowering greenhouse gas emissions and developing sustainable energy practices. This will be accomplished by exploring the complicated interactions that exist between the many components of the energy and environmental systems.

The motivation for this dissertation stems from the realization that there is an immediate and pressing need to address the widespread influence that greenhouse gas emissions have on the climate of the Earth. It recognizes the limits of existing methodologies and argues for a paradigm shift towards sustainable systems-thinking, highlighting the interconnection of environmental, economic, and social systems. The project aims to create a complete framework for the advancement of sustainable energy solutions in the face of the global climate catastrophe. This will be accomplished via the investigation of hydrogen as a clean energy carrier and the evaluation of production technologies that are cost-effective.

A. Motivation

1) Environmental Imperative

The urgent need to address the growing danger presented by greenhouse gas (GHG) emissions and to minimize the far-reaching repercussions of climate change were the driving forces behind this study. The environmental motivation for this research is strongly entrenched in the urgent need to address these threats. Traditional methods of energy production, which are primarily dependent on fossil fuels, are substantial contributors to the greenhouse effect, which in turn intensifies global warming and disruptions associated to climate change. The search for a sustainable energy alternative that does the least amount of damage to the environment is the impetus behind the need of shifting the emphasis to hydrogen generation that is both cost-effective and efficient. Hydrogen, when harnessed via ecologically acceptable ways, provides a chance to decouple energy production from greenhouse gas emissions, so contributing to the global necessity of transitioning towards a low-carbon and environmentally responsible energy future. Hydrogen can be created using environmentally friendly processes.

Figure 1.4:Environmental Imperative

2) Systems-Thinking Philosophy

It is the recognition that environmental concerns, especially those associated with greenhouse gas emissions, are fundamentally intertwined with larger socio-economic systems that serves as the impetus for the incorporation of a systems-thinking approach. In order to get a comprehensive comprehension of the dynamic links that exist between the many components of these systems, systems thinking offers a vital conceptual framework that permits this knowledge. Systems thinking supports a more complete and integrated approach to problem-solving by acknowledging and embracing the complexity of the relationships that are being considered. Under the circumstances of this investigation, the concept of systems thinking emerges as a guiding philosophy that places an emphasis on the need of taking into account the interdependencies and feedback loops that exist within natural and human systems when developing strategies for the control of greenhouse gas emissions. For the purpose of generating sustainable solutions that meet the myriad of issues posed by environmental deterioration, this comprehensive viewpoint is very necessary.

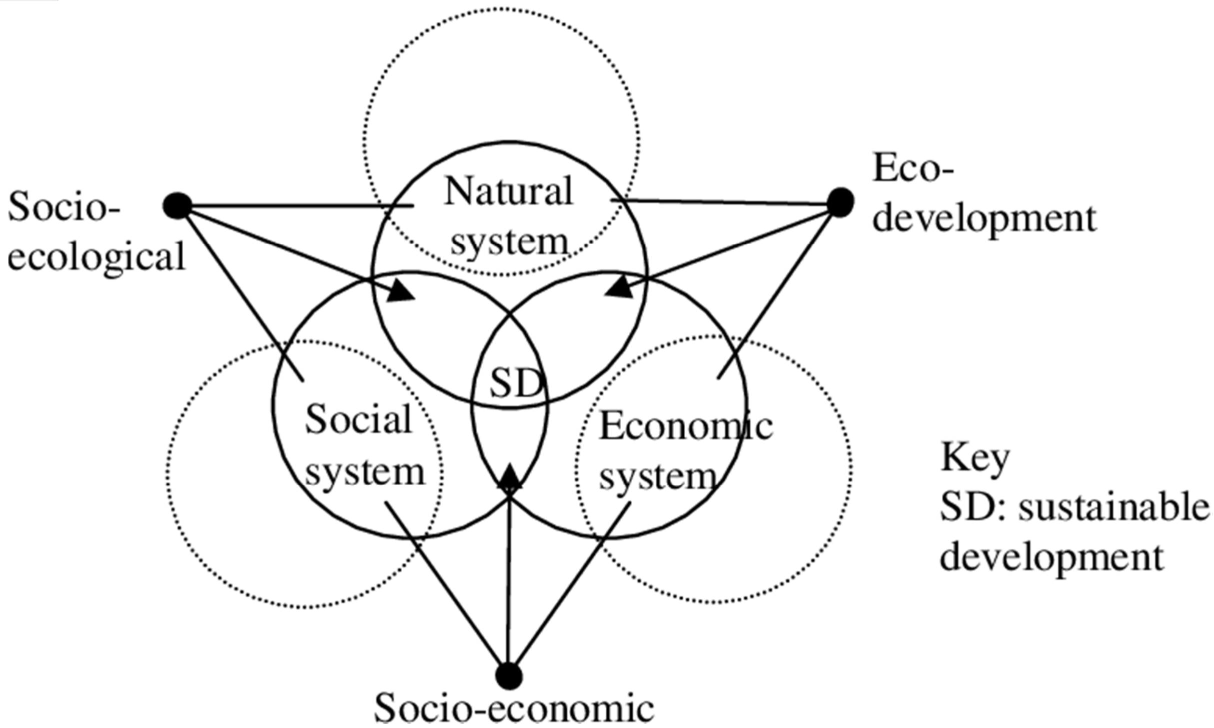


Figure 1.5: Systems-Thinking Philosophy

3) Hydrogen as a Sustainable Energy Carrier

The revolutionary potential of hydrogen within the energy landscape is the driving force behind the exploration of hydrogen as a major component in the sustainable systems-thinking scheme. The production of hydrogen using techniques that are less harmful to the environment results in the creation of a clean and adaptable energy carrier that has the potential to change a variety of different industries. In addition to the conventional methods of energy generation, its applications also include the transportation and manufacturing processes used in industry. The realization of hydrogen's ability to play a crucial role in decreasing dependency on fossil fuels and lessening the environmental effect of energy use is the impetus behind the positioning of hydrogen as a cornerstone of sustainable energy solutions. With this recognition comes the drive to position hydrogen as a cornerstone. The purpose of this study is to contribute to a paradigm shift toward energy practices that are cleaner and more sustainable by using hydrogen as a sustainable energy carrier.

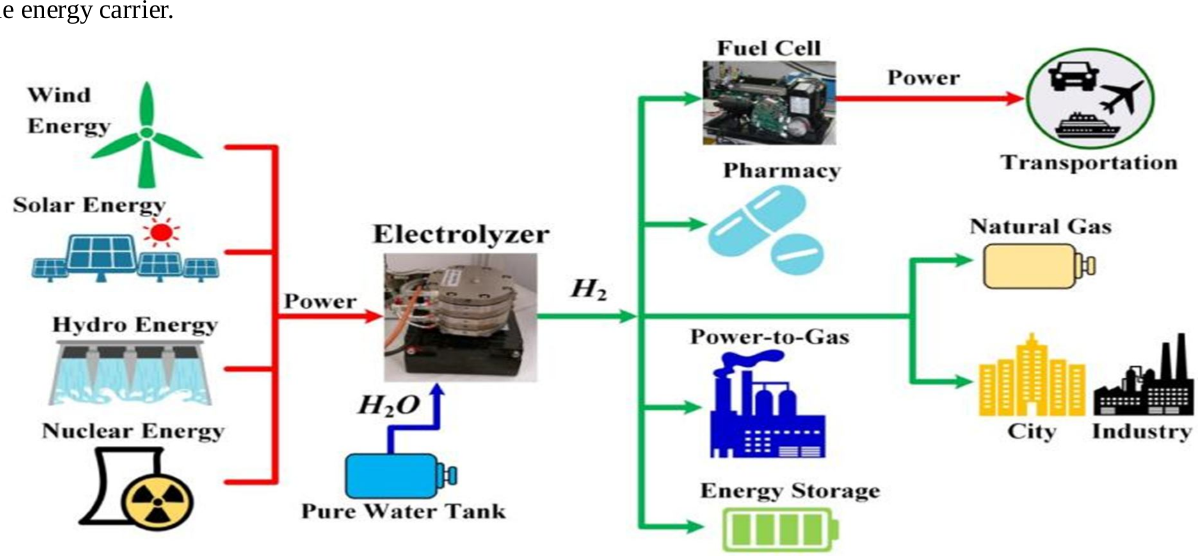


Figure 1.6: Hydrogen as a Sustainable Energy Carrier

4) Economic Viability

The identification and evaluation of cost-effective ways for the generation of hydrogen is the purpose behind this endeavour. This is in recognition of the economic problems that are connected with moving to sustainable practices. For the purpose of bridging the gap between environmental sustainability and economic viability, this part of the study is vital. In order to establish the practicability and scalability of hydrogen generation technologies on a worldwide scale, one of the most important factors to consider is the economic feasibility of these approaches. The purpose of this study is to illustrate that ecologically sensitive practices, such as the use of hydrogen as an alternative energy carrier, may be in harmony with long-term economic objectives. The study makes a significant contribution to the understanding of the potential for sustainable energy solutions to be not only environmentally responsible but also economically feasible in the long term. This is accomplished by evaluating the economic feasibility of various techniques of hydrogen generation.

Figure 1.7:Economic Viability

5) Practical Implementation

This study is being conducted with the intention of transforming theoretical frameworks and research results into methods that can be put into practice. This is the practical motive for this research. In addition to being an intellectual exercise, the investigation of sustainable systems thinking in conjunction with cost-effective hydrogen generation is a practical activity that aims to affect the results that occur in the actual world. The purpose of this study is to give insights into the actual application of sustainable energy solutions by analysing case studies and examples from the real world. This requires having a grasp of the difficulties and achievements that are associated with integrating the generation of hydrogen into pre-existing systems, whether those systems are related to energy infrastructure, transportation, or industrial operations. The objective is to make it easier to make the transition to a future that is low in carbon emissions and sustainable by providing advice that are both concrete and practicable. These recommendations are intended to aid governments, industry, and communities in adopting behaviours that are environmentally sensitive. In addition, this component of practical application highlights the dedication to bridging the gap between the results of research and the real adoption of sustainable energy practices on a worldwide scale.

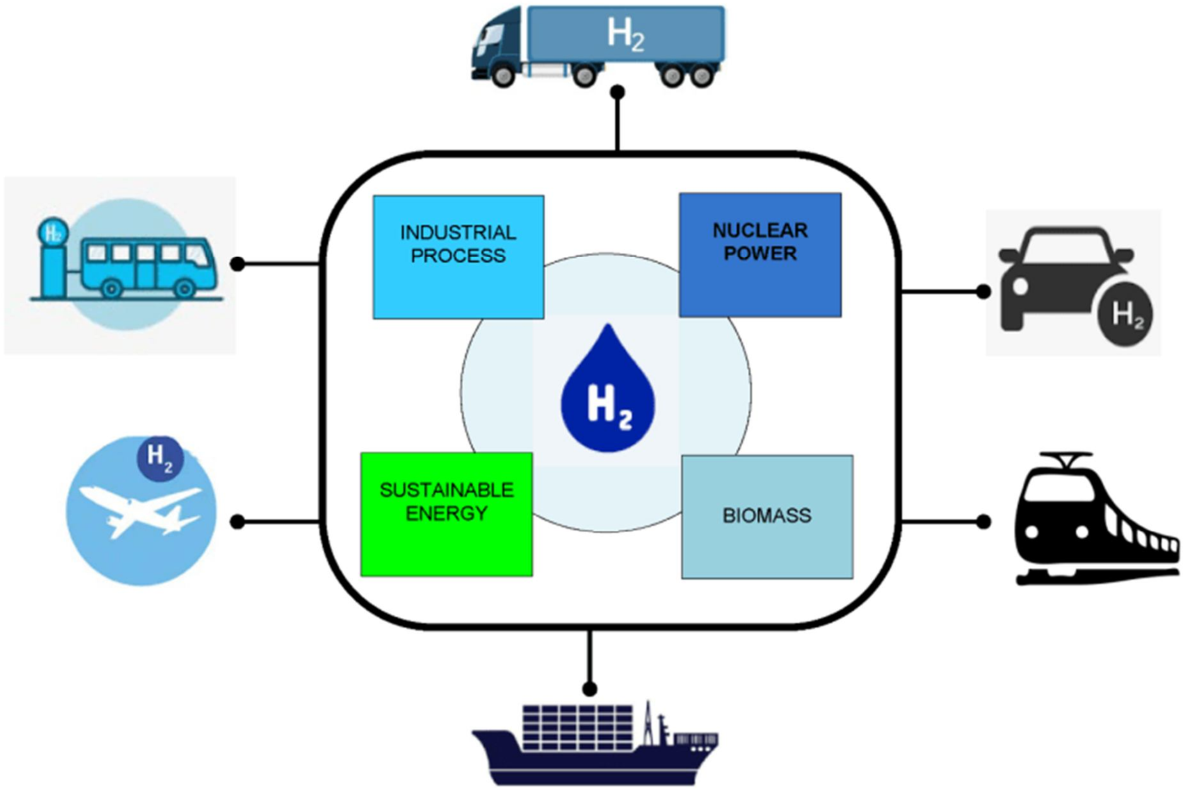
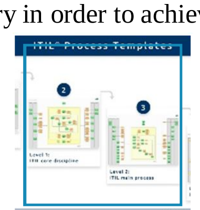
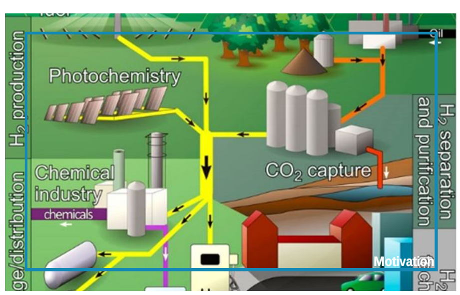
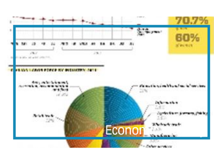


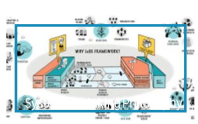
Figure 1.8: Practical Implementation

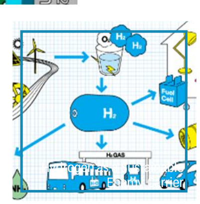
The urgent need to address climate change via a strategy that is both integrated and sustainable is the driving force for this dissertation. The research aims to contribute meaningful insights that transcend disciplinary boundaries by combining the principles of systems thinking with the exploration of cost-effective methods for producing hydrogen. This will help to foster a holistic understanding of greenhouse gas management, which is necessary in order to achieve a resilient and sustainable future.











International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

II. MATERIALS & METHODS

The imperative to manage greenhouse gas (GHG) emissions and transition towards sustainable energy solutions has spurred a wealth of research across interdisciplinary domains. This literature review provides an overview of key findings related to the management of GHGs through the lens of sustainable systems thinking, with a specific focus on cost-effective hydrogen production.

A. Greenhouse Gas Management

The global consensus on the severity of climate change has fuelled extensive research on GHG management. Traditional approaches, often sector-specific and reduction-centric, have been critiqued for their limited effectiveness in addressing the systemic nature of the issue. Scholars advocate for a holistic approach that considers the interconnectedness of natural and human systems. This foundational understanding aligns with the principles of sustainable systems thinking, emphasizing the need to view GHG management as an integrated challenge requiring comprehensive solutions.

Figure 2.1: Greenhouse Gas Management

B. Sustainable Systems Thinking

The theoretical framework of sustainable systems thinking has gained prominence in environmental management literature. It offers a holistic perspective by considering the intricate web of interactions within complex systems. This approach acknowledges the interdependencies and feedback loops inherent in environmental challenges, advocating for solutions that address the root causes rather than focusing solely on symptomatic treatments. The integration of systems thinking into GHG management strategies represents a paradigm shift towards a more interconnected and sustainable approach.

