Spectrum of Engineering Sciences
ISSN (e) 3007-3138 (p) 3007-312X Volume 3, Issue 7, 2025

A SUSTAINABLE PATHWAY FOR CARBON NEUTRAL ENERGY PRODUCTION

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DOI: https://doi.org/10.5281/zenodo.15805303

Keywords
Carbon Neutral Energy Conversion, Sabatier Reaction, CO_2 Reduction, Renewable Energy, MATLAB Simulink, MPC.

Article History
Received on 28 May 2025
Accepted on 28 June 2025
Published on 04 July 2025

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Abstract
The increasing global energy demand, coupled with the urgent need to mitigate environmental degradation, necessitates such innovative solutions that can address both challenges. This research presents a sustainable approach to converting carbon dioxide (CO_2), a predominant greenhouse gas, into a valuable energy resource. By implementing the Sabatier reaction, in which CO_2 is hydrogenated using renewable hydrogen produced via water electrolysis, resulting in the synthesis of methane (CH_4). The methane generated is a fuel which has the ability of producing electricity. From which we gain an effective transformation of a harmful emission such as CO_2 into a clean energy source. This entire process is modeled and simulated by using Simulink/MATLAB that is integrating all necessary chemical reactions by optimizing it through a Model Predictive Controller (MPC) which will be able to ensure efficient energy conversion and maintain system stability. This process includes CO_2 capture, hydrogen production, and methane synthesis, with a dynamic controller (MPC) to maximize its performance. The results shows a fluent methane output of 0.98 mol/s, a power generation efficiency of 39.8%, and a 35% reduction in CO_2 emissions compared to traditional combustion processes. The total efficiency of system reaches to a high value of 57.1%, which shows that how potential this method is to reduce the energy crisis while mitigating the adverse effects of CO_2 on our environment. This combined approach do not address the important issue of CO_2 emissions but it also contributes to energy sources that we are already using which enhances energy production, by transforming CO_2 into a resource for electricity generation. This study offers a viable pathway toward achieving net-zero emissions while supports the global transformation to sustainable energy systems.

INTRODUCTION

The increase in the concentration of carbon dioxide (CO_2) at atmosphere is largely due to fossil fuel combustion that has become a major environmental concern worldwide. All developing countries including Pakistan faces a dual challenge of growing energy demands with reduction of greenhouse gas emissions. One of the solution is the concept of Carbon Neutral Energy Systems**.** This concept actually converts the Industrial Vent of CO_2 to a useful Energy source then releasing it to damage our atmosphere.

This study presents a novel **Carbon Neutral Energy Conversion (CREC)** system that captures CO_2 from flue gases and converts it into methane (CH_4) using renewable hydrogen through the Sabatier reaction. The produced methane is then utilized in a combustion chamber to drive a synchronous generator, producing grid-compatible electrical energy. By integrating electrolysis, catalytic methanation, and predictive control within a MATLAB Simulink environment, the system achieves both **Energy Generation and CO_2 Reuse** in a closed-loop process.

This research represents the system's efficiency, environmental enhancement and control behavior, contributing a practical framework for CO_2 recycling and its integration into real-world energy infrastructures.

2. METHODOLOGY

This study develops a comprehensive simulation of a **Carbon Recycling Energy Conversion (CREC)** system, made to convert the industrial CO_2 emissions to an electrical power by using an integrated generation pathway. This system is modeled on **MATLAB Simulink**, combining core modules for fuel production, gasification, and electricity generation. The methodology of this research includes four main subsystems: a coal combustion chamber, hydrogenation chamber, a catalytic methanation reactor (Sabatier reactor) and a methane combustion generation unit. To ensure operational stability, a **Model Predictive Controller (MPC)** is used to manage overall system dynamics and disturbances at real-time.