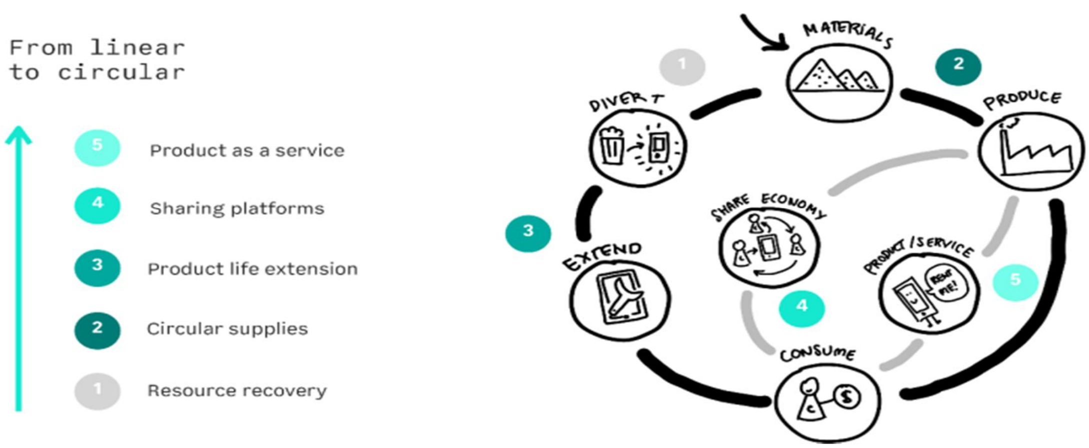


Figure 2.2: Sustainable Systems Thinking

C. Hydrogen Production as a Sustainable Energy Carrier

The exploration of hydrogen as a clean and versatile energy carrier is a prominent theme in the literature. Hydrogen stands out as a potential solution to decarbonize various sectors, including transportation and industry. The literature highlights the importance of environmentally friendly hydrogen production methods, such as electrolysis powered by renewable energy sources or methane reforming with carbon capture and storage. The versatility of hydrogen positions it as a key player in the transition towards a low-carbon energy future.

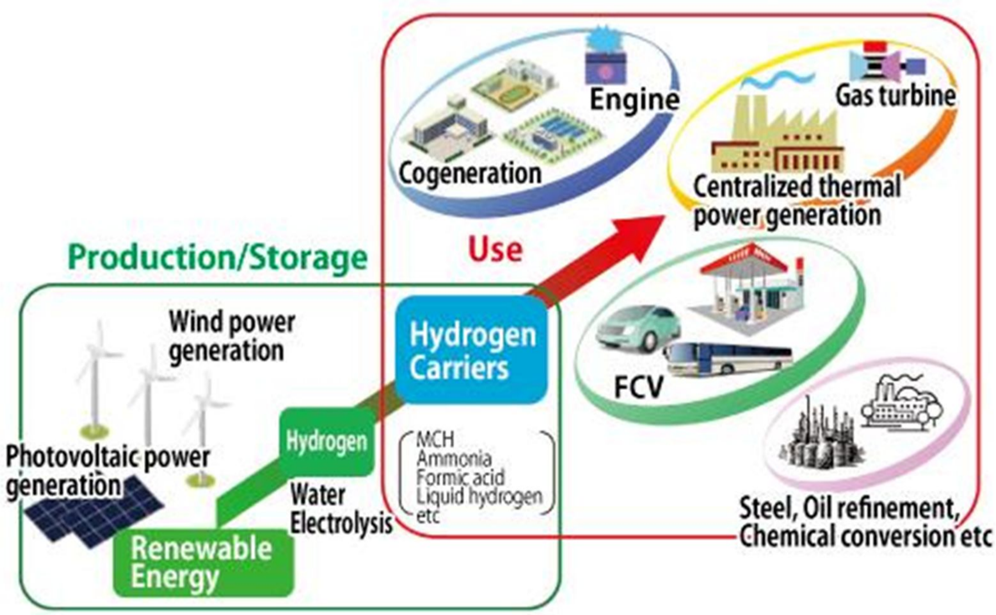


Figure 2.3: Hydrogen Production as a Sustainable Energy Carrier

D. Cost-Effective Hydrogen Production

Addressing the economic viability of hydrogen production methods is a critical aspect explored in the literature. The high cost traditionally associated with hydrogen production has been a barrier to its widespread adoption. Researchers have delved into various methods, including steam methane reforming, electrolysis, and biomass gasification, analysing their economic feasibility. The literature underscores the importance of advancements in technology, economies of scale, and policy incentives in achieving cost-effective hydrogen production.

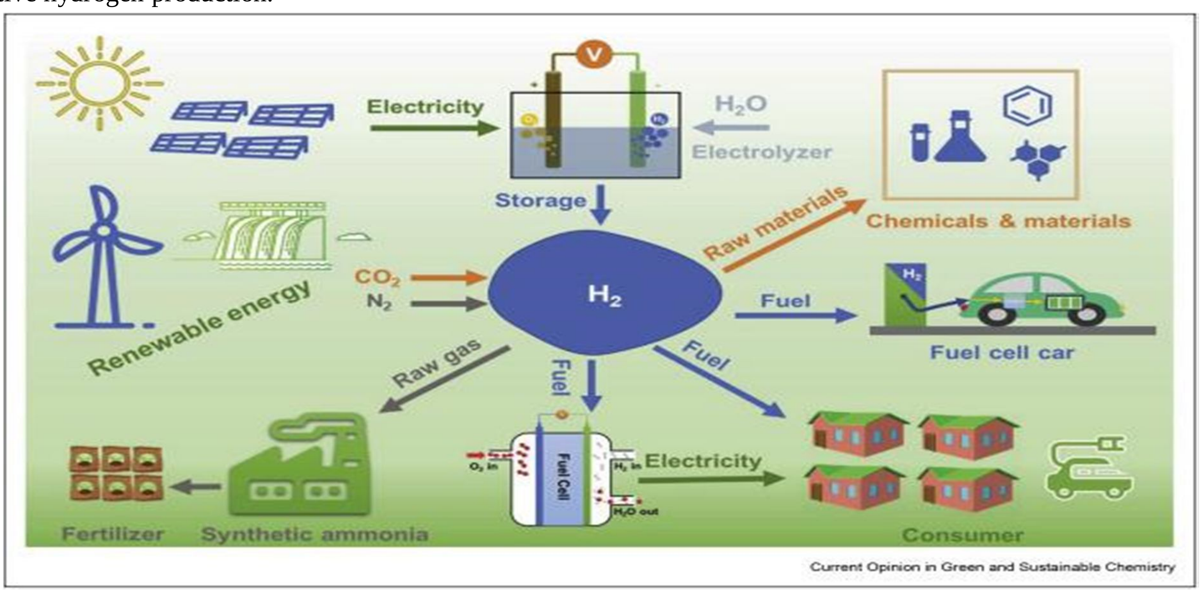


Figure 2.4: Cost-Effective Hydrogen Production

E. Integration of Sustainable Systems Thinking and Hydrogen Production

The nexus of sustainable systems thinking and cost-effective hydrogen production is a relatively nascent but promising area of inquiry. Few studies have explicitly connected these domains to develop a comprehensive framework for managing GHGs. The literature suggests that integrating sustainable systems thinking into the design and implementation of hydrogen production methods can lead to more effective and environmentally conscious solutions. This involves considering the entire life cycle of hydrogen production, from raw material extraction to end-use applications, within the broader context of sustainable systems.

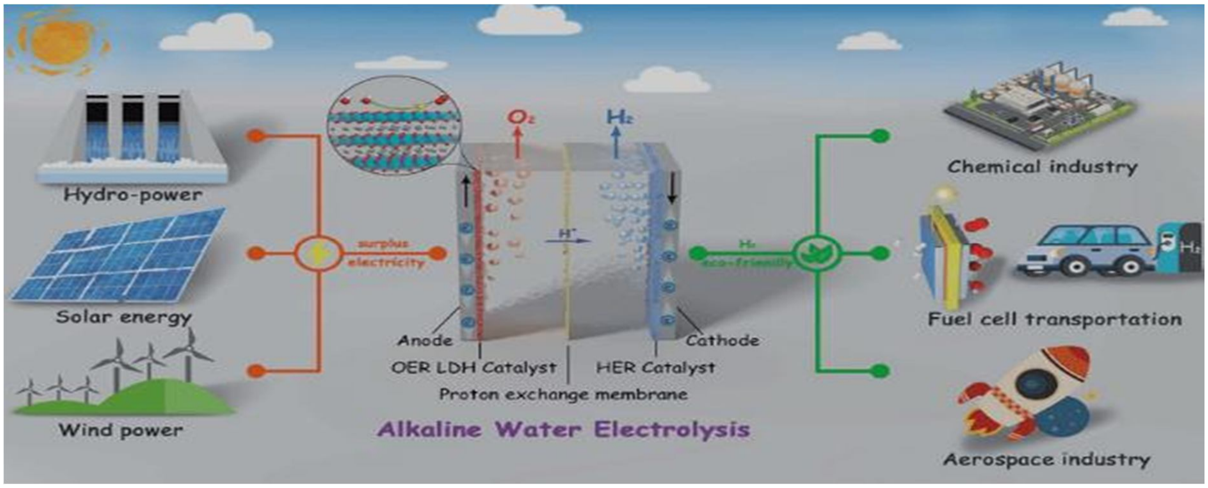


Figure 2.5: Integration of Sustainable Systems Thinking and Hydrogen Production

F. Equational Derivation of Sustainable Hydrogen Production

In deriving equations pertinent to sustainable hydrogen production, a fundamental starting point is the balance equation for the chemical reactions involved. For example, in electrolysis, where water is split into hydrogen and oxygen, the equation $2H_2O \rightarrow 2H_2 + O_2$ encapsulates the process. Equations for the energy input, considering electrical efficiency and the energy required for water electrolysis, become crucial. Similarly, for methane reforming, the reaction $CH_4+H_2O \rightarrow CO+3H_2$ requires an understanding of the thermodynamics involved. The cost-effectiveness equation incorporates factors such as capital and operational costs, energy efficiency, and the market value of the produced hydrogen. Economic models often consider the levelized cost of hydrogen production, integrating the various cost components over the project's lifetime. This equational derivation is vital for assessing the feasibility of different hydrogen production methods, aligning with both sustainable and economic considerations. The literature review provides a comprehensive understanding of GHG management, sustainable systems thinking, and the potential of hydrogen production as a clean energy carrier. The integration of sustainable systems thinking into hydrogen production methods is a promising avenue for addressing both environmental and economic challenges. The equational derivation aspect underscores the quantitative foundation essential for assessing the feasibility and sustainability of different hydrogen production techniques.

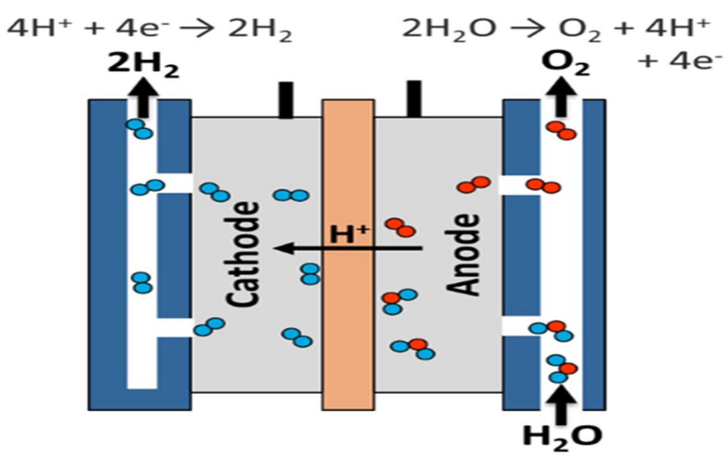


Figure 2.6: Equational Derivation of Sustainable Hydrogen Production

G. Thermodynamics of Hydrogen Production

The thermodynamics of hydrogen production methods play a pivotal role in understanding the efficiency and feasibility of these processes. For example, the Gibbs free energy change (ΔG) is a critical parameter in electrolysis and steam methane reforming. In electrolysis, ΔG relates to the energy input required to drive the reaction, while in steam methane reforming, it determines the spontaneity of the reaction. Equations derived from thermodynamic principles help quantify the energy requirements and potential efficiencies of these hydrogen production pathways.

$\Delta G = \Delta H - T\Delta S$

Where:

- ΔG is the Gibbs free energy change.
- ΔH is the enthalpy change.
- T is the absolute temperature.
- ΔS is the entropy change.

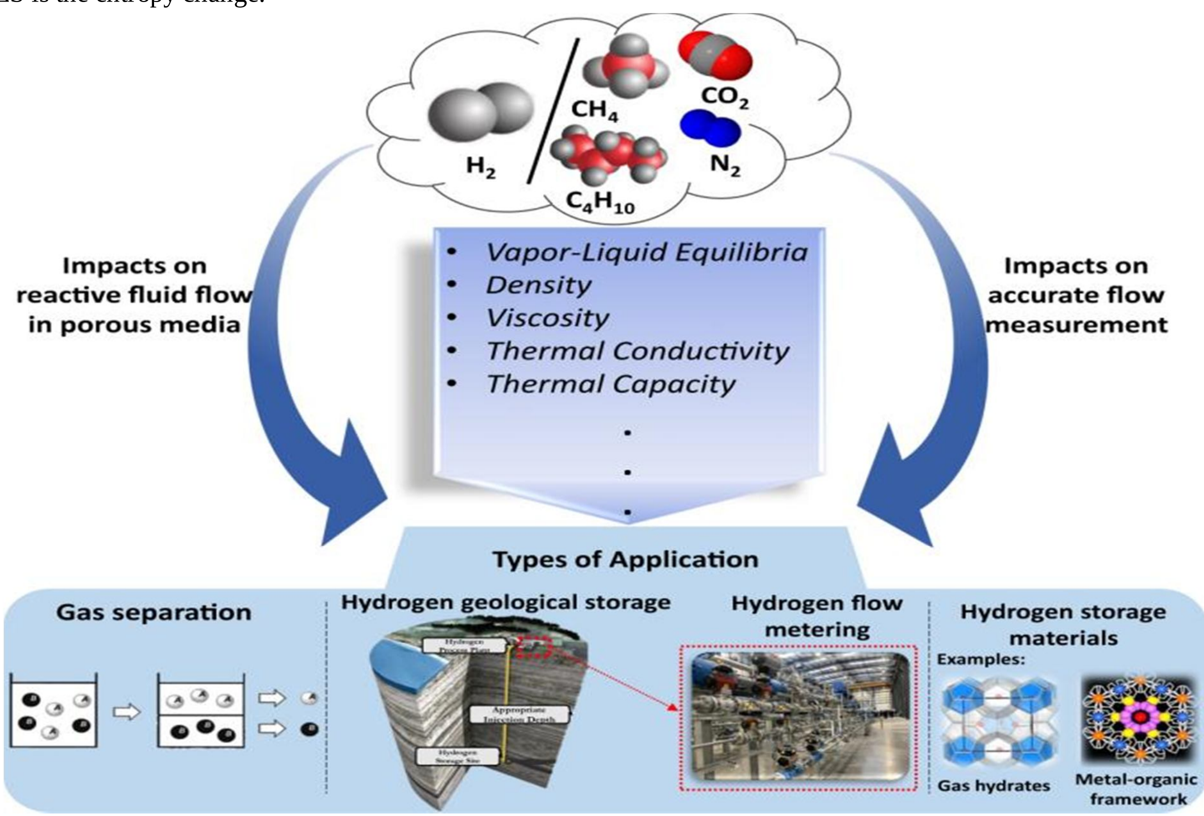


Figure 2.7: Thermodynamics of Hydrogen Production

H. Electrolysis Efficiency Equation

In the context of electrolysis, the Faraday efficiency (FE) is a crucial parameter that quantifies the efficiency of converting electrical energy into chemical energy stored in hydrogen. The equation for Faraday efficiency is derived from the ratio of the experimentally observed amount of hydrogen produced (n_{exp}) to the theoretically calculated amount (n_{theory}) based on the applied current (I) and time (t).

$$FE = \frac{\square_{\square\square\square}}{\square_{\square h\square\square\square\square}} = \frac{\square.\square}{(\square.2.).\square}$$

Where:

- FE is the Faraday efficiency.
- I is the applied current.
- t is the time.
- F is Faraday's constant.
- V is the volume of hydrogen gas produced.