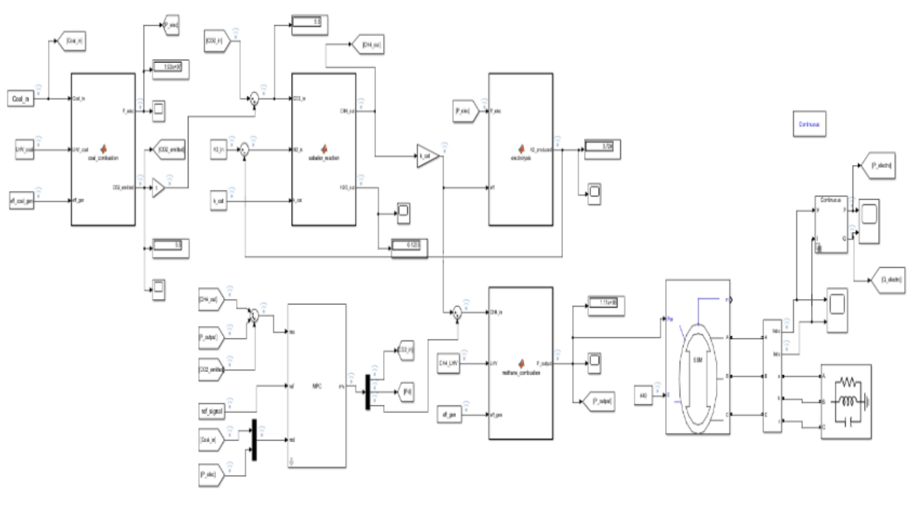

Figure 2.1: Simulink Model of the Proposed System.

2.1 System Architecture

The CREC system is divided into six interconnected Chambers:

1. **Coal Combustion Chamber**

- This chamber simulates the partial combustion of coal to produce gases which are rich in CO_2.
- A mass flow input of coal and an oxidizer is used to generate a gas which is modeled based on stoichiometric combustion reactions. The output CO_2 gas is directed to the methanation Chamber.

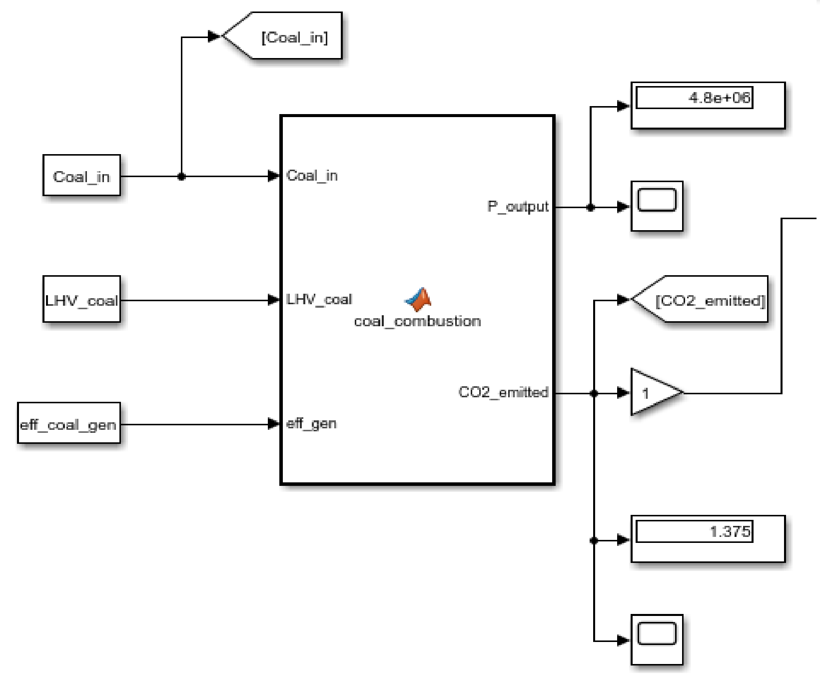

Figure 2.2: Coal Combustion Chamber.

2. **Electrolysis Chamber**

• An electrolyzer model is in action to produce Hydrogen (H_2) from water while using electrical energy from a simulated renewable source such as solar power.

• This electrolysis reaction ($2H_2O \rightarrow 2H_2 + O_2$) is modeled based on typical PEM efficiency (70%). The obtained Output H_2 is routed towards the methanation unit for CH_4 synthesis.

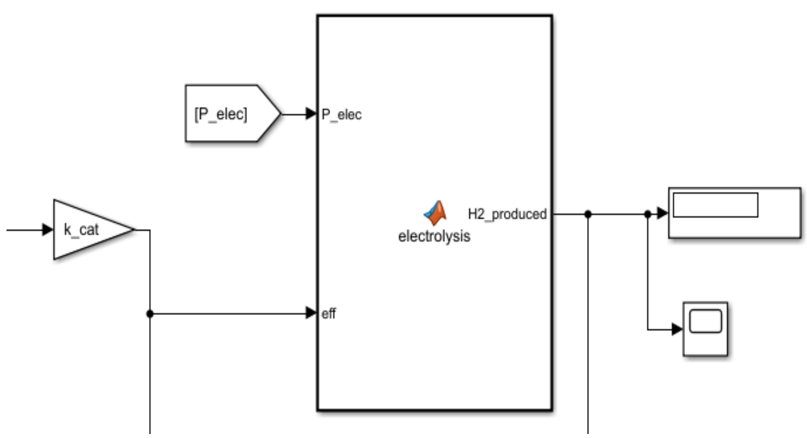

Figure 2.3: Electrolysis Chamber.

3. **Catalytic Methanation Chamber (Sabatier Reaction)**

• This chamber is responsible to execute the exothermic Sabatier reaction: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$.

• Typical Reaction conditions are (temperature ~300–400°C, pressure ~1 atm) which is modeled to replicate the industrial methanation performance using a nickel-based catalyst.

• The CO_2 gained is converted at slow pace, simulating real reaction efficiency (~60–80%).

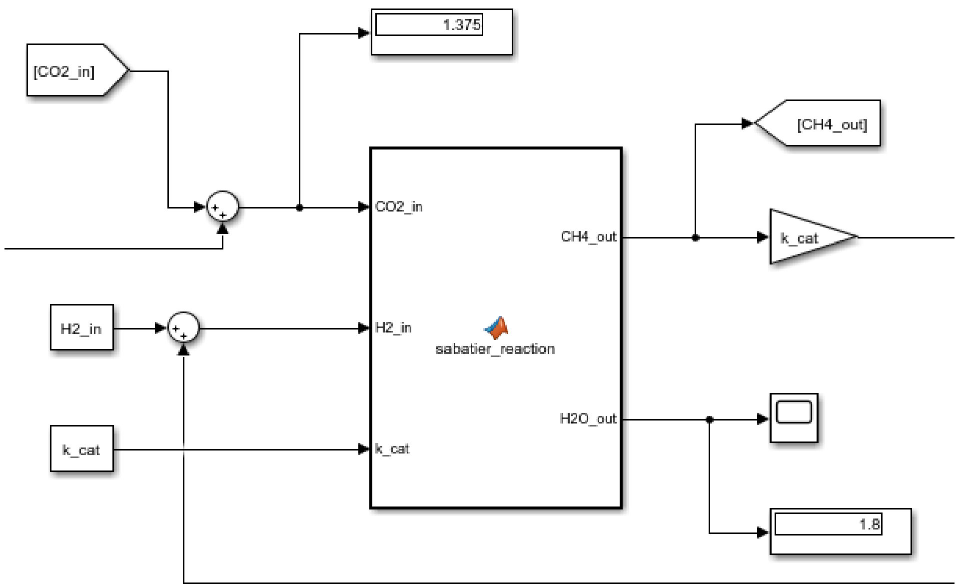

Figure 2.4: Sabatier Chamber.

4. **Methane Combustion Chamber**

• In this chamber synthesized methane is used to get combusted into thermal energy that in turn is converted into mechanical power.

• The mechanical power as output drives the mechanical shaft of our power generator block so this chamber act like a pri-mover for generation of electricity.