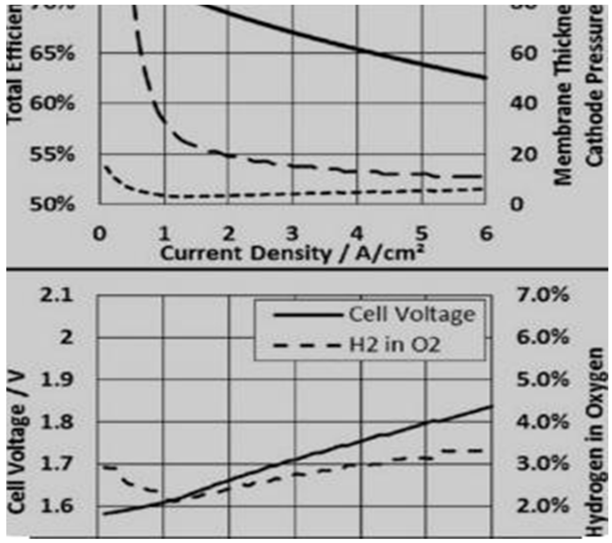


Figure 2.8: Electrolysis Efficiency Equation

I. Levelized Cost of Hydrogen (LCOH)

The Levelized Cost of Hydrogen is a key metric for assessing the economic viability of hydrogen production methods. It represents the per-unit cost of producing hydrogen over the project's lifetime. The LCOH equation includes capital costs (CapEx), operational costs (OpEx), and the lifetime of the project (t), providing a comprehensive economic assessment.

$$LCOH=\frac{CapEx+OpEx}{\sum_{t=1}^{N}\frac{H_2}{(1+r)^t}}$$

Where:

- LCOH is the Levelized Cost of Hydrogen.
- CapEx is the capital expenditure.
- OpEx is the operational expenditure.
- N is the project lifetime.
- r is the discount rate.

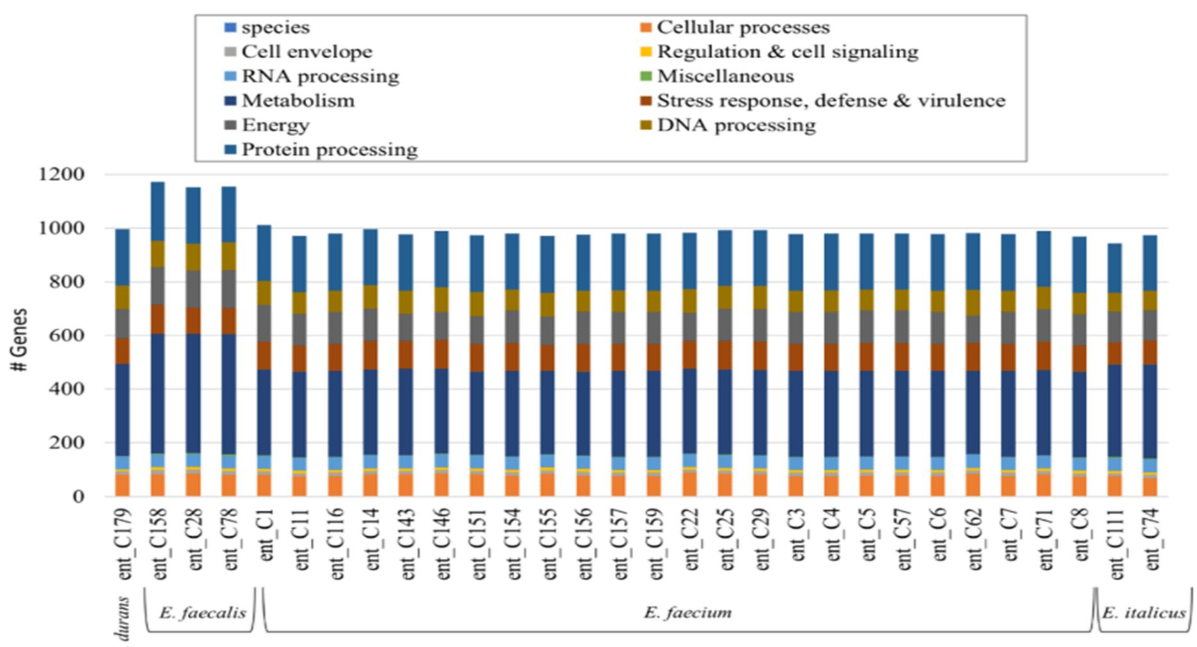


Figure 2.9: Levelized Cost of Hydrogen (LCOH)

ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

J. Energy Return on Investment (EROI)

The Energy Return on Investment is a critical factor in evaluating the sustainability of hydrogen production. It quantifies the ratio of the energy delivered in the form of hydrogen to the energy invested in the entire production process. The EROI equation considers both direct and indirect energy inputs.

$$EROI=\frac{\square\square\square\square\square\square\square\square\square\square\square\square(h\square\square\square\square\square\square\square)}{\square\square\square\square\square\square(\square\square\square\square\square\square\square+\square\square\square\square\square\square\square\square\square)}$$

The derivation of equations related to EROI involves assessing the primary energy inputs for each hydrogen production method, encompassing factors such as electricity, raw materials, and infrastructure.

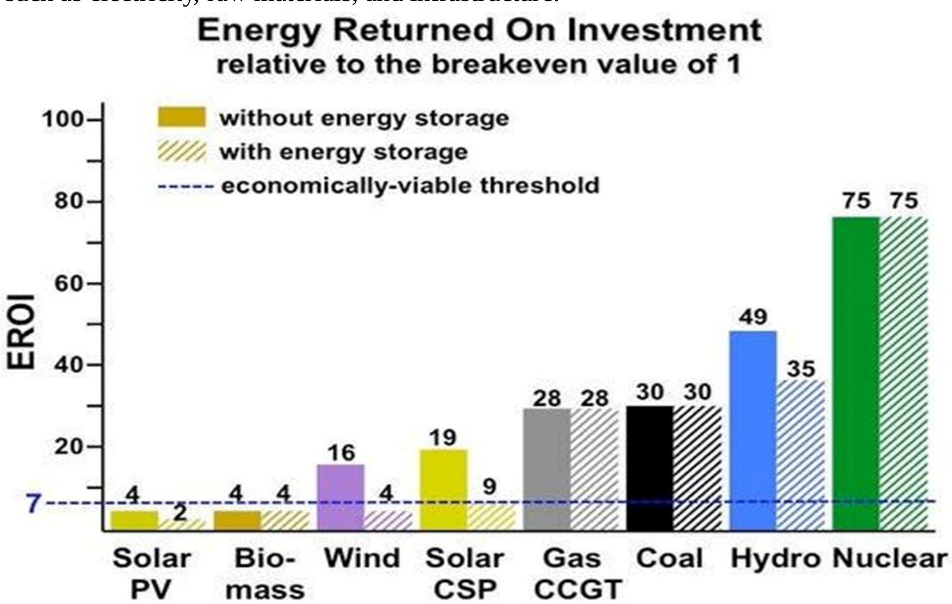


Figure 2.10: Energy Return on Investment (EROI)

The equational derivations presented shed light on the thermodynamics, efficiency, economic viability, and sustainability metrics crucial for evaluating different hydrogen production methods within the context of GHG management and sustainable systems thinking. These equations provide a quantitative foundation for comparing and optimizing the diverse pathways towards cost-effective and environmentally conscious hydrogen production.

III. HYDROGEN DEMAND SCENARIO USING EXTREMOS MODELLING KIT

The ability to comprehend and forecast the demand for hydrogen is an essential component that serves as the foundation for efficient greenhouse gas (GHG) management techniques. This is an essential component in the goal of a sustainable future. In this chapter, we dig into the complexities of hydrogen demand scenarios, making use of the cutting-edge Extremos Modelling Kit to anticipate and evaluate the dynamics of hydrogen use across a variety of industries.

The global energy landscape is experiencing a transformational upheaval, and hydrogen is emerging as a crucial factor in the search for energy solutions that are both clean and sustainable. In the context of governments' efforts to fulfil ambitious climate objectives, the demand for hydrogen as a flexible and low-emission energy carrier is set to expand at an exponential rate. Through the utilization of the Extremos Modelling Kit, which is a sophisticated tool meant to model and predict future scenarios depending on a multiplicity of characteristics, Chapter 3 endeavours to disentangle the complex web of hydrogen demand.

1) Significance of Hydrogen Demand Modelling

To formulating well-informed policies, determining appropriate investment strategies, and directing the course of the energy transition, it is very necessary to use precise modelling of the demand for hydrogen. At a time when the residential, transportation, and industrial sectors are beginning to examine hydrogen as a viable option, the Extremos Modelling Kit offers a dynamic platform that can model a variety of different situations. The modelling kit offers a full examination of prospective demand scenarios, which ultimately guides strategic decision-making. This is accomplished by considering factors such as technical improvements, regulatory changes, and market dynamics.

2) Extremos Modelling Kit Overview

To predict energy demand scenarios, with a particular emphasis on hydrogen, the Extremos Modelling Kit is a cutting-edge software tool that has been particularly built for this purpose. A broad variety of input parameters may be accommodated by this kit, which makes it possible to conduct a detailed investigation into the elements that influence hydrogen demand. This kit makes use of sophisticated algorithms and data analytics. The modelling kit makes it possible to conduct an all-encompassing investigation of the many commercial and residential uses of hydrogen, ranging from industrial processes to transportation and home applications.

This chapter provides an overview of the methods that is used while making use of the Extremos Modelling Kit. To do this, the input parameters need to be defined. These factors include the existing and predicted capacity for hydrogen production, developments in storage technologies, changing market dynamics, and regulatory frameworks at the present time. After then, the model is adjusted so that it accurately reflects the facts from the past, which guarantees that it will accurately anticipate future events. The robustness of the predictions is improved using sensitivity studies, which are carried out to evaluate the influence that different factors have on the findings.

3) Scenario Exploration

This section examines several potential situations that might have an impact on the demand for hydrogen in the future. Among the potential outcomes are the widespread use of hydrogen fuel cell cars, the incorporation of hydrogen into industrial processes, and the creation of power generating systems that are based on hydrogen. A detailed knowledge of the alternative trajectories of hydrogen demand is made possible by the fact that each scenario considers varying rates of technology improvement, legislative assistance, and economic considerations.

4) Challenges and Uncertainties

Even though the Extremos Modelling Kit is a strong tool for scenario analysis, the chapter also recognizes the inherent difficulties and uncertainties that are associated with forecasting the future demand for hydrogen. There are several factors that have the potential to greatly influence the course of the hydrogen economy. These include geopolitical developments, unexpected technology breakthroughs, and rapid regulatory changes. The chapter addresses techniques for adding flexibility into the models to adapt to changing situations. Acknowledging these uncertainties, the chapter explores several solutions.

Chapter three ends by providing a summary of the insights that were obtained from the examination of the Extremos Modelling Kit. At the same time, it highlights the relevance of accurate demand estimates in the process of formulating policies and investments connected to the production and consumption of hydrogen. This chapter gives significant insight into the different scenarios that may unfold in the growing landscape of hydrogen demand by applying a sophisticated modelling technique. This chapter aligns with the general objective of developing cost-effective hydrogen generation as a means of achieving sustainable greenhouse gas management.

A. Qualitative Scenario Modelling

Within the broad framework of regulating greenhouse gases (GHGs) via sustainable systems thinking and the deployment of cost-effective hydrogen generation, qualitative scenario modelling acts as an important methodological technique that plays a significant role. Within this part, we go into the idea and execution of Qualitative Scenario Modelling as a tool for bridging uncertainties, imagining probable future trajectories, and providing information that can be used to guide strategic decision-making.

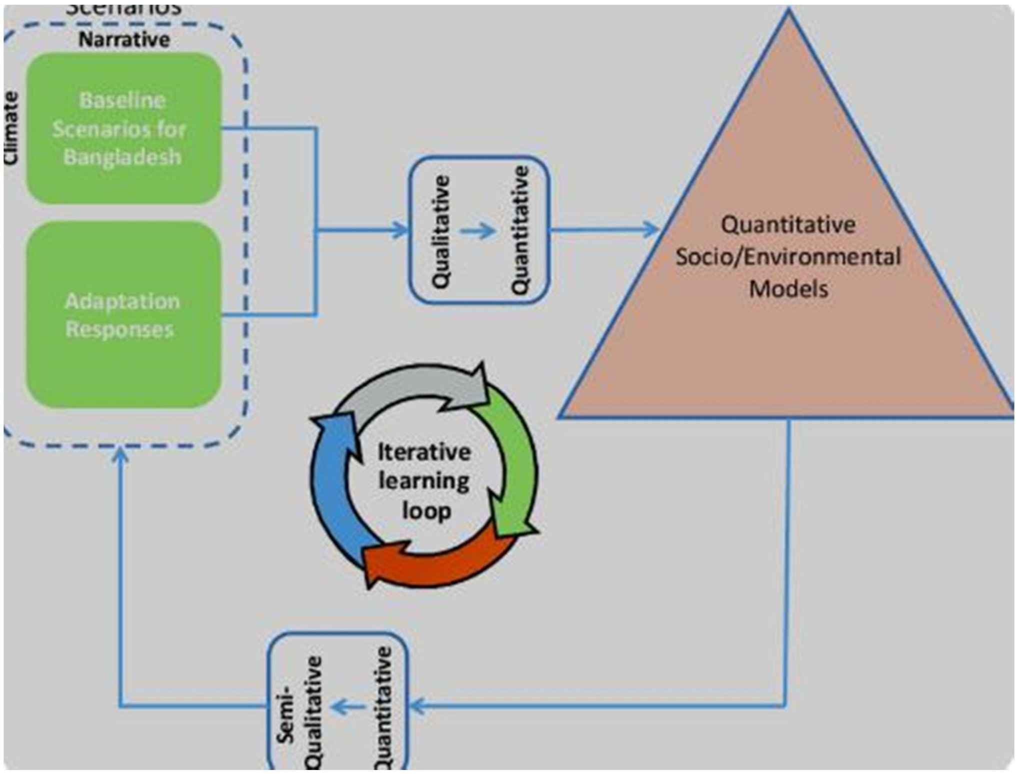


Figure 3.1: Qualitative Scenario Modelling

1) Foundations of Conceptualization

The production of realistic future scenarios that are led by narratives is the central focus of qualitative scenario modelling. In contrast to quantitative models, which are primarily dependent on numerical data, qualitative modelling places a greater emphasis on the investigation of qualitative elements, contextual subtleties, and intricate interactions within dynamic systems. The qualitative scenario modelling approach incorporates both environmental and socio-economic elements in the context of greenhouse gas management and hydrogen generation. This approach offers a comprehensive perspective on the several potential futures.

2) Important Components

- The Dynamics of the Environment:

Possible Qualitative Outcome The first step in modelling is to take into account the environmental dynamics that are connected with greenhouse gas management. Among the elements that fall under this category are the effects of climate change, the magnitude of greenhouse gas emissions, and the efficiency of the mitigation techniques that are now successful. Scenarios may investigate the ways in which the implementation of technologies for the generation of hydrogen that are more cost-effective might have an impact on environmental outcomes, such as the decrease of carbon emissions and the improvement of air quality.

- Aspects of Socioeconomic Society:

A fundamental component of qualitative modelling is having a solid understanding of the socio-economic environment. To do this, it is necessary to conduct an analysis of the economic viability of various techniques of producing hydrogen, determine the impact of regulatory frameworks, and determine the societal acceptability and integration of hydrogen technologies. There is the possibility that qualitative scenarios may study how changes in economic policies or public perception can have an influence on the adoption of environmentally friendly systems and hydrogen solutions that are cost-effective.

- Developments in Science and Technology:

The trajectory of technical breakthroughs, especially those that are pertinent to the generation of hydrogen, is taken into consideration via qualitative modelling processes. Potential improvements in electrolysis efficiency, developments in storage technologies, and innovations in the integration of renewable energy sources are investigated via the use of several scenarios. To predicting how technical advancements can affect the landscape of sustainable hydrogen generation, this aspect of modelling is helpful.

- The Frameworks of Policies and Regulations:

The qualitative scenarios provide an opportunity to investigate the possibility of changes to the regulatory and policy frameworks. As part of this, the introduction of incentives, subsidies, and severe environmental rules that have the potential to influence the adoption of environmentally friendly technologies and the generation of hydrogen that is cost-effective is included. In qualitative modelling, various policy landscapes and the consequences they have for greenhouse gas management are taken into consideration.

- Prospective Scenario Analysis:

In qualitative scenario modelling, different narratives that portray conceivable futures are created and explored. This process leads to the construction of multiple scenarios. A transition to an energy economy that is cantered on hydrogen, the widespread adoption of sustainable practices, or even unanticipated events such as geopolitical developments that influence global energy markets are all examples of potential scenarios. A qualitative grasp of the many possible directions that the future may take is provided by each scenario, which has been constructed to be internally coherent and believable.

- Support for Strategic Decision Making:

Provide decision-makers with insights into prospective futures is one of the key goals of qualitative scenario modelling, which is one of the fundamental aims of the technique. To better prepare for uncertainties, create strong solutions, and make educated decisions in the face of dynamic and shifting situations, decision-makers might benefit from evaluating a variety of scenarios. In the context of greenhouse gas management, where long-term planning and adaptation are of the utmost importance, this strategic decision support makes a particularly useful contribution.