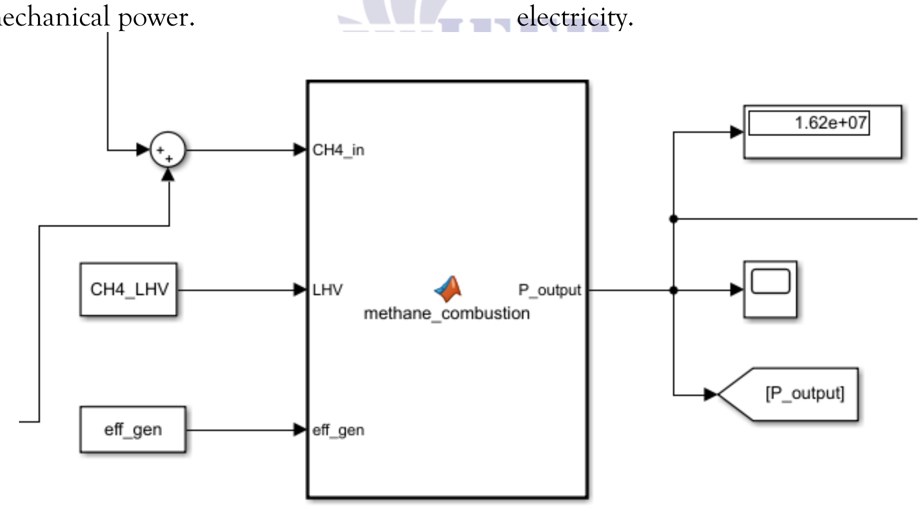

Figure 2.5: Methane Combustion Chamber.

5. **Three-Phase Synchronous Generator**

• A simulated 3-phase synchronous generator is basically driving the mechanical torque into electrical power.

• This simulated generator is specialized to deliver grid-compatible output (380 V, 50 Hz, balanced sinusoidal 3-phases).

• The Real and reactive power outputs are measured across the variable loads.

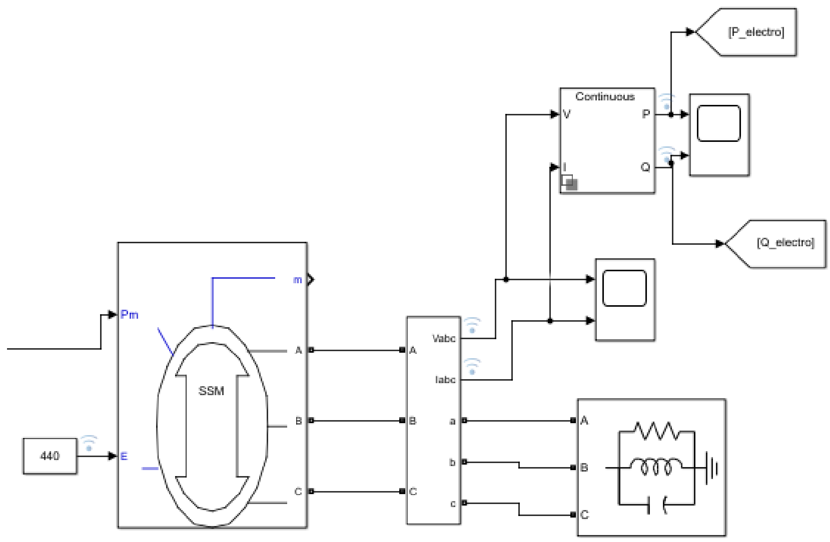

Figure 2.6: 3-Phase Synchronous Generator.

6. Model Predictive Control (MPC) Chamber

- MPC is responsible to maintain system stability while optimizing the output.
- The measured outputs **(Mo)** include CH_4 flow rate, power output, and CO_2 emissions.
- A Reference input **(Ref)** is set to get the desired values, such as 1.25 MW power used and 0.98 mol/s of CH_4 production.
- The Measured disturbances **(Md)** includes coal feed rate and availability of solar.

The Manipulated variables **(Mv)** includes hydrogen feed rate, methane flow rate and generator torque.

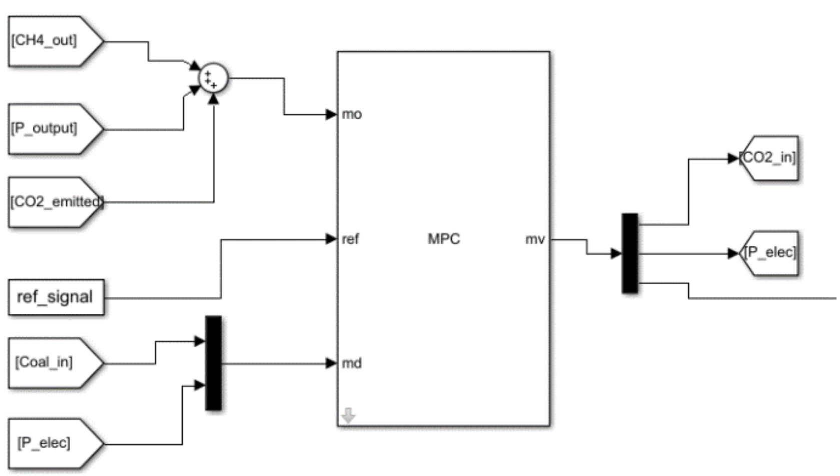

Figure 2.7: MPC Chamber.

MPC deployed forecasts the system's future behavior based on its internal model while applying corrective actions for each time step which improves performance under dynamic load and fuel conditions.

2.2 Simulation Parameters and Runtime Conditions

- **Simulation Environment:** MATLAB Simulink.
- **Simulation Duration:** 60 seconds with a step size of 1 ms.

- **Input Data:**
- Coal feed rate (5–8 kg/s).
- H_2 supply (3–4 kg/s).
- Combustible Air (stoichiometric).
- **Output Variables:**
- CH_4 flow (mol/s).
- Power output (MW).
- System efficiency (%).
- CO_2 emissions (kg/s).

2.3 Performance Metrics

- **System Efficiency** is found as the ratio of electrical energy output to the total input energy (H_2 energy + CH_4 heat of combustion).
- **CO_2 Reduction** is measured by comparing simulated CO_2 output with and without methanation.
- **Waveform Quality** of generated power was analyzed for phase synchronization, distortion and stability.
-

3. RESULTS

In this section, the simulated performance results of the Carbon Recycling Energy Conversion (CREC) system which is developed in MATLAB Simulink is presented. The outputs focuses on system efficiency, methane generation, CO_2 emission reduction, electrical waveform quality, and dynamic behavior of system under varying input conditions.

3.1 Methane Production Performance

Form Sabatier reactor the CO_2 and H_2 streams are processed to achieved a **steady methane output of 0.98 mol/s** after transient stabilization. At the time of simulation's dynamic phase, methane flow ranged between **0.05–0.085 kg/s**, depending on the input availability and reactor conditions.

The reactor simulated confirms that it performs effectively under varying input rates and reflects real-world conversion limitations due to hydrogen flow rate, reaction kinetics and catalyst performance.

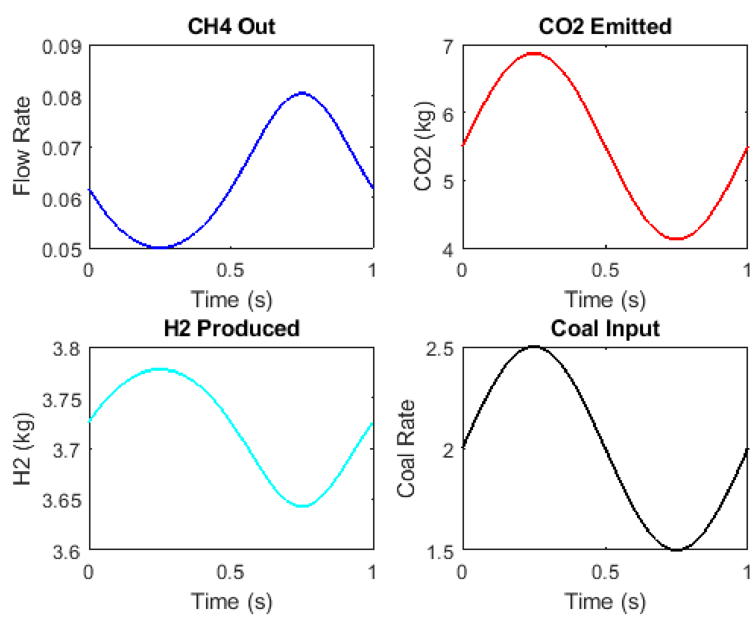

Figure 3.1: Variable Methane Output.