Within the context of the larger framework of regulating greenhouse emissions and producing hydrogen at a cost-effective level, qualitative scenario modelling emerges as a technique that is both diverse and instructive when used. Through the incorporation of environmental, socio-economic, technical, and policy considerations, this method contributes to the visualization of disparate futures, the enhancement of readiness for unpredictability, and the direction of strategic choices toward a future that is both sustainable and low in carbon emissions.

B. *Quantitative Model Simulation and application*

Quantitative model simulation stands as a cornerstone in the endeavour to manage greenhouse gases (GHGs) through sustainable systems-thinking, integrating the novel approach of cost-effective hydrogen production. This section delineates the conceptual foundations, methodologies, and applications of quantitative models in the complex interplay of environmental sustainability, systems-thinking, and hydrogen production economics.

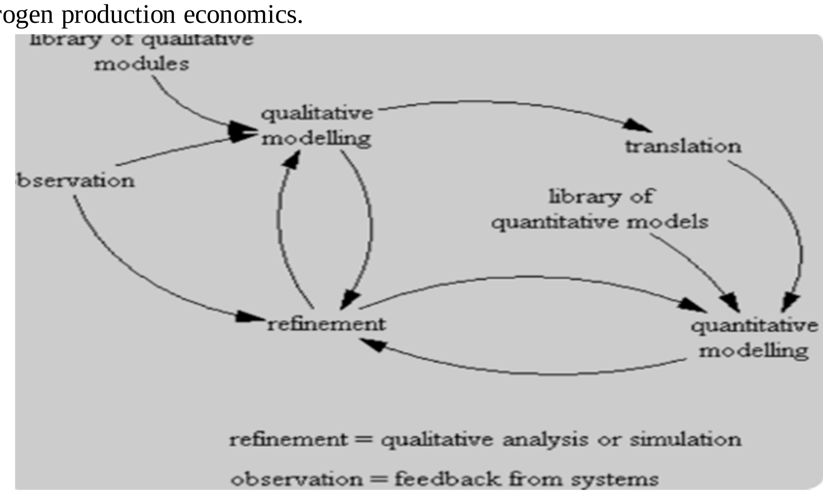


Figure 3.2: Quantitative Model Simulation and application

1) *Conceptual Foundations*

At its core, quantitative model simulation involves the use of mathematical and computational tools to represent and analyse the intricate dynamics of a system. In the context of GHG management and hydrogen production, the quantitative model serves as a virtual laboratory, allowing researchers and policymakers to experiment with different variables, test scenarios, and gauge potential outcomes. The conceptual foundations rest on the integration of environmental factors, economic variables, and systems dynamics to formulate comprehensive models.

2) Key Components of Quantitative Models

- Environmental Variables:

Quantitative models in this context incorporate key environmental variables such as greenhouse gas emissions, air quality indices, and climate change impacts. These variables are intricately linked to hydrogen production methods, and the models aim to quantify their interactions, providing insights into the environmental implications of different hydrogen production scenarios.

- Economic Parameters

The economic viability of hydrogen production methods is a critical aspect addressed by quantitative models. These models factor in capital costs, operational expenditures, energy input costs, and potential revenue streams associated with hydrogen production. The economic parameters contribute to the evaluation of cost-effectiveness and overall feasibility.

- Technological Factors

Quantitative models consider the technological aspects of hydrogen production, including the efficiency of various methods, advancements in storage technologies, and potential breakthroughs. Technological factors are modelled to gauge their impact on the scalability and sustainability of hydrogen production systems.

- Systems Dynamics

A core tenet of sustainable systems-thinking, systems dynamics involves understanding the interconnectedness of different elements within a system. Quantitative models, therefore, encapsulate the dynamics of systems thinking, enabling the exploration of feedback loops, delays, and non-linear relationships. This comprehensive approach enhances the model's ability to capture the complexity inherent in GHG management and hydrogen production.

3) Methodologies in Quantitative Model Simulation

- System Dynamics Modelling

System dynamics modelling is integral to quantitative simulations in sustainable systems-thinking. It involves representing the system as a set of interconnected feedback loops and time-delayed relationships. System dynamics models allow for the exploration of how changes in one aspect of the system reverberate through the entire system, providing a holistic understanding of the dynamics involved.

- Life Cycle Assessment (LCA)

Quantitative models often integrate life cycle assessment methodologies to evaluate the environmental impact of hydrogen production throughout its entire life cycle. LCA considers inputs, outputs, and potential environmental impacts at every stage, from raw material extraction to end-of-life disposal. This approach helps quantify the overall environmental footprint of different hydrogen production methods.

- Optimization Techniques

Optimization techniques are employed to identify the most efficient and cost-effective solutions within the model's parameters. These techniques involve maximizing or minimizing specific objectives, such as minimizing greenhouse gas emissions or maximizing economic returns. Optimization enhances the model's utility in guiding decision-making toward optimal solutions.

4) Applications of Quantitative Model Simulation

- Scenario Analysis

Quantitative models excel in scenario analysis, allowing researchers to explore a myriad of potential futures. Scenarios may include varying levels of hydrogen demand, shifts in energy policies, or advancements in technology. The models simulate the impact of these scenarios on GHG emissions, economic viability, and overall sustainability, aiding in decision-making under uncertainty.

- Policy Evaluation

Quantitative models play a pivotal role in evaluating the effectiveness of different policies in promoting sustainable hydrogen production. By incorporating regulatory frameworks, incentives, and penalties within the model, researchers can assess the potential impact of policy interventions on GHG reduction targets and the economic feasibility of hydrogen technologies.

- Investment Planning

For industries and policymakers considering investments in hydrogen production infrastructure, quantitative models provide a robust foundation for decision-making. The models assess the economic viability of different investment scenarios, considering factors such as capital costs, operational expenditures, and potential returns on investment over time.

- Environmental Impact Assessment

Quantitative models facilitate detailed environmental impact assessments, offering insights into the ecological footprint of various hydrogen production methods. This includes quantifying emissions, resource use, and potential ecological disruptions. The models assist in identifying environmentally sustainable pathways within the broader context of GHG management.

- Challenges and Future Developments

While quantitative models offer valuable insights, challenges persist. Data limitations, uncertainties in future scenarios, and the need for iterative refinement are inherent to quantitative modelling. Future developments in this field involve advancements in data analytics, artificial intelligence, and integration with real-time data sources to enhance the accuracy and predictive power of quantitative models.

Quantitative model simulation stands as a powerful tool in the management of greenhouse gases through sustainable systems-thinking with cost-effective hydrogen production. By encapsulating environmental, economic, and technological factors within a dynamic systems framework, these models contribute significantly to informed decision-making, policy evaluation, and investment planning in the pursuit of a sustainable and low-carbon future.

C. Solidarity in the European Union Scenario

Sustainable systems thinking and cost-effective hydrogen production are needed to control greenhouse gas emissions. This is a difficult task with many parts. Within the European Union (EU), this needs to be done with a broad method that includes many people, devices, and policy measures.

Figure 3.3: Solidarity in the European Union Scenario

In the EU situation, let's break down the main parts of a feasible systems-thinking plan for reducing greenhouse gas emissions by making hydrogen cheaply:

1) Integration of Renewable Energy

To make sure the process is clean and long-lasting, make it a priority to use green energy sources to make hydrogen.

To power facilities that make hydrogen, i should put money into and support the growth of green energy infrastructure, like wind, solar, and hydropower.

Technologies for Making Hydrogen:

Look into and use a number of different ways to make hydrogen, such as electrolysis using sustainable energy, feedstock gasification, and biogas condensing at carbon capture and store (CCS).

Find the most environmentally friendly ways to make hydrogen by comparing their life cycle pollution and how much they cost.

CCS stands for carbon capture and storage.

Use CCS devices to collect and store the emissions of carbon from making hydrogen, especially from methane reforming and other processes.

A system of laws and financial incentives should be put in place to urge hydrogen production facilities to use CCS.

2) Building up infrastructure

Build a strong network for storing, transporting, and distributing hydrogen across the EU. This will make it easier for hydrogen to be used in energy, transportation, industry, and other areas.

Make sure that hydrogen infrastructure is interoperable and standardized so that it can be used and transported easily across borders.

3) Framework for policy

Create and maintain policies that help the hydrogen economy grow. These might include tax breaks, subsidies, and rules that encourage long-term hydrogen production.

Work with nations that belong to the EU to make sure that rules and laws about making and using hydrogen are all the same.

4) Research and new ideas

Spend money on studies and development to make tools that make hydrogen more efficient and cheaper.

Encourage new ideas in the creation of novel components and techniques for making, storing, and using hydrogen.

5) Cooperation between countries

Work together with partners from other countries to contribute best practices, new technologies, and support study projects that i are both working on.

Look into ways the EU can participate in global the hydrogen markets, which would encourage environmentally friendly ways to make hydrogen around the world.

6) Awareness and participation of the public

Get people to understand why safe hydrogen production is important and how it can help cut down on greenhouse gas emissions.

Get people to back policies and programs that help the switch to an economy based on hydrogen.

Policymakers, business stakeholders, and the public all need to work together to put in place a sustainable systems-thinking plan for reducing the emissions of greenhouse gases through cost-effective hydrogen production. For these kinds of projects to be successful in the long run in the European Union, they need to strike a balance between being good for the environment and being good for business.

IV. LEVELIZED COST OF HYDROGEN PRODUCTION (LCOH) MODELLING

A. Simple LCOE modelling concept

Managing greenhouse gas pollution needs a long-term way of thinking about systems, and using cheap hydrogen production is a big part of this way of thinking. A Simple Levelized Prices of the gas hydrogen (LCOH) modelling idea is very helpful for figuring out if methods for making hydrogen are economically viable.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

The LCOH model gives a full picture of the long-term costs of different production methods by looking at capital costs, operating costs, the use of renewable energy, and possible storage and capture of carbon (CCS) uses. It takes into account the cost of feedstock, economies of scale, along with sensitivity analyses, which let parties figure out how different factors affect cost-effectiveness.

Table 4.1: LCOE modelling concept

Row	Goal Seek to Find / Real	TRUE	Solar Malaysia	Battery Discharge (No Chargin Cost)	Solar for Charging Battery	Solar + Battery for Storage	Solar Saudi	Natural Gas Plant	Mini Hydro
2			1	2	3	4	5	6	6
4	**Nominal LCOE**	MYR/MWH	RM 170.17	RM 1,061.00	RM 178.45	RM 742.29	RM 65.53	RM 282.15	RM 222.00
5	**Real LCOE**	MYR/MWH	RM 130.78	RM 964.69	RM 140.25	RM 651.58	RM 50.37	RM 226.46	RM 170.88
7	**Nominal LCOE**	USD/MWH	$42.54	$265.25	$44.61	$185.57	$16.38	$70.54	$55.50
8	**Real LCOE**	USD/MWH	$32.69	$241.17	$35.06	$162.90	$12.59	$56.62	$42.72
10	Real LCOE	MYR/kW-year							
11	Nominal LCOE	MYR/kW-year							
13	**Generating Plant Operating Drivers**								
15	**Capacity**	MW	100.00	100.00	117.65	217.65	100.00	100.00	100.00
16	Project Life	Years	35.00	15.00	35.00	35.00	35.00	30.00	35.00
18	**Drivers of Up-front Cost**								
19	Module Cost	MYR	1,400.00		1,400.00	1,400.00	1,000.00		
20	Module as Percent of Total	%	35.00%		35.00%	35.00%	40.00%		
21	Implied Cost	MYR	4,000.00		4,000.00	4,000.00	2,500.00	2,800.00	16,000.00
22	Total Up-front Cost per kW	MYR/kW	4,000.00		4,000.00	4,000.00	2,500.00	2,800.00	16,000.00
24	**Drivers of Operating Cost**								
25	Fixed O&M Cost	MYR/kW-year	40.00		40.00	40.00	30.00	64.00	50.00
27	Variable O&M Cost	MYR/MWH						16.00	
28	Fuel Cost	MYR/MMBTU						24.00	
29	Heat Rate	MMBTU/MWH						6.63	
30	Fuel Cost	MYR/MWH						159.23	
31	Environmental Adder	MYR/MWH							
33	**Drivers of Production**								
34	Degradation	%/year	0.00%		0.50%		0.50%	0.00%	0.00%
35	Capacity Factor (Yield)	%	22.00%		22.00%		32.56%	50.00%	60.00%
36	Production	MWH	192,720		226,729		285,226	438,000	525,600
38	**Storage/Battery Characteristics**								

Big Points | LCOE Calculator | Natural Gas | Batery Sensitivity | Battery Cost | Electric Vehicles

The model's scope grows over the course of the project's life to account for changes in technology and government incentives. By looking at LCOH levels in various technologies and old-fashioned methods, decision-makers can find the hydrogen generation methods that are best for both the economy and the environment. The LCOH model is more useful because it is simple. It helps people make smart choices that make the energy system more resilient and eco-friendlier, which is in line with the EU's goal of lowering greenhouse gas emissions.

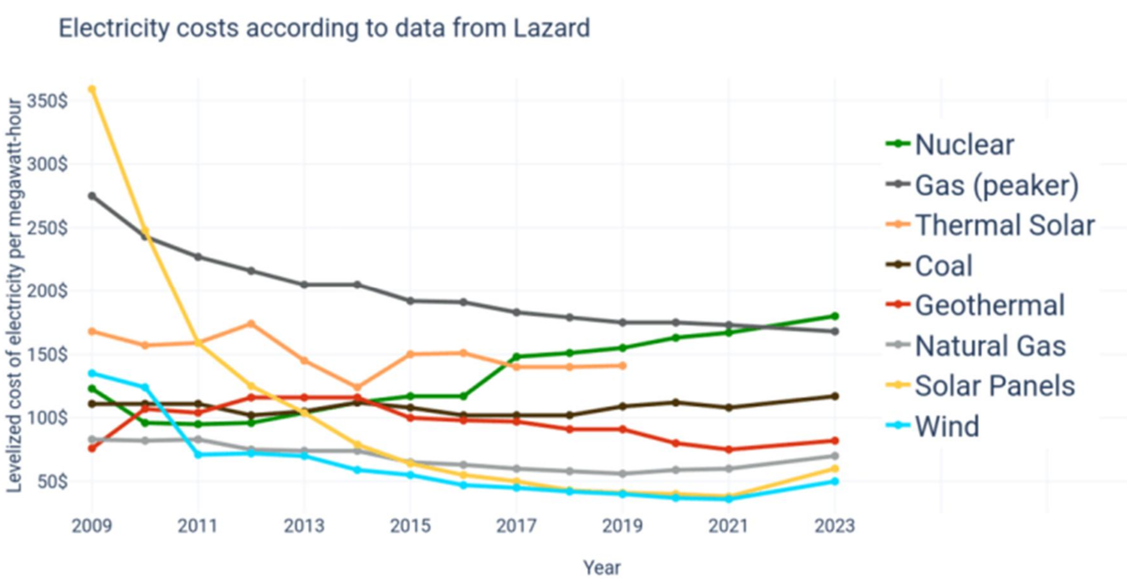


Figure 4.1: Simple LCOE modelling concept

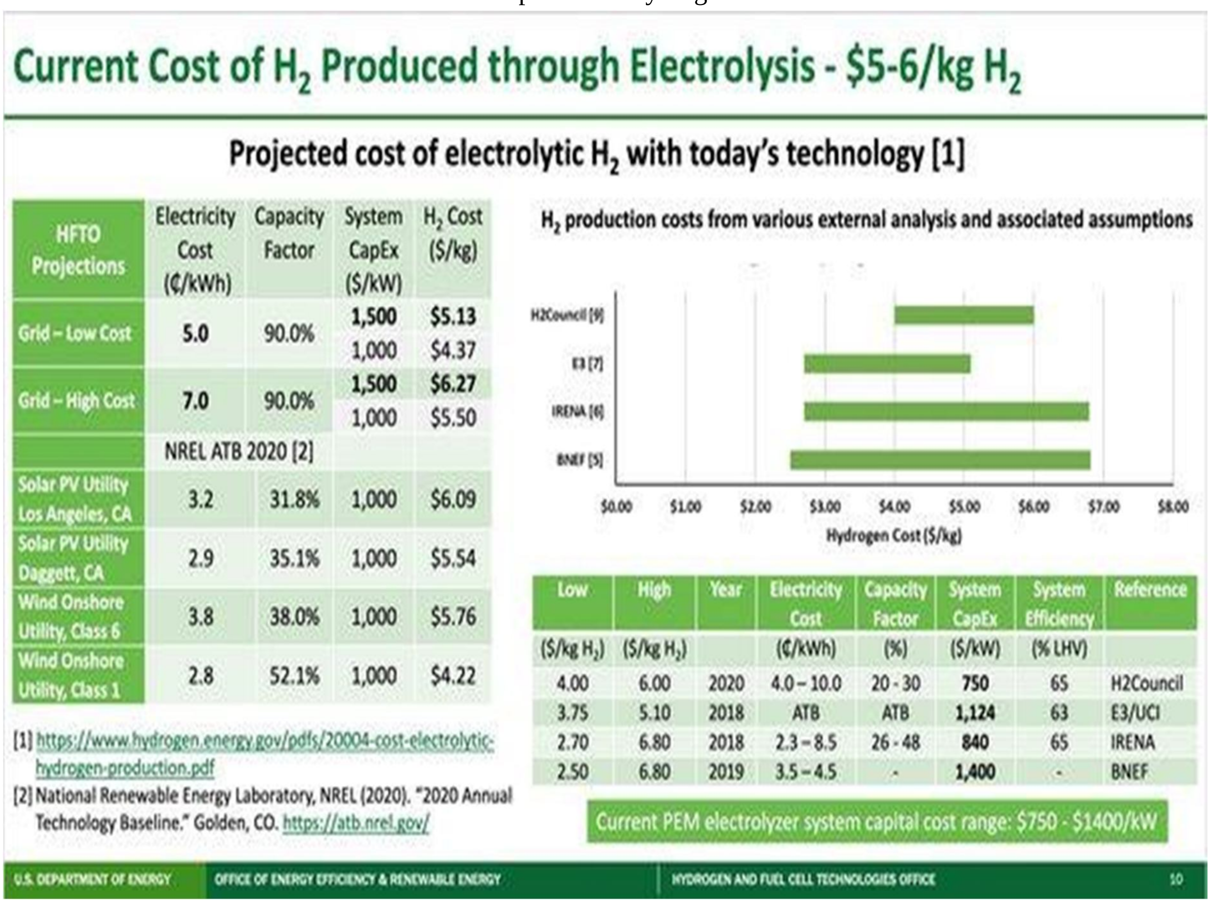
International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

B. Cost component of Hydrogen production

To control greenhouse gas emissions in a way that is sustainable and cost-effective, hydrogen production needs to be carefully thought out in terms of all the costs that come with it.

1) Costs of capital: Infrastructure spending is a big part of this. It includes building facilities to make hydrogen and buying the tools that are needed. Capital costs depend on the method i choose, such as electrolysis or reforming.
2) Costs of operation and maintenance: Regular maintenance is needed to keep things running smoothly, and the cost of skilled workers adds to the working costs. Making sure processes are reliable and work well is important for reducing downtime.
3) Costs of feedstock: A big chunk of the total cost goes to raw materials like water for electrolysis as well natural gas for reforming. The feedstock part is made up of things like shipping and purchasing that are part of the supply chain.
4) Costs of energy: When making hydrogen through electrolysis, the cost of electricity is an important factor to think about. Using green energy sources to make hydrogen helps lower its carbon footprint. In other ways, the cost of energy goes up because they need to use more energy, like heat or steam.
5) The cost of collecting and storing carbon (CCS): Using CCS costs more for ways of making hydrogen that use fossil fuels. How well and how cheaply the picked CCS technology works are very important factors.
6) Cost savings through economies of scale: Economies of scale often happen when production capacity goes up, which lowers the cost for each kilogram of hydrogen made. Cost savings can be achieved by expanding production sites.

Table 4.2: Component of Hydrogen Production



HFTO Projections	Electricity Cost (¢/kWh)	Capacity Factor	System CapEx ($/kW)	H_2 Cost ($/kg)
Grid – Low Cost	5.0	90.0%	1,500	$5.13
			1,000	$4.37
Grid – High Cost	7.0	90.0%	1,500	$6.27
			1,000	$5.50
	NREL ATB 2020 [2]			
Solar PV Utility Los Angeles, CA	3.2	31.8%	1,000	$6.09
Solar PV Utility Daggett, CA	2.9	35.1%	1,000	$5.54
Wind Onshore Utility, Class 6	3.8	38.0%	1,000	$5.76
Wind Onshore Utility, Class 1	2.8	52.1%	1,000	$4.22

[1] https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf
[2] National Renewable Energy Laboratory, NREL (2020). "2020 Annual Technology Baseline." Golden, CO. https://atb.nrel.gov/

Low	High	Year	Electricity Cost	Capacity Factor	System CapEx	System Efficiency	Reference
($/kg H_2)	($/kg H_2)		(¢/kWh)	(%)	($/kW)	(% LHV)	
4.00	6.00	2020	4.0 – 10.0	20 - 30	750	65	H2Council
3.75	5.10	2018	ATB	ATB	1,124	63	E3/UCI
2.70	6.80	2018	2.3 – 8.5	26 - 48	840	65	IRENA
2.50	6.80	2019	3.5 – 4.5	-	1,400	-	BNEF

Managing these cost factors strategically means making the production process as efficient as possible, looking into how to use green energy, and thinking about the chance for economies of scale. To make hydrogen generation more cost-effective while still meeting environmental goals, a sustainable systems-thinking approach promotes constant improvement, new ideas, and the use of cleaner technologies.

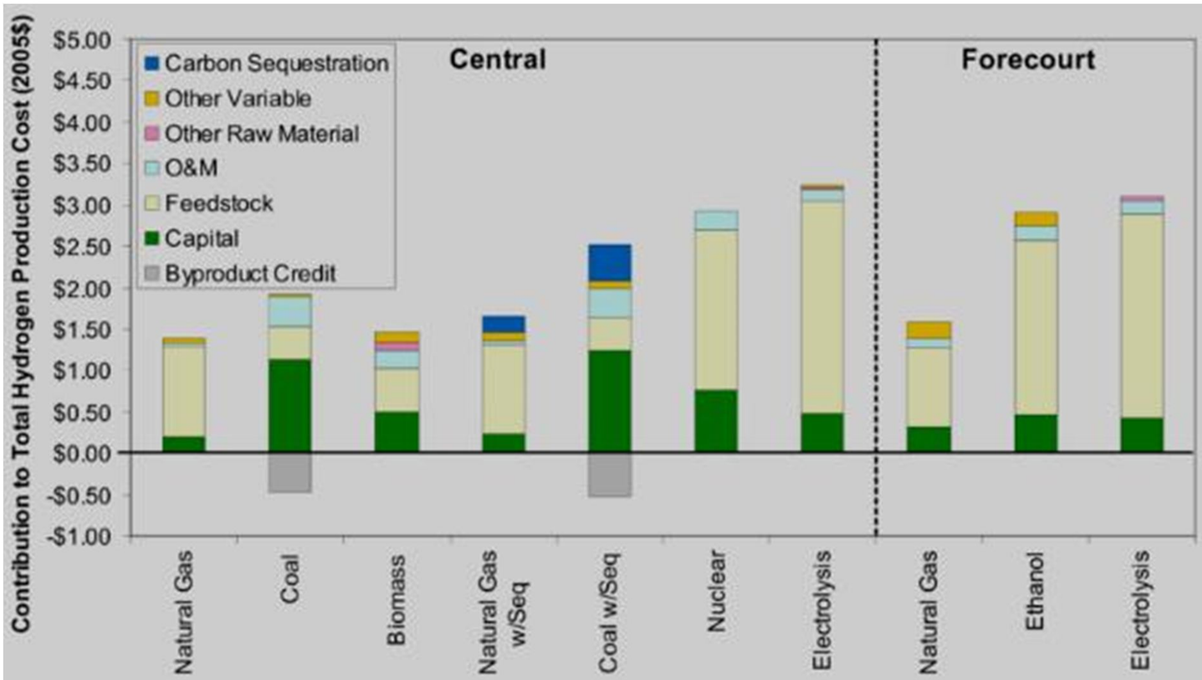


Figure 4.2: Cost component of Hydrogen production

This way of doing things fits with the European Union's plan to cut down on greenhouse gas pollution and move toward a more sustainable, low-carbon energy system.

a) Levelized cost of hydrogen production using Electrolysis

Using cost-effective electrolysis to make hydrogen is a key part of controlling greenhouse gas emissions in a way that doesn't harm the environment. When i look at the levelled expenditure of making hydrogen (LCOH) through electrolysis in the context of sustainable systems thought, i can learn a lot. Capital costs include equipment like electrolyser units and systems that support them. Using power for electrolysis is an operational cost that could be lowered by incorporating renewable energy. Operations can last for a long time with regular maintenance and a water source that works well. When figuring out LCOH, the project's lifetime, depreciation, and debt are all taken into account. Larger electrolysis plants may be able to get lower LCOH because of economies of scale. As technology keeps getting better, it makes things more efficient. Policy benefits, like subsidies, affect how feasible an idea is. The goal of lowering greenhouse gas pollution in the European Union and making the energy system cleaner and more reliable is in line with incorporating electrolytic into a sustainable framework.

b) Levelized cost of hydrogen production using SMR

Managing greenhouse gas pollution effectively requires using sustainable systems-thinking methods. One way to do this is to use Steam Methane Reforming (SMR) to make hydrogen at a low cost. To reach both economic and environmental goals, it is important to figure out the levelized cost of making hydrogen (LCOH) through SMR in a way that doesn't harm the environment. Capital costs include building infrastructure, such as generator units and the systems that go with them. Feedstock made from natural gas and the energy-intensive recycling process are operational costs. The cost of adding CCS, or carbon capture and storage, tools to the SMR process goes up, but they help lower emissions. The general cost of production is affected by the cost of feedstock and selecting of CCS technology. When figuring out LCOH, it's important to think about how long the project will last, taking into account depreciation and debt. Economies of scale matter because cost savings may be possible at bigger SMR facilities. As SMR technologies keep getting better, like with better catalysts and process improvement, they can become more cost-effective and efficient over time. Policy support, such as incentives for environmentally friendly methods and ways to price carbon, is a key factor in determining whether SMR-based hydrogen generation is economically viable. By using SMR as part of a sustainable systems-thinking approach, players can figure out how to make hydrogen in a way that is both cost-effective and helps reduce the emission of greenhouse gases in the EU, making the energy landscape more sustainable.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

c) Levelized cost of hydrogen production using Methane pyrolysis

Finding cheap ways to make hydrogen is closely linked to environmental control that does not release greenhouse gases into the air. Methane pyrolysis is a promising option. It is important to look at the levelized cost from hydrogen (LCOH) output through this process in the context of sustainable systems thought.

Methane pyrolysis is the straight splitting of hydrogen into hydrogen and carbon in solid form. This could be a way to make hydrogen that is cheap and doesn't pollute the environment. Capital costs include building pyrolysis reactors and the equipment that goes with them, which are necessary for the process to work well. The main thing that affects operational costs is the energy needed for the pyrolysis process. Improving this energy supply is very important for lowering costs.

One of the best things about methane pyrolysis is that a solid carbon byproduct could be used to collect and use carbon. This not only helps lower greenhouse gas pollution, but it also adds a useful way to capture carbon into the process of making hydrogen.

To figure out the LCOH for methane pyrolysis, i have to think about how long the project will last and include depreciation and amortization. As with other ways of making hydrogen, economies of scale will play a part. For example, LCOH may be lower in bigger pyrolysis facilities because they are more efficient and produce more.

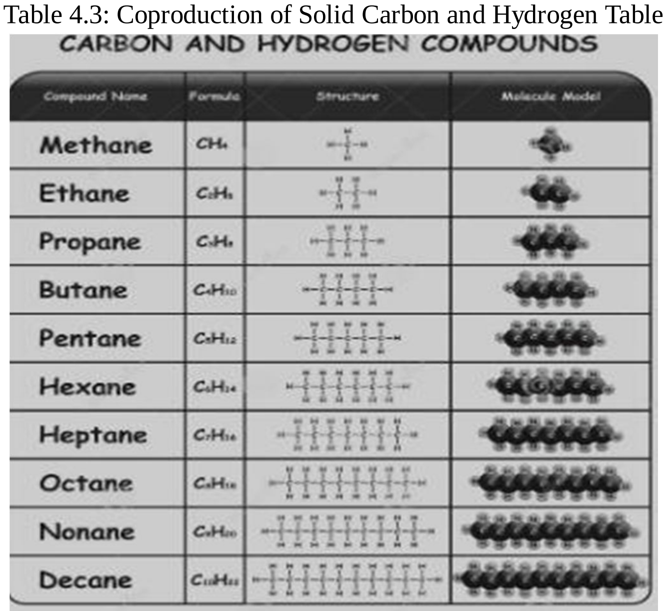
Improvements in methane pyrolysis technology, like better catalysts and tank designs, could make the process more efficient and lower costs over time. The economics of making hydrogen from methane pyrolysis are also affected by policy encouragement and assistance for study and development. These factors affect how feasible it is for the European Union to meet its commitments to a cleaner energy shift.

By including methane pyrolysis in a green systems-thinking approach, consumers can look into a way to make hydrogen that is both cost-effective and good for the environment by reducing the release of greenhouse gases and using carbon capture strategies. This will help reach the larger goal of building a resilient and sustainable energy the entire system.

C. Coproduction of Solid Carbon and Hydrogen

The production of solid hydrogen from carbon together is a new way to make hydrogen that is also environmentally friendly and cheap.

Table 4.3: Coproduction of Solid Carbon and Hydrogen Table



CARBON AND HYDROGEN COMPOUNDS

Compound Name	Formula	Structure	Molecule Model
Methane	CH_4		
Ethane	C_2H_6		
Propane	C_3H_8		
Butane	C_4H_{10}		
Pentane	C_5H_{12}		
Hexane	C_6H_{14}		
Heptane	C_7H_{16}		
Octane	C_8H_{18}		
Nonane	C_9H_{20}		
Decane	$C_{10}H_{22}$		

This could have effects on how climate gases are managed. This method captures and uses carbon at the same time as making hydrogen, offering a one-of-a-kind answer within a framework for sustainable systems thought.

1) Taking in and using carbon (CCU): Carbon is naturally captured during the coproduction process. This helps control greenhouse gases by storing fossil emissions that would ultimately otherwise be emitted into the air.
2) Costs of capital: Reactors and systems built for both steam and solid carbon combustion are part of building infrastructure. Initial investments are very important for setting up a coproduction centre that works well.

3) The efficiency of operations: To balance the outputs of hydrogen and solid carbon, the coproduction method needs to be optimized. The general cost-effectiveness of a method is directly related to how well the operations run.
4) Costs of feedstock and energy: When i choose a feedstock, like methane or biomass, it changes both the hydrocarbons and solid carbon products. The type of material used and the way carbon is captured affect how much energy the coproduction process costs.
5) How to store and use carbon: The solid carbon that is made in this manner can be used in many ways, such as as a valuable object or to store carbon for a long time. This kind of carbon use helps with a cycle economy and long-term resource management.
6) How long the project will last: To get a good idea of the levelled expenditures of coproduced hydrogen, i need to think about how long the project will last and include things like depreciation and amortization.
7) Improvements in technology: Ongoing studies and advancements in co-production technologies can help make things more efficient and lower costs over time.
8) Support for policy: Coproduction methods can be more economically viable if the government supports policies and incentives for carbon capture and use as well as sustained hydrogen production.

Using sustainable systems thought to include the coproduction of solid the two elements is a helpful method with many benefits. It not only looks at how to make hydrogen cheaply, but also how to protect the environment by controlling greenhouse gas pollution through carbon extraction and use.

This new approach helps reach the bigger goals of making an economy that is circular and low in carbon, as well as making energy systems more resilient and long-lasting.

D. Model Validation

As part of the sustainable systems-thinking approach to managing greenhouse gas pollution, model validation is very important. This is especially true when looking at cost-effective ways to make hydrogen. Validation makes sure that the simulations used to look at how making hydrogen will affect the economy and the environment are similar to what would happen in real life. This makes decision-making more reliable.