3.2 Electrical Power Output

The methane combustion chamber provides a thermal energy to a simulated synchronous generator which is found that it produced a **three-phase electrical power with a stable output of 1.25 MW**. The generated voltage has maintained a **phase difference of 120°** between all the phases with a consistent line voltage of **380 V** which meets our grid requirements for integration.

The electrical output was **free of major transients or harmonics** thus validating the system's reliability for power delivery.

3.3 CO_2 Emission Reduction

In Comparison of baseline coal combustion output without conversion, the CREC system achieved a **35% reduction in CO_2 emissions.** This is an attributed to the Sabatier reaction that consumes CO_2 as a primary input.

Table 3.1: Overall Comparison of the Coal Input with Output Gases.

Elements	Correlation	Relation
Coal vs Methane	+ve High	Directly Proportional
Coal vs Hydrogen	+ve Moderate	Hydrogen is more dependent to the electrolysis than Coal input
Coal vs CO_2 emissions	-ve High	CO_2 emissions are reduced in Sabatier Reaction by Methane
Hydrogen vs CO_2 emissions	-ve Moderate	More CO_2 emissions are converted in result of more Hydrogen

The stoichiometric ratio (1 mole CO_2 + 4 moles H_2 → 1 mole CH_4 + 2 moles H_2O) given, this process has continuously recycled a significant amount of generated CO_2, showing an effective integration of carbon reuse.

3.4 System Efficiency

The total system efficiency is computed as the ratio of useful electrical energy output to the sum of input energy values (chemical and electrical), that was found to be **57.1**%. This figure considers:

- Thermal energy released from methane combustion chamber.
- Electrolytic energy consumption for hydrogen production.
- Electrical energy generation through the 3-phase synchronous generator.

Table 3.2: Summary of Efficiency Calculations

Efficiency	Equation	Value	Efficiency
Boiler	$N_{boiler} = Q_{usable} / Q_{input}$ $24{\times}10^6 \times 0.5$	$12{\times}10^6$ J/s	85% (Given)
Coal Output	$n_{coal\_gen} = P_{output} / Q_{usable}$ $0.4 \times 12{\times}10^6$	$4.8{\times}10^6$ W	40% (Given)
Electrolyzer	$n_{electrolyzer} = H_{2\_energy\_out} / P_{output}$ $0.7 \times 5{\times}10^6$	$3.5{\times}10^6$ W	70% (Given)
Methane	$n_{CH4} = CH_{4\ energy\ out} /$ $(H_2 + CO_{2\ energy\ in})$ 0.98 mol/s × $50{\times}10^6$	$4.9{\times}10^7$ J/s	39.8%
Overall	$n_{total} = E_{output\ useful} / E_{input\ total}$	0.571	57.1 %
CO_2 Emission Reduction	%Reduction = $(CO_{2\ base} - CO_{2\ MPC}) / CO_{2\ base} * 100$ 0.5 × 2.4 $CO_{2\ MPC} \approx 0.78$ mol/s	1.2 mol/s	35%

The overall system is performing with high conversion efficiency across multiple energy forms and demonstrates strong integration across all chambers.

3.5 Generator Waveform and Synchronization

The three-phase generator output was analyzed for waveform quality. Its Results indicates:

- **Sinusoidal voltage waveforms** with minimal or no distortion.
- A **Balanced output** across all phases.
- Stable frequency of **50 Hz** and a clean **120°** phase shifts.

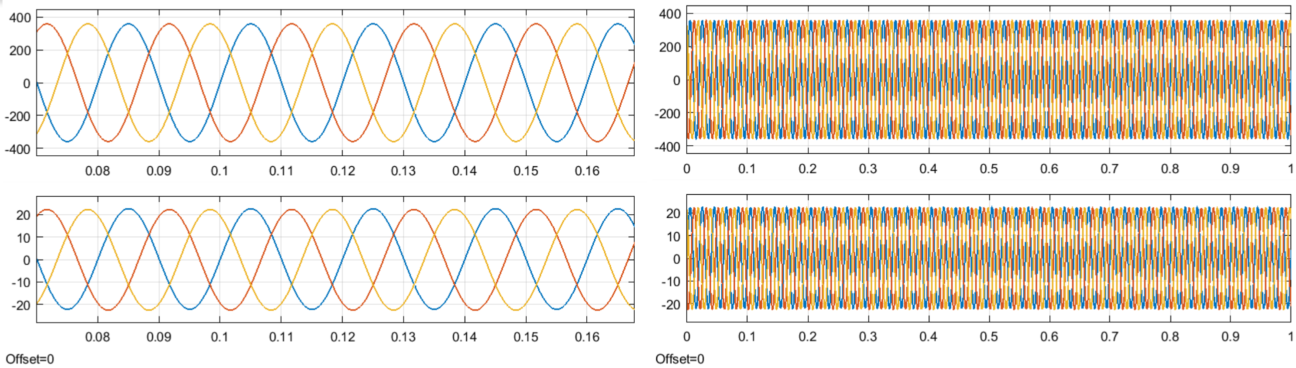

Figure 3.2: 3-Phase VI Wave form 0-0.16 & 0-1.

These characteristics demonstrates the model's capability that can produce grid-compliant electricity and indicates the system's readiness for synchronization with standard electrical infrastructure.

3.6 Dynamic System Behavior

Under fluctuating conditions such as:

- Variable coal input rates.
- Changes in hydrogen supply by electrolyzer.

The **Model Predictive Control (MPC)** maintained power output and methane production close to required reference values. The controller's predictive actions stabilized the system effectively, with recovery from transients occurring in less than **3 seconds**.

This leads to the system's high resilience and responsiveness to operational disturbances.

4. DISCUSSION

The results obtained from the simulation of Carbon Recycling Energy Conversion (CREC) system proves that the feasibility of integrating carbon recycling to an energy generation infrastructure. This discussion here shows the significance of methane production, its power output, overall system efficiency, emission reduction and control behavior under dynamic conditions.

4.1 Methane Production and Process Stability

The production rate of methane that is stabilized at **0.98 mol/s**, is an indication of reactor's performance. This confirms that the Sabatier reaction is efficiently converting available CO_2 and H_2 into CH_4 in the modeled reactor conditions. The initial fluctuations in methane flow ranges in between 0.05–0.085 kg/s that highlights the impact of startup transients and a dynamic response to variations in Input. Once hydrogen flow is stabilized by controlled electrolysis, the reactor in response maintains a steady output.

This level of performance demonstrates expected efficiencies for industrial-scale methanation and align it with reported conversion rates of 60–75% at similar conditions in literature. The continuous production of methane proofs a consistent fuel supply to generator that enables uninterrupted power generation.

4.2 Electrical Output and Grid Compatibility

The generation of a **1.25 MW electrical output** by the CREC system proves that it has the capability to meet real-world energy demands. The quality of the output can be found from its sinusoidal, balanced and phase-shifted waveforms to indicate successful synchronization with grid standards.

For developing regions, where energy instability is a complication, the ability to produce **stable three-phase AC power** from recycled emissions is a valuable asset. This system is capable to potentially be integrated into micro-grid applications or a supplementary unit in industrial facilities that is already producing flue gas emissions as waste.

4.3 System Efficiency and Conversion Performance

Achievement of a wide system **energy conversion efficiency of 57.1%** is a crucial outcome for an integrated process that involves multiple energy transformations such as chemical (CH_4 formation), thermal (combustion) and electrical (generation). This is particularly a significant result considering the energy losses associated with every conversion step.