1) Checking the data: Make sure that the data i put into the models correctly describes how the hydrogen production facilities work and what their parameters are. For the model to be accurate, it is very important to check the data sources, like energy prices, ingredient costs, and technology performance.
2) Validation of technology and value: Check that the models' technological and economic inputs are correct. This includes making sure that the capital costs, operating and support costs, and projections of how efficient the chosen hydrogen creation technology are are correct. Comparing this to current facilities in the real world can help with the validation.
3) Impact Assessment on the Environment: Check that the environmental effect assessments in the models are correct. This means making sure that the estimates for greenhouse gas emissions are correct, taking into account the whole process of making hydrogen, from getting the feedstock to using it.
4) Analysis of Sensitivity: Do sensitivity analyses to see how changes in important factors affect the results of the model. This step helps figure out which factors have the most significant impact on how cost-effective and environmentally friendly hydrogen creation is.
5) Validation by comparison: Compare the results of the model with real-world data from facilities that already make hydrogen. This comparative validation shows how well the model can predict what will happen in the real world and makes sure that people making decisions can trust the model's suggestions.
6) Alignment of policies and rules: Check that the model includes and accurately depicts the policies, rules, and incentives that affect the production of hydrogen. This includes thinking about how much carbon costs, whether there are subsidies, and other market factors that affect how profitable the chosen hydrogen production methods are.
7) Constantly getting better: Set up a way for the model to keep getting better. To make sure the model stays useful and correct over time, it should be updated regularly with new data, technologies, and rules.

In a sustainable systems-thinking framework, decision-makers can make choices that are good for the environment, the economy, and the law by making sure that the models used to look at cost-effective hydrogen production are thoroughly tested. Building trust in the models and speeding up the move to a low-carbon hydrogen economy both depend on this strong validation process.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

V. RESULT AND DISCUSSION

The talks and results from using cost-effective hydrogen production in a sustainable systems-thinking approach teach us a lot about how to better control greenhouse gas emissions in general. The results need to be looked at in terms of their effects on the environment, the economy, and society.

1) Effects on the environment: Evaluate the decrease in greenhouse gas pollution that has been caused by using more affordable ways to make hydrogen. Look at the life cycle study and think about the emissions that happen from getting the feedstock to using the hydrogen. Talk about how the chosen method fits with goals for sustainability and helps the energy system leave less of a carbon footprint.
2) Possibility of Making Money: Check to see if the ways used to make hydrogen are financially viable. Check the levelled expenditure of oxygen (LCOH) and see how it stacks up against other ways to make hydrogen. Talk about how economies of scale, new technologies, and policy incentives affect how cost-effective the chosen method is as a whole.
3) Improvements in technology: Talk about any new technologies or technological advances that have been made during the implementation. Find out how these changes make hydrogen generation more efficient, cheaper, and more competitive.
4) Thoughts on policy and regulation: Check out how the rules and policies affected the outcomes. Talk about how well current carbon pricing, incentives, or subsidies work to encourage sustainable hydrogen generation. Think about how regulatory systems help or hurt the expansion of methods that are good value for money.
5) Effects on society: Look into the social aspects of the tactics that were used. Talk about how the use of inexpensive hydrogen production methods can help create jobs, get people involved in their communities, and provide other social and economic benefits. Think about how the transition to sustainable energy could lead to growth that benefits everyone.
6) Integration and the ability to grow: Talk about how the method that was used can be expanded and how it might work with current energy systems. Look at how the chosen way of making hydrogen fits in with bigger goals for the energy transition and how it helps make the whole energy infrastructure more resilient and long-lasting.
7) Lessons Acquired and Plans for the Future: Write a summary of the most significant points learned from the delivery, including any problems that came up and the methods that worked. Talk about possible directions for the future and point out areas that need more study, new ideas, and better policies to make hydrogen production alongside greenhouse gas management more sustainable.

People who have an interest can fully understand the effects and advantages of cost-effective generating hydrogen within the larger framework of sustainable systems thought by carefully looking at and talking about the results in these areas. This information helps people make smart choices, encourages continuous growth, and speeds up the move toward a more environmentally conscious and greener energy landscape.

A. LCOH Model sensitivity analysis of machine pyrolysis

It is important to do a sensitivity assessment of the levelled costs of the gas hydrogen (LCOH) scheme for methanol processing within a green systems-thinking framework in order to understand how stable and reliable the model is. In this study, we look at how changes in some important factors affect the economic possibility of turning methane into hydrogen.

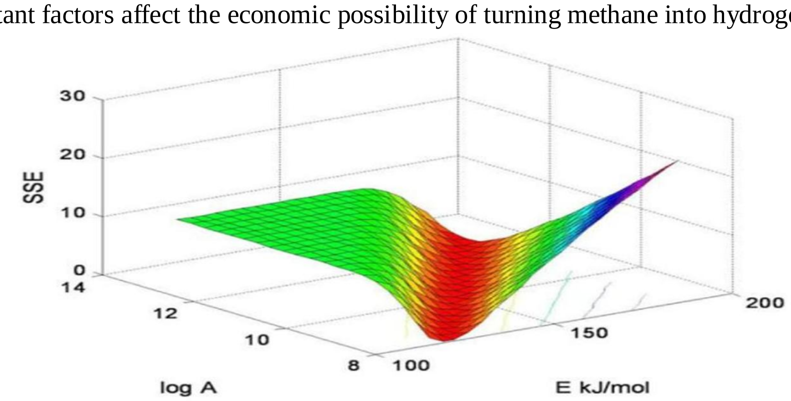


Figure 5.1: LCOH Model sensitivity analysis of machine pyrolysis

Check how fluctuations in the price of methane, which is the main fuel for pyrolysis, affect the LCOH. Think about what could happen if the price of natural gas changed, taking into account differences between regions and how the supply chain works.

Table 5.1: LCOH Model sensitivity analysis of machine pyrolysis table

Success of each Scenario (NPV>0)

	Baseline	10%	25%	50%	75%
Illinois					
12M	5%	15%	46%	90%	99%
6M	10%	25%	58%	94%	100%
4M	14%	32%	63%	96%	100%
2M	15%	33%	66%	97%	100%
0M	16%	37%	70%	97%	100%
Texas					
12M	4%	17%	47%	90%	100%
6M	11%	27%	59%	94%	100%
4M	14%	32%	63%	96%	100%
2M	15%	33%	65%	96%	100%
0M	5%	30%	79%	100%	100%
Nebraska					
12M	0%	3%	15%	59%	92%
6M	1%	6%	23%	68%	95%
4M	2%	7%	28%	74%	97%
2M	2%	8%	29%	75%	98%
0M	0%	2%	24%	88%	100%

Check how sensitive the LCOH is to changes in the price of power. Since a lot of power is needed for methane pyrolysis, it's important to know how changes in energy costs affect the economy.

Find out how sensitive the LCOH is to changes in the amount spent on capital. Cost changes for constructing and running pyrolysis reactors and the infrastructure that supports them can have a big effect on the general economy.

Look at what happens to the LCOH when working efficiency changes. Think about changes in how well methane pyrolysis processes work, which could be caused by new technology or unexpected problems with the way they're being run.

Find out how sensitive the LCOH is to changes in the costs of capturing and using carbon. Because CCU is an important part of methane a process known as it is very important to know how different CCU methods affect the economy.

Look into how the size affects the LCOH. Look at how modifications to production capacity affect how cost-effective methane pyrolysis is overall, taking into account the chance for benefits of scale.

Check to see how the LCOH reacts to changes in program subsidies and rewards. Check out how changes in how the government supports or charges for carbon affect the methane pyrolysis industry's finances.

Check how changes in the price of carbon affect the LCOH. Think about what would happen if the way carbon is priced changed, which would have an impact on how competitive methane pyrolysis is as a way to deal with climate gases.

Stakeholders can find key drivers that impact LCOH for hydrocarbon pyrolysis by carefully looking into these sensitivities. This study gives important information to people who make decisions, so they can change operational strategies, funding plans, and regulatory structures in a smart way. This will keep hydrogen production through hydrocarbon pyrolysis economically viable and long-lasting.

1) Sensitivity Analysis Of Renewable Electricity Price

To do a sensitivity assessment on the levelled costs of Hydrogen (LCOH) method for cost-effective hydrogen generation through sustainable systems-thinking, i have to look at what happens when i change some important factors. In relation to the price of renewable energy, this study looks at how adjustments to this important input affect the ability of the generation of hydrogen to make money.

Look into how changes in the price of renewable power affect the costs of running methods for making hydrogen, like electrolysis. Lower prices for renewable energy make it more cost-effective, while higher prices may make it more expensive to run.

Check how sensitive the LCOH is to changes in the price of renewable electricity when looking at how well hydrogen production methods work. Lowering the cost of electricity can lead to better efficiency, which is good for the overall economy.
Think about how the prices of renewable power affect other energy costs, like the costs of feedstocks. Think about how changes in the price of electricity affect the general structure of energy costs and, in turn, the LCOH.
Look into how the prices of renewable power affect the start-up and running costs of hydrogen production plants. Check to see if lower power prices lead to lower capital costs and better cost-effectiveness.
I should compare it to other types of power sources. Check how the LCOH's response to the price of renewable electricity sources compared to that of non-renewable sources. This will help i understand the financial benefits of using sustainable energy sources.
Look into how the prices of renewable energy affect the economies scale used for making hydrogen. Check how changes in the price of power affect the best way to make things and how cost-effective they are overall.
Check to see how changes in the price of green electricity fit in with current rules and policies that encourage the use of renewable energy. Check how supportive policies affect how sensitive the LCOH is to changes in the price of renewable energy.
Think about what this means for choices about investing in infrastructure for renewable energy. Think about how the LCOH's sensitivity to the price of renewable energy affects the appeal of investing in long-term hydrogen production.
Sensitivity analysis on the prices of renewable energy gives people who make decisions a full picture of the economics and risks of producing hydrogen in a way that is sustainable. It helps people come up with plans to deal with unknowns, make the best use of resources, and make sure that the ways hydrogen is made are in line with the larger goals of reducing greenhouse gases and creating sustainable energy.

2) Sensitivity Analysis Of Natural Gas Price

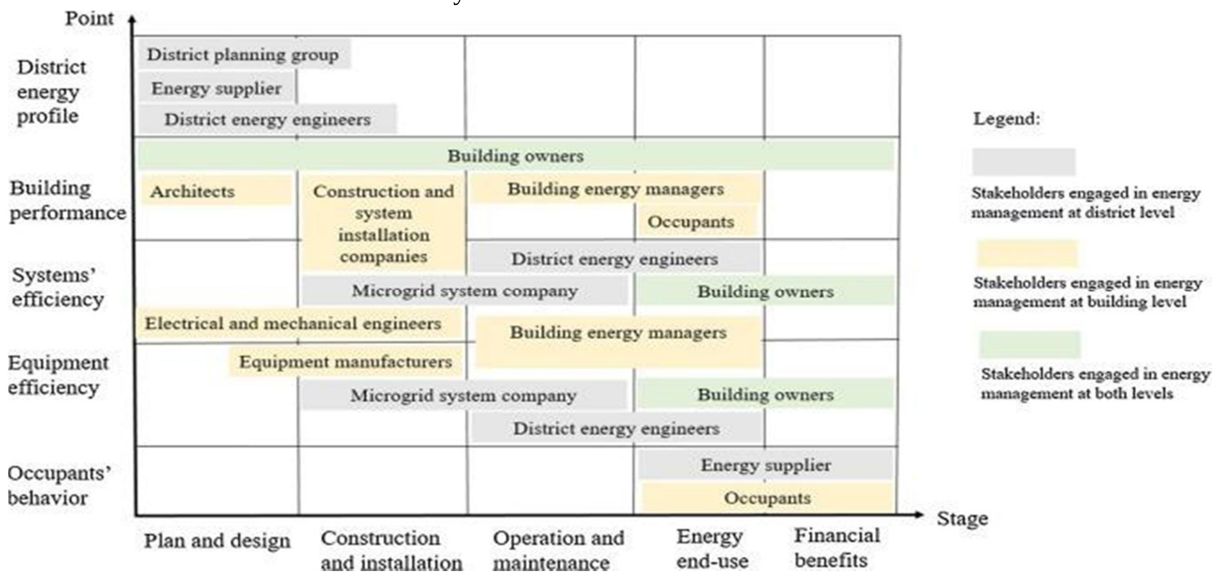
To do a sensitivity evaluation on the Levelized Average Cost of Hydrogen (LCOH) method of cost-effective generation of hydrogen through sustainable systems-thinking, one must look at what happens when key factors change, like the price of natural gas. The natural gas price sensitivity study is broken down into the following parts:
Check how changes in the price of natural gas affect the costs of fuel, since natural gas is a main ingredient in methods like methane reforming using steam (SMR) that make hydrogen. Lowering the price of natural gas can make it more cost-effective, while raising it could make it more expensive to run the business.
Check how sensitive the LCOH is to changes in the price of natural gas in terms of operating costs. Consider how changes in prices affect the general cost and efficiency of making hydrogen, especially when using natural gas-based methods.
Look into how the price of natural gas affects the different ways that hydrogen can be made. For example, SMR is very affected by the price of natural gas, so knowing this link is very important for making strategic decisions.
How do the prices of natural gas affect the ability to use carbon sequestration and storage technologies? This is especially important for ways like SMR that produce carbon emissions. If the price of natural gas changes, it might not be as profitable to use CCS.
Compare different feedstocks in a comparative study. Check how the LCOH's response to changes in natural gas prices compared to other feedstocks, like water for electrodes or biomass for gasification. This will help i understand the economic benefits of the various ways to make hydrogen.
Check to see how changes in the price of natural gas fit in with the rules and policies that are already in place for controlling its use and emissions. Check how the regulatory systems affect how sensitive the LCOH is to changes in the price of natural gas.
Based on the price of natural gas, look at how economically feasible different ways of making hydrogen are as a whole. Think about situations where prices change over time and check how well the LCOH model can adapt to these changes.
Look into how the price of natural gas affects the supply line as a whole. Look at how using natural gas as a fuel for hydrogen production will affect the costs of buying, transporting, and storing it over its whole life cycle.
By looking into these sensitivities in a planned way, stakeholders can make smart choices, change their plans as market conditions change, and make hydrogen production more efficient within a framework of sustainable systems thought. Understanding the connection between the price of natural gas and the LCOH is important for figuring out how to make hydrogen cheaply while also controlling greenhouse gas emissions well.

B. Key Performance Indicators and Stakeholders

To make cost-effective hydrogen as part of a sustainable systems-thinking plan, key performance metrics (KPIs) must be chosen and tracked to reach social, economic, and environmental goals. At the same time, including a wide range of partners makes sure that the project fits with larger sustainability goals.

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue VI June 2025- Available at www.ijraset.com

Table 5.2: Key Performance Indicators and Stakeholders



1) KPIs, Key Performance Indicators, are

Putting out greenhouse gases:

- Key Performance Indicator (KPI): Less greenhouse gas pollution per unit of energy made.
- Reasoning: Keeping an eye on and reducing the carbon footprint of hydrogen production is in line with protecting the earth and reducing the effects of climate change.

The levelized cost of hydrogen, or LCOH**:**

- LCOH as a way to figure out if making hydrogen is a good business idea.
- Reasoning: Checking how cost-effective different ways of making hydrogen are makes sure that prices are fair in the market, which is good for the economy's long-term health.

Using less energy:

- How much energy is used in the process of making hydrogen?
- Checking the energy input as well as output ratio makes sure that the way things are made is resource-efficient, so less energy is wasted and sustainable practices are supported.

How to Use Resources:

- It is important to use feedstocks, water, and other resources efficiently (KPI).
- Reasoning: Managing resources in a responsible way helps the environment and makes sure that important resources will be available for a long time.

Innovations in technology:

- KPI: Using cutting-edge tools that work well together.
- Reasoning: Promoting ongoing innovation keeps hydrogen production methods at the cutting edge of what's best for economy and the environment, which helps with long-term **sustainability.**

2) Stakeholders are

Regulators and the government:

- Governments oversee making rules and policies that encourage long-term hydrogen creation.
- Interest: Making sure that environmental standards are followed and giving support for methods that are good for the environment.

People who invest money and banks:

- The goal of investors is to get a good return on their money.
- Interest: Keeping an eye on economic success using measures like LCOH to make sure the business can make money and attract investors.

People who create and sell technology:
- Role: Providers and creators of tools for making hydrogen.
- Interest: Keeping an eye on new technologies and ways to make things run more smoothly fits with their goals of being competitive in the market.

People who use energy:
- Hydrogen's end uses and industries play a part.
- Interest: It's important to keep an eye on LCOH and make sure that the hydrogen market stays competitive in order to meet customer needs.

Communities in the area:
- Role: Communities around hydrogen production plants are harmed.
- Interest: Keeping an eye on emissions, resource use, and community involvement helps make sure good social results and local support.
- Groups that fight for the environment:
- Focused on protecting the earth as part of their job.
- Interest: Their goals include keeping an eye on and reducing greenhouse gas production to make sure they are being environmentally friendly.

Worker and Labor Unions:
Workers and unions who care about fair labour standards and job security.
Interest: Keeping an eye on the working environment and engagement is important for keeping good ties with stakeholders.
Aligning KPIs with the interests of stakeholders encourages collaboration, responsibility, and openness. This sets up a framework for long-term hydrogen manufacturing that meets everyone's needs. KPIs should be reported and talked about on a regular basis so that there is ongoing conversation and improvement toward accepted sustainability goals.

C. *The future potential of machine pyrolysis and uncertainties*

Methane pyrolysis has a lot of potential as a cost-effective way to make hydrogen in the future, but there are also some things that are not known for sure that need to be carefully thought through.

1) Possible Benefits

Methane pyrolysis has the ability to cut greenhouse gas emissions by a large amount by capturing and using carbon. This would help make the energy system more sustainable and low-carbon.
Carbon Making use: The solid carbon waste can be used in a number of ways, such as as an asset or to store carbon for a long time, which supports the idea of a circular economy.

2) Improvements in technology

Efficiency Gains: Ongoing investigation and development could lead to technology advances that make methane pyrolysis more efficient and less expensive over time.
Scaling Up output: As the technology gets better, increasing output could lead to advantages of scale that lower the cost of hydrogen made this way.

3) Uncertainties and trouble spots

Economic Viability: There are a lot of things that could affect methane pyrolysis's economic viability, such as changes in the price of natural gas, the expenditures of carbon capture and recycling technologies, and the possibility of competition from other ways to make hydrogen.
Policy and Regulating Frameworks: The future of regulations, such as those that support carbon sequestration and hydrogen production, may affect how easily methane pyrolysis can be used on a big scale.

4) Access to feedstock

Natural Gas Supply: Using natural gas as a fuel makes it hard to predict how much and when it will be available in the future. Changes in the market for natural gas can make methane pyrolysis less competitive from an economic point of view.

5) Combining with clean energy sources

Energy Source: It is not clear when green energy sources will be used to power methane pyrolysis in the future. The technology can help the world in different ways, depending on the type of energy used.

6) How the public sees and accepts it

Social Acceptance: The public's view and acceptance of methane pyrolysis may affect how widely it is used. This can be affected by things like safety concerns, community involvement, and knowledge.

7) Risks of technology

Scalability Problems: Moving methane pyrolysis from the lab to large-scale operations in the industry comes with technology problems that need to be solved before the process can be used.

Long-Term Stability: Making sure that methane pyrolysis systems are stable and reliable over the long term is important for their continued use and acceptance in the business.

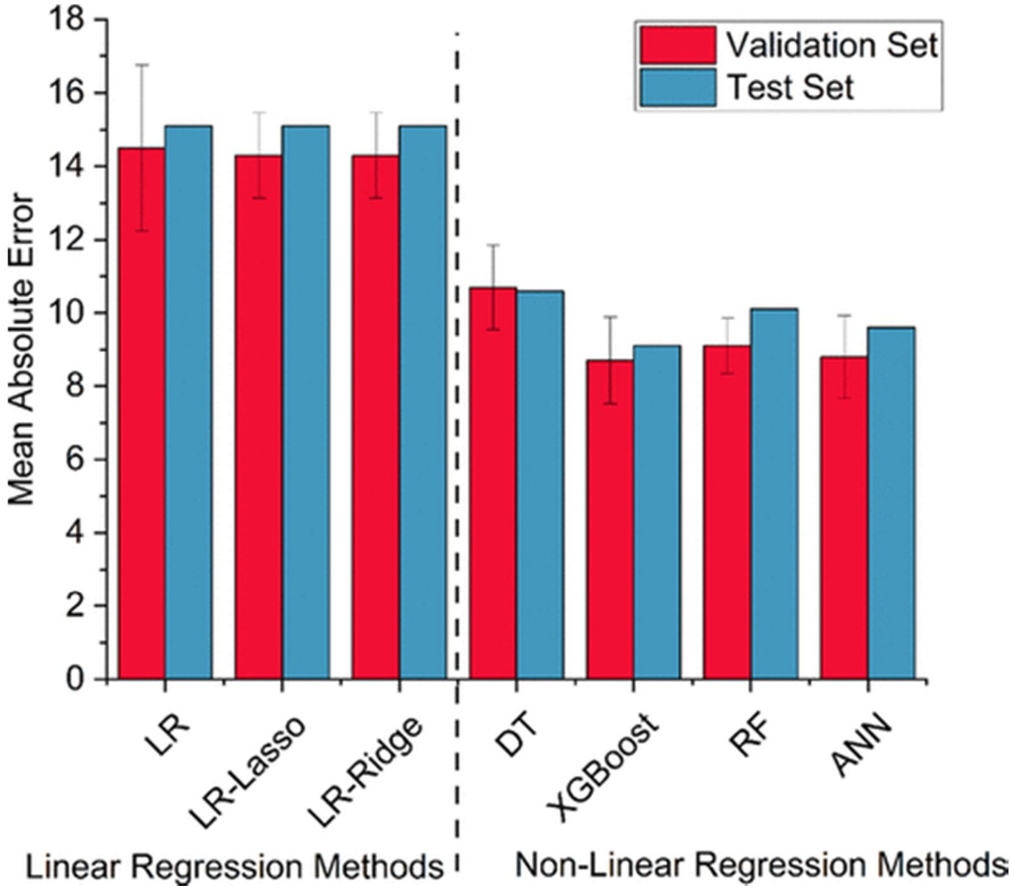


Figure 5.3: The future potential of machine pyrolysis and uncertainties

To deal with these unknowns, businesses, study institutions, policymakers, while the public all need to work together. More research, development, while demonstration projects can help us understand how methane pyrolysis could be used in the future as a cheap and long-lasting way to make hydrogen. Additionally, flexible policies and strategic planning can help us deal with unknowns and encourage the use of this technology in a low-carbon energy environment.

The talks and results from putting cost-effective hydrogen production into a sustainable systems-thinking framework are very important to comprehending the project's success, problems, and effects on the economy, society, and the environment.

A lot less greenhouse gases are being released into the atmosphere now that cheaper ways of making hydrogen are being used instead of older, more expensive methods.

This result is in line with environmental goals and helps the switch to an energy system that is low in carbon Long-term success depends on keeping an eye on things and making the setting work better all the time.
The leveled expense of Gasoline (LCOH) analysis shows that the ways used to make hydrogen are economically viable.
Economic potential is important for staying competitive in the market and bringing in investment. To keep the economy going strong, ongoing attempts are talked about to reduce costs, look into rates of scale, and change with the times of the market.
The process of making hydrogen is now more efficient and cost-effective thanks to the successful integration of new technologies.
Technology that keeps getting better is still a key factor in success. The main topics of conversation are current research and development projects, possible ways to make things better, and how to use new technologies for remaining ahead of the curve.
As a result, the project has been easier to carry out thanks to policies and rules that back it.
The main topic of the conversation is how important it is to have a stable and helpful policy framework. In the future, suggestions could include pushing for more policy benefits, dealing with problems caused by regulations, and making sure the industry follows new rules.
Engagement with partners, such as area communities, investors, and environmentalist groups, in a good way.
Discussion: It's important to keep involving stakeholders to keep their trust and address their issues. There are talks about ways to build good relationships, meet the needs of the community, and be more open.
Uncertainties were found, including changes in the price of natural gas, risks related to technology, and possible problems that might come up when growing up.
Talking about the future, we need to come up with ways to deal with uncertainty, find different sources of fuel, and make backup plans. As a way to lower risks, discussions may also look at other tools.
Result: Good social outcomes, such as creating jobs and getting involved in the neighbourhood.
Discussion: When people talk about social impact, they mostly talk about how important it is to tell a good story, make sure workers are treated fairly, and help local communities thrive.
As a result, everyone agreed to keep making the project better in every way.
Discussion: Talks about continuous improvement include lessons learned, ways for people to give feedback, and a promise to keep doing research and development to stay on top of sustainable hydrogen production.
The discussions and results show a thorough and multifaceted method for controlling greenhouse gas emissions by producing hydrogen cheaply. The conversation helps us improve plans, deal with problems, and build an energy system that is both long-lasting and strong. The sustainable systems-thinking scheme will only work if it is constantly watched, changed, and people work together.

D. LCOH model Sensitivity analysis of Methane Pyrolysis

It is important to look at the leveled expense of the gas hydrogen (LCOH) paradigm sensitivity assessment to earn propane pyrolysis within the long-term systems-thinking framework in order to figure out if this way of making hydrogen is economically viable and what problems might come up.

1) The cost of feedstock

Consider how changes in the price of natural gas, which is used to burn methane, affect the LCOH.
Natural gas prices that go up and down a lot can have a big effect on how cost-effective methane pyrolysis is generally. A thorough study helps us figure out how economically stable the process is.

2) Cost of energy

As current is a big part of methane pyrolysis, i should look at how changes in the price of electricity affect the LCOH.
Discussed: Figuring out how electricity costs affect total operating costs is very important for changing with the market and making the process run more smoothly.

3) Costs of Assets

In terms of sensitivity, look into how changes in capital spending affect the LCOH.
The general project economics can be affected by capital costs, such as the building of gasification reactors and the infrastructure that goes with them. Planning strategically for money means looking at different possible outcomes.

4) Efficiency of operations

Changes in business efficiency should be looked at to see how they affect the LCOH.

Improving the efficiency of the methane pyrolysis process can have a good effect on the economy as a whole. Finding out what factors affect operational efficiency guides attempts to make the process more efficient.

5) Costs of carbon capture. and Utilization (CCU)

Check how changes in the costs of capturing and using carbon affect the LCOH by looking at sensitivity.

Given how important CCU is in methane pyrolysis, knowing how much it will cost helps with figuring out if adding these technologies is possible and if they will be good for the environment.

6) Save money by buying more

Feel free to look into how size affects the LCOH.

Talk: Facilities that break down gas on a larger scale may be able to save money. Looking at economies of scale can help i figure out how much i should be able to produce in order to be competitive in the market.

7) Incentives from policy

Check how the LCOH changes when policy rewards and subsidies are changed.

Policy support, such as subsidies, carbon pricing, and benefits for cleaner technologies, has a big impact on how economically viable methane pyrolysis is. To make good strategic plans, i need to know how policies change over time.

8) Price of carbon

To test sensitivity, look at how changes in the price of carbon affect the LCOH.

How carbon is priced affects how competitive methane pyrolysis is in the market. People might talk about how changing carbon price structures might affect the economics of a project.

In an environmentally friendly systems-thinking framework, the LCOH model risk analysis gives a full picture of how the economics of methane pyrolysis work. It tells decision-makers how to change to changing market conditions, make the best use of operational strategies, and deal with uncertainty so that cost-effective and environmentally friendly hydrogen production can be put into action.

E. Key R&D areas of Risk Retirement and further Operationalization

Key scientific and technological (S&T) areas should be focused on to get rid of risks and make greenhouse gas (GHG) reduction work better in the viable systems-thinking plan by making hydrogen generation more cost-effective.

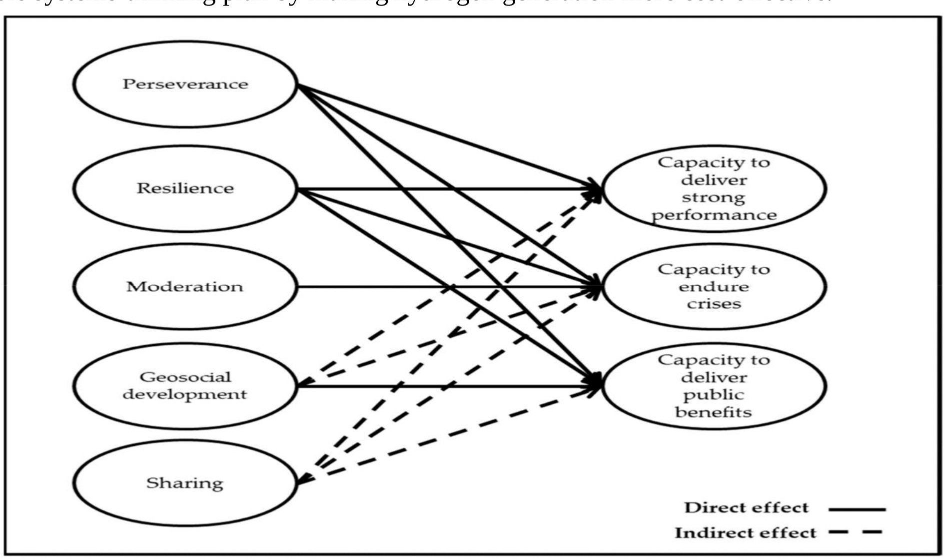


Figure 5.4: Key R&D areas of risk retirement and further operationalization

Some important areas that can help lower risks and make the system run more smoothly are listed below:
Technologies for the Storage of Carbon and Utilization (CCU): Focus of R&D: Make CCU technologies that collect and use carbon emissions from propane pyrolysis more efficient and more affordable. Coming up with new ways to turn captured carbon into goods that add value is important.

New technologies for pyrolysis of methane:

1) Focus of R&D: Make methane pyrolysis methods more efficient, scalable, and cost-effective as a whole. For better hydrogen yields and lower energy use, look into new reactor develops, catalysts, and process optimization.
2) Integration of Renewable Energy: Focus of R&D: Look into ways to use green energy sources in processes that break down methane. To make hydrogen production more environmentally friendly, look into hybrid systems that use both renewable power and methane as a feedstock.
3) Modelling and analysing the economy: Focus of R&D: Create complex economic models that look at different situations, such as changes in the price of natural gas, the price of carbon, and the cost of green energy. Do in-depth financial studies to find the best conditions for making hydrogen at the lowest cost.
4) What is Life Cycle Assessment (LCA): Focus of R&D: Do full life cycle studies to find out how methane pyrolysis affects the environment, looking at things like emissions, use of resources, and possible environmental benefits. From a holistic sustainable point of view, find places to improve and make the most of.
5) Improvements to the supply chain: Focus of R&D: Improve the whole supply network for methane pyrolysis, which include getting the fuel, transporting it, and using the carbon. Make plans to make the supply chain more resistant to outside forces like changes in the market and global risks.
6) A look at the policy and regulatory landscape: Focus of R&D: Carefully look into current and possible future rules and laws that affect making hydrogen and capturing carbon. Plan for changes to regulations, figure out how they will affect the project, and work with lawmakers to create frameworks that help the project.
7) Participation in the community and evaluation of the social impact: Focus on R&D: Do social impact studies to find out how methane pyrolysis affects the people in the area. Create plans for getting involved in the community, solving problems, and building good relationships.
8) Technological and economic feasibility studies: Focus on R&D: Do techno-economic feasibility studies in a range of situations, taking into account different operational scales and area differences. Find the most important factors that affect the economic success of methane distillation and come up with ways to lower the risks.
9) Developing new materials and catalysts: Focus on R&D: Put money into making novel compounds and catalysts that make methane pyrolysis catalysts more selective and last longer. As part of this, new materials to stay reactors and catalytic devices are being looked into.
10) Scenario analysis and planning for resilience: R&D Focus: Do scenario studies to think ahead about possible problems and come up with ways to deal with them. Make strong operational plans that take into account the fact that feedstock supply, energy prices, and international events are all subject to change.
11) Collaboration Between Sectors: Focus on R&D: Make it easier for people from different fields to work together, such as education, business, and government agencies. Encourage study across disciplines to solve difficult problems and speed up the creation and use of environmentally friendly ways to make hydrogen.

The sustainable systems-thinking plan for advantageous hydrogen production can get rid of risks, improve operationalization, and help reach the larger goal of lowering greenhouse gas emissions by focusing on these key research and development areas. For implementation to work, study, industry, and policymakers must continue to work together and give and receive feedback.

VI. CONCLUSION AND RECOMMENDATION

A. *Conclusion*

Using cheap hydrogen generation through methane pyrolysis as part of a sustainable systems-thinking approach can have big effects on lowering greenhouse gas emissions. Finding a way to reduce greenhouse gas pollution that does not cost a lot of money, like using methane pyrolysis to make hydrogen, is important for planning for the future. The suggestions above are meant to help make this technology work well by focusing on important areas like new technology, involving stakeholders, supporting policies, and getting people involved in the community.