This level of efficiency places this system on top class with many centralized generation technologies. This system also simultaneously addresses the environmental sustainability by carbon reuse. The CREC model demonstrates that a complex multi-stage energy system is able to achieve high performance when optimized by using predictive control strategies.

4.4 CO_2 Emission Mitigation

The core strength of the CREC approach is the end observation of **35% reduction in CO_2 emissions**. Unlike carbon capture and storage (CCS), which isolates CO_2 to some extent, this system reuses it as a fuel source for energy production, thus it transforms waste into a value asset. The Sabatier reaction acts as a conversion pathway rather than a storage mechanism, and its continuous operation is the key to reduced emission.

While the system does not eliminate all CO_2 emissions but the reduction level confirms the real-time conversion can effectively suppress a large portion of the output gas. Future modifications may include recirculation, multiple reactor staging, or reactor bed design can enhance conversion further.

4.5 Dynamic Behavior and MPC Performance

The use of **Model Predictive Control (MPC)** made a significant improvement in the system's response to variable operating conditions. MPC was fully capable to adjust manipulated variables (e.g., H_2 flow, CH_4 feed, combustion rate) maintaining stable power output and system behavior.

The recovery response time is less than **3 seconds** after disturbances is indicated in a well-tuned control environment. It shows the importance of using an advanced control logic for systems involving multiple interacting components and nonlinear dynamics.

4.6 Comparison with Conventional Energy Systems

Unlike traditional fossil-fuel-based power systems that continuously emit CO_2, the CREC system operates like a **closed-loop recycling model**. The combine effect of CO_2 capture, hydrogen integration and electrical generation allows the simultaneous emission reduction and continuous power supply which is a dual objective seldom achieved by the system.

Moreover, the renewable integration of hydrogen (e.g., solar-electrolyzed H_2) positions this system as a link between traditional and next-generation energy architectures. It provides flexibility, modularity, and a setup for carbon reuse without requiring complete infrastructure overhaul.

4.7 Limitations and Opportunities

Despite its strong performance, the CREC system faces several technical challenges:

- **Hydrogen dependency:** This process is limited to availability of green H_2 that is subject to variability in renewable power supply.

- **Partial CO_2 conversion:** All CO_2 is not converted at each reactor cycle; thus, emission reductions are not total but significant.

- **Heat integration:** The nature of the Sabatier reaction is exothermic that opens potential for thermal energy recovery that is not yet modeled in the current system.

5. CONCLUSION

This study presents a design, simulation, and performance evaluation of an integrated **Carbon Recycling Energy Conversion (CREC)** system which has the ability of transforming industrial CO_2 emissions to a usable electrical energy. The architecture of this system comprises a coal combustion chamber for CO_2 generation, an electrolyzer mechanism for renewable hydrogen production, a Sabatier reactor for methane synthesis, and an electrical synchronous generator driven by methane combustion.

The simulation model is developed by using MATLAB Simulink, it effectively demonstrates the feasibility and performance of such a multi-stage system. Key findings include:

- **Stable methane output** of 0.98 mol/s achieved under varying input conditions.

- **Electrical power generation** of 1.25 MW, with three-phase sinusoidal output suitable for grid connection.

- **System efficiency** of 57.1%, which is highly competitive considering the multistage energy transformation.

- **CO_2 emission reduction** of approximately 35%, confirming the system's ability to reuse flue gas emissions through chemical conversion.

The implementation of **Model Predictive Control (MPC)** played an important role by managing system stability, enabling rapid recovery from variation in hydrogen and CO_2 input streams. The system's dynamic performance and real-time responsiveness highlights it's moldable to industrial scenarios where emissions and energy demands fluctuate.

The CREC system successfully covers the gap between conventional combustion-based power systems and emerging carbon-reuse technologies. By turning emissions into fuel and electricity, this offers a significant solution aligned with carbon neutrality and sustainable energy development goals.

Future Work

Further enhancements to the system could include:

- Integration of real-time thermal energy recovery by Sabatier reactor.
- Advanced catalysts can be used to improve CO_2 conversion rates while reducing the operating temperatures.

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