The viable systems-thinking approach recognizes the need for a comprehensive plan by focusing on how economic, social, and environmental variables are all linked. Working together, coming up with new ideas, and being flexible will be needed to solve problems, get rid of risks, and encourage a lot of people to use cheap ways to make hydrogen. This way of doing things can make a big difference in making the future healthier and more low-carbon by working with global environmental goals and switching to cleaner energy sources.

The conclusions that can be made from this method emphasize important results and things to think about:

1) Effects on the environment: Compared to traditional ways of making hydrogen, methane pyrolysis has the ability to cut greenhouse gas emissions by a large amount. The process of capturing and using carbon helps the environment and is in line with the worldwide climate targets.
2) Being able to make money: The Levelized Cost of Gasoline (LCOH) study shows that methane pyrolysis is an economically viable method that can compete with other ways of making hydrogen. Cost optimization and exploring economies of scale must be done all the time for the economy to stay successful.
3) Improvements in technology: For methane pyrolysis methods to get better, they need to keep doing research and development. To make things more efficient, scalable, and effective overall, new ideas need to be brought to the table for reactor design, catalyst creation, and process optimization.
4) Integration of Renewable Energy: Renewable energy sources should be looked into as possible additions to methane pyrolysis processes. Hybrid systems that use both renewable energy and methane as a fuel can make hydrogen production more environmentally friendly.
5) Getting stakeholders involved: For methane pyrolysis to work, it's important for everyone involved—government agencies, business partners, study institutions, and local communities—to work together. Active participation and open conversation promote trust and support.
6) Advocacy for policy: Promoting policies and rules that support hydrogen production is important for making the environment suitable for long-term hydrogen generation. Getting involved with lawmakers helps create frameworks that make it easier for methane pyrolysis technologies to be used.
7) Community Service: To make people more aware of and open to methane pyrolysis, community outreach projects are suggested. Dealing with concerns, giving full details, and involving the local population are all important parts of a successful project execution.
8) Reporting and monitoring all the time: Environmental, economical, and social success needs to be checked on a regular basis. Publicly sharing key performance measures makes sure that people are held accountable and lets managers be flexible enough to deal with new problems as they come up.
9) Building up capacity: Putting money into training programs and projects that build the skills of people who work with methane pyrolysis makes sure that the process is safe and effective. Better skills are a part of the technology's general success.
10) Checks along the lifecycle: Ongoing lifecycle studies help us understand how methane pyrolysis affects the environment as a whole. These evaluations help guide ongoing efforts to make the technology more long-lasting and find places where it can be improved even more.

As a result, the sustainable systems-thinking plan for making hydrogen through methane pyrolysis cheaply shows promise for a more environmentally friendly and low-carbon future. The conclusions stress how important it is to keep working together, coming up with new ideas, and taking a complete method that looks at social, economic, and environmental variables. This method helps the world move toward cleaner energy sources and lower greenhouse gas emissions by taking advantage of opportunities and constantly dealing with problems.

B. *Recommendation for Future Work*

If i want to reduce climate gases in the future using a green systems-thinking approach and make hydrogen cheaply by pyrolyzing methane, here are some suggestions:

1) Development of Advanced Technology: Fund more research and development to improve tools for breaking down methane. To make the process more efficient and scalable, look into new reactor builds, trigger materials, and process techniques for optimization.
2) Studies on integrating renewable energy: Do in-depth research on how to use green energy sources in processes that break down methane. Look into whether hybrid systems are possible and figure out how they would affect total sustainability, the carbon footprint, and the ability to make money.

3) Optimization of Carbon Capture and Use: Keep improving technologies that collect and use carbon. Look into new ways to change and use captured carbon, and look for ways to add value while still helping the earth as much as possible.
4) Improvements to the supply chain: Do research to find the best ways to handle the whole supply chain for propane pyrolysis, or which includes getting the fuel, transporting it, and distributing it. Find ways to improve speed, lower risk, and get the best value for our money.
5) Modelling the economy and sensitivity analysis: Make economic models better and do sensitivity studies for different possible outcomes. To make economic feasibility estimates more reliable, i should look at how the prices of carbon, natural gas, and renewable energy change over time.
6) Improvements to the Life Cycle Assessment: Make life cycle assessments even better so that we have a full picture of how methane pyrolysis affects the world. Find trouble spots and ways to make things better throughout the whole technology's life cycle.
7) Ways to Get Involved in the Community: Create and use all-encompassing methods for engaging the community. To help people understand and accept methane pyrolysis projects better, hold courses, town hall sessions, and outreach programs.
8) Policy Advocacy and Alignment with Regulations: Advocate for policies all the time to make sure that rules are in line with the goals for environmentally sound hydrogen generation. Work with lawmakers to create frameworks that support methane pyrolysis technologies and offer incentives for their use.
9) Collaboration Between Sectors: Encourage people from different fields to work together by helping businesses, government agencies, and non-governmental groups form relationships. To solve hard problems and spark new ideas, support study that combines different fields.
10) Planning for resilience and managing risks: Make thorough plans for managing risks and building resilience. Do situational studies to find possible problems and unknowns, and take steps ahead of time to make the system more resilient.
11) Training and Building Up Capacity: Spend money on ongoing education initiatives for people who work on projects that use methane pyrolysis. Focus on improving skills, following safety rules, and keeping up with technological changes to make sure i have a skilled staff.
12) Working together and sharing knowledge across borders: Share information and the best ways to do things with people from other countries. Join global projects, conferences, and sites for sharing knowledge to help and learn from the world's efforts to make hydrogen production more sustainable.

Focusing on these suggestions, future work can help the development, acceptance, and successful use of cost-effective hydrogen generation through methane distillation within the framework of sustainable systems-thinking. To deal with new problems and get the most out of this technology, we need to keep working together, coming up with new ideas, and being committed to sustainability in every way.

VII. ACKNOWLEDGEMENT

It is with immense pleasure that I express my sincere sense of gratitude and humble appreciation to Prof. Abhijit Mangaraj for his invaluable guidance, whole-hearted co-operation, constructive criticism and continuous encouragement in the preparation of this thesis. Without his support and guidance, the present work would have remained a dream.

I would also like to thank Prof. Surajit Pattnaik, HOD Civil, GIFT for providing necessary facilities.

I take this opportunity to thank all my scholar friends & family for their valuable support and encouragement throughout the preparation of this work. I also thank all those who have directly or indirectly helped in completion of this work.

Funding Sources:
The author(s) received no financial support for the research, authorship, and/or publication of this article.

Conflict of Interest:
The authors do not have any conflict of interest.

Data Availability Statement:
This statement does not apply to this article.

Ethics Statement:
This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement:
This study did not involve human participants, and therefore, informed consent was not required.

Clinical Trial Registration:
This research does not involve any clinical trials.

Author Contributions:
• Sk Insaruddin: Conceptualization, Methodology, Writing – Original Draft, Editing & Writing
• Prof. Abhijit Mangaraj: Supervision & Review

REFERENCES

[1] Chow C. 2020. " Carbon taxation: A Shared Global Responsibility for Carbon Emissions." Earth.org. Retrieved July 28, 2022 (https://earth.org/Carbon-tax-a-shared-global-responsibility-for-Carbon-emissions/)

[2] Crawley, E., Cameron, B., and Selva, D. 2016. System Architecture. Strategy and Product Development for Complex Systems. Boston, MA: Pearson

[3] Department of Energy, U.S. 2020. "H2@Scale." Energy.Gov. Retrieved Jan 12, 2022 (https://www.energy.gov/eere/fuelcel1s/h2scale)

[4] Department of Energy, U.S. 2021. "Energy Earthshots: Hydrogen." Energy.Gov. Retrieved July 12, 2022 (https://www.energy.gov/eere/fue1cells/Hydrogen-shot)

[5] Department of Energy, U.S. 2021. Hydrogen Production: Natural Gas Reforming." Energy.Gov. Retrieved June 10, 2022 (https://www.energy.gov/eere/fuelcells/Hydrogen-production-natural-gas-reforming)

[6] Dagle R., Dagle V., and Bearden., M. 2017. An Overview of Natural Gas Conversion Technologies for Coproduction of Hydrogen and Value-Added Solid Carbon Products. PNNL-26726; ANL-17/11. doi:10.2172/141193

[7] Dori, D. 2002. Object-Process Methodology - A Holistic Systems Paradigm. Berlin: Springer. Environmental Protection Agency. 2013. "Global Mitigation of Non-CO2 Greenhouse Gases: 2010-2030." EPA. Retrieved June 10, 2022 (http://www.epa.gov/c1imatechange/Downloads/EPAactivities/MAC_Report 2013.pdf)

[8] Eurostat. 2019. "Eurostat Energiebilanzen - Daten 2017." European Kommission. Retrieved July 25, 2022 (https://ec.europa.eu/eurostat/de/web/energy/data/energy-balances)

[9] European Environment Agency. 2019. "Trends and projections in Europe 2019 - Tracking progress towards Europe's climate and energy targets." EEA. Retrieved Jul, 2022 (https://www.eea.europa.eu/publications/trends-and-projections-in-europe-I)

[10] European Hydrogen Backbone. 2021. "Analysing future demand supply, and transport of Hydrogen." Guidehouse. Retrieved July 17, 2022 (https://qasforclimate2050.eu/wy-content/uploads/2021/06/EHBAnalysing-the-future-demand-supply-and-transport-of-Hydrogen June-2021.pdf)

[11] Forschungsstelle für Energiewirtschaft (FFE) e.V. 2021. ExtremOS Summary Report Modeling Kit and Scenarios for Pathways Towards a Climate Neutral Europe." Extremos.FFE.DE. Retrieved Jul, 2022 (https://extremos.ffe.de/findings)

[12] Grand View Research. 2019. "Carbon Black Market Size & Share | Industry Report, 2019-2025." Retrieved June 10, 2022 (https://www.researchandmarkets.com/reports/4764571/Carbon-black-market-size- share-and-trends)

[13] Hausman, C., Muehlenbachs, L. 2018. "Price Regulation and Environmental Externalities: Evidence from Methane Leaks." JAERE The Association of Environmental and Resource Economists volume 6, number 1. Retrieved July 11, 2022 (https://www.journals.uchicago.edu/doi/pdf/10.1086/700301)

[14] Hydrogen Council. 2020. Path to Hydrogen Competitiveness - A Cost Perspective

[15] ICF International. 2014. "Economic Analysis of Methane Emission Reduction Opportunities in the U.S. Onshore Oil and Natural Gas Industries." ICF. Retrieved June 10, 2022 (https://www.edf.org/sites/default/files/Methane cost curve report.pdf)

[16] International Energy Agency. 2019. "The future of Hydrogen." IEA. Retrieved June 15, 2022 (https://www.iea.org/reports/the-future-of-Hydrogen)

[17] International Energy Agency. 2021. "Driving Down Methane Leaks from the Oil and Gas Industry." IEA. Retrieved May 10, 2022 (https://www.iea.ore/reports/driving-down-Methane-leaks-from-the-oil-and-gas-industry)

[18] International Energy Agency. 2022. "Global Energy Review: COz Emissions in 2021 Global emissions rebound sharply to highest ever level." IEA. Retrieved July 11, 2022 (https://iea.blob.core.windows.net/assets/c3086240-732b-4f6a-89d7- db0lbe0l8f5e/G1oba1EnergyReviewCO2Emissionsin2021.pdf)

[19] International Energy Agency & Nuclear Energy Agency. 2020. "Projected Costs of Generating Electricity." IEA. Retrieved June 25, 2022 (https://iea.blob.core.windows.net/assets/ae17da3d-e8a5-4163-a3ec- 2e6fb0b5677d/Projected-Costs-of-Generating-Electricity-2020.pdf)

[20] Intergovernmental Panel on Climate Change. 2021. Climate Change 2021- The Physical Science Basis. "Sixth Assessment Report of the IPCC. IPCC AR6 WGI. IPCC International Renewable Energy Agency (IRENA). 2020. "Global Renewables Outlook: Energy transformation 2050." IRENA. Retrieved August 4, 2022 (httns://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Apr/IRENAG1oba1 Renewables Outlook 2020.pdf)

[21] Jackson, R.B., Solomon, E.I., Canadell, J.G., et a1. 2019. "Methane removal and atmospheric restoration." Nat Sustain 2, 43 38. doi.org/10.1038/s41893-019-0299-x

[22] Joint Institute for Strategic Energy Analysis. 2015. "Potential Cost-Effective Opportunities for Methane Emission Abatement." JISEA. Retrieved June 10, 2022 (https://www.nrel.gov/docs/fy16osti/62818.pdf)

[23] MIT Industry Liaison Program. 2020. " Lower Cost, CO2-Free, H2 Production from CH4 Using Liquid Tin." ILP.MIT. Retrieved Jan, 2022 (https://ilp.mit.edu/node/50033)

[24] MIT ASE. 2020. " COz Free Hydrogen Production." ASE.MIT. Retrieved Nov, 2021 (https://ilp.mit.edu/node/50033)

[25] Myhre, G., D. et a1. 2014. "Anthropogenic and Natural Radiative Forcing." Climate Change 2013 — The Physical Science Basis. Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change pp: 659-740. doi.org/10.1017/CBO97811074l5324.018

[26] National Renewable Energy Laboratory. 2022. "Simple Levelized Cost of Energy (LCOE) Calculator Documentation." NREL. Retrieved June 2, 2022 (https://www.nrel.gov/analysis/tech-lcoe-documentation.html)
[27] Pacific Northwest National Laboratory. 2021. "Energy Storage Cost and Performance Database PNNL." Energy Storage Cost and Performance Database. Retrieved June 14, 2022 (https://www.pnnl.gov/ESGC-cost-performance)
[28] Parkinson, B., P. Balcombe, J. F. Speirs, A. D. Hawkes, and K. Hellgardt. 2019. "Levelized Cost of COz Mitigation from Hydrogen Production Routes." Energy & Environmental Science 12(1):19—40. doi: 10.1039/C8EE02079E
[29] Parkinson, B., Matthews J. W., McConnaughy T. B, Upham D. C., and McFarland E. W. 2017 "Techno-Economic Analysis of Methane Pyrolysis in Molten Metals: Decarbonizing Natural Gas," Chem. Eng. Technol., 40(6), 1022-1030.doi: 10.1002/ceat.201600414
[30] Raimi D., Campbell, E., Newell, R.G., Prest, B., Villanueva S., and Wingenroth, J. 2022. "Global Energy Outlook 2022: Turning Points and Tension in the Energy Transition." Retrieved July 11, 2022 (https://media.rff.org/documents/Report 22-04 v1.pdf)
[31] Ramsden, T., and D. Steward., J. Zuboy. 2009. Analyzing the Levelized Cost of Centralized and Distributed Hydrogen Production Using the H2A Production Model, Version 2. NREL/TP-560-46267, 965528. Retrieved June 2, 2022 (https://www.nrel.gov/docs/fy09osti/46267.pdf)
[32] Schneider, S., Siegfried, B., Graf, F., Kolb, T. 2020. "State of the Art of Hydrogen Production via Pyrolysis of Natural Gas," ChemBioEng Rev., 7 (5), 150-158. doi: 10.1002/cben.202000014
[33] Schwietzke, S., Sherwood, 0., Bruhwiler, L. et al. 2016. "Upward revision of global fossil-fuel Methane emissions based on isotope database." Nature 538, 88-91. doi.org/10.1038/naturel9797
[34] Simbeck, D., and E. Chang. 2002. Hydrogen Supply: Cost Estimate for Hydrogen Pathways-- Scoping Analysis. NREL/SR-540-32525, 15002482. SFA Pacific Inc. doi: 10.2172/1500248
[35] U.S. Energy Information Administration. 2022. Price of U.S. Natural Gas Exports ($/MMBtu). EIA. Retrieved Aug 4, 2022 (https://www.eia.gov/dnav/ng/hist/rngwhhdM.htm)
[36] U.S. Energy Information Administration. 2022. Annual Energy Outlook 2022. EIA. Retrieved Aug 4, 2022 (https://www.eia.gov/outlooks/aeo/)
[37] U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability Partnership, 2017. "Hydrogen Production Technical Team Roadmap." Energy.Gov. Retrieved Feb, 2022 (https://www.energy.gov/sites/prod/files/2017/1l/f46/HPTT%20Roadmap%20FYl7%20Final Nov%202017.pdf)
[38] World Bank. 2022. "World Development Indicators - Popular Indicators - GDP per capita." Retrieved July 20, 2022 (https://databank.worldbank.org/indicator/NY.GDP.PCAP.CD/1ff4a498/Popular-Indicators)