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Virtual Replica: A Conceptual Digital Twin Framework for Fuel-Quality Control in A Rice Husk-Fired Power Plant in Taal, Bocaue

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***Abstract* – This study proposes a conceptual Digital Twin framework for supporting the fuel quality control in the rice husk-fired power plant located at Taal, Bocaue, Bulacan. Variations in the moisture content of rice husk remains to be a major operational challenge which affects combustion efficiency, steam output, and emission intensity. Current practices in similar biomass power plants heavily relies on manual inspection which can introduce human error and inconsistency. As a response, the proposed framework unifies real-time moisture sensing, Digital Twin-based analysis, and robotic arm reprocessing mechanism into a closed-loop system intended to guide future plant automations. In the conceptual model, moisture readings from near-infrared sensors are processed by the Digital Twin to classify the moisture content of rice husks that can affect combustion. Based on these assessments, the robotic arm mechanism executes the diversion and reprocessing to maintain the moisture level within the set threshold of 13.5-14.5% and prevent unsuitable batches from entering the combustion feedline. Even though the study does not involve prototyping, simulations, and on-site data collection, the scenario-based evaluations show that the framework can operate logically and consistently even in varying moisture conditions. Generally, this framework provides a grounded conceptual reference for future development of an automated fuel-quality control systems in rice husk-fired power plants such as the HyperGreen's 12MW Rice Husk-Fired Power Plant in Taal, Bocaue, Bulacan.**

***Keywords:* Digital Twin, Automation, Sensors, Biomass, Combustion, Fuel Quality**

I. INTRODUCTION

The urgent need to transition to a sustainable and reliable operation have driven the exploration of renewable energy sources and energy technologies. Alongside this, climate change is the most visible impact of using non-renewable resources for decades. The severe changes in climate patterns present a significant challenge to electricity generation as it reduces the efficiency and potential of power plants due to its potential to disrupt the regular operation of power systems such as solar, wind, and hydropower. These challenges highlight the importance of updating plant operations and adapting advanced technologies that are capable of minimizing these emissions.

As national energy demand grows, the Department of Energy provided a Philippine Energy Plan (PEP) which identifies the integration of emerging technologies as one of the strategies in ensuring energy security and meet the sustainability targets of the country.

Rice Husk Biomass Energy in the Philippine Context

Biomass energy shows both opportunity and complexity. Its utilization has been widely used and emerged as a promising alternative in many countries due to its availability, renewability, and potential for energy conversion. Biomass feed stocks often include corn, soybeans, husks, wood, algae, and wastes.[1]

With sustainability being the most important aspect to run a biomass power plant, rice husk is a significant energy resource and it contains approximately 30-50% carbon, 15-20% silica, and residual minerals which makes them an effective fuel for combustion when properly dried.[2]

Rice husk is a by-product of agriculture and is abundant in rice-growing regions such as the Philippines which produces over 2.5 million tons of rice husks annually.[3]

Challenges in Rice Husk-Fired Powerplant

In the Philippines, rice husk fueled plants operate by combusting rice husk to produce steam that drives the turbine for electricity generation.[4] Despite being the widely used biomass for fuel, power plants still experience challenges in terms of operational efficiency because the moisture content present in rice husk affects combustion and has been cited as a key source of performance fluctuations. The heating value of a rice husk determines if it can provide a complete combustion. Rice husk feedstock provides an optimal combustion at 14% moisture content.[5]

According to the study conducted by Saeed *et. al,* the moisture contents of 12% and 16% showed that the

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heating value raised significantly from 13.87 MJ/kg to 14.04 MJ/kg and 13.08 MJ/kg to 13.11 MJ/kg, respectively. The rice husk having the moisture content of 14% produced the highest heating value, therefore it will provide a good combustion behavior.

Table 1: HHV of Rice Husk at Various Moisture Content (Saeed, et. al., 2021)

Moisture Content	HHV (MJ/kg)
12 %	13.87
14%	14.23
16%	13.08

The 12-MW rice husk-fired power plant operated by HyperGreen Energy Corporation is situated in a province with agricultural abundance yet exposed to flooding which is in Taal, Bocaue, Bulacan. The plant demonstrates the challenge in both renewable energy generation and fuel quality. As the rice husk is exposed to rainfalls, fog, and humid storages, the moisture can be affected because it can alter the ideal moisture range which could result in an incomplete combustion, increased fuel consumption, and a low overall power output.[6]

Climate Vulnerability of the Philippines

Asia is experiencing the highest frequency of severe weather events where floods and storms being the most prevalent,[7] and the Philippines has been ranked as one of the most vulnerable countries exposed to climate change as it has been affected by extreme weather events in the last 30 years which affected its economy and social structure.[8]

The country also experiences a rising energy demand due to its population greatly increasing and energy resources decreasing, climate instability, and need for sustainable development.[9] As one of the world's most typhoon-prone country, it experiences an increasingly unpredictable temperature and humidity changes due to intensified rainfalls. Furthermore, heatwaves, typhoons, and floods are experienced which disrupts both fuel supply and plant operations.[10,11] All of which are considered to be an environmental fluctuation that threatens the efficiency of renewable energy systems.

The challenge is not only limited to maximizing the operational efficiency but also ensuring the quality of fuel in the face of climate change.

Energy infrastructures in agricultural and flooded regions face the challenge of maintaining the operational efficiency of their plants while adapting to a climate-induced environmental changes. In response, the energy sector begun adapting digital transformations and technological strategies to improve its efficiency. Showing the growing importance of integrating emerging technologies capable of real-time monitoring conditions in renewable power operations.

Digital Transformation in Biomass Power Plants

Digital transformation driven by the fourth industrial revolution such as Internet of things (IoT), Artificial Intelligence, and Blockchains shows a great impact on the way electricity is being generated and distributed.

The efficiency and reliability of smart grids and renewable energies are increased as technologies provide real-time monitoring and power distribution control. Implementing predictive analysis allowed the more efficient and easy monitoring of equipment which reduced downtime and sudden shutdowns. The utilization of advanced data analytics optimizes the power plant's operation as it provides better data collection, analysis, and management. It is shown that technologies have a significant impact in the area of power generation as it has been used to improve its efficiency and reliability.[12]

The application of a Digital Twin technology has a potential in revolutionizing energy production of a biomass gasification powerplant. The real-time information from the physical plant allowed the comprehensive simulation to predict the plant's behavior and improve operational efficiency.[13]

Energy efficiency and energy technologies both impact one another and are equally important. Advancements in technology leads to significant changes in the way energy is produced.

Digitalization Gaps in Philippine Power Plants

Despite the global movement towards advancements, the Philippines' transition remains slow. Majority of the renewable energy facilities, specifically biomass and mini-hydro plants operate under manual supervision and relies on analog instruments or basic SCADA systems without advanced analytics as reported by the Asian Development Bank on 2025. The country still faces challenges in implementing predictive maintenance in power plants resulting to the continued dependence on corrective maintenance practices which leads into downtimes due to the lack of early detection.

Real time sensors that are capable of detecting operational data which is essential for early fault detection and effective predictive analysis are still absent.[14] This gap is evident especially in older power plants that lack the advancements present today.

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Expanding the digitalized grid infrastructure in the Philippines will help in keeping up with integrating renewable energy sources as it provides enhanced energy security, creation of green jobs, and expansion of electricity access.[15] These would also align the country with the international progress towards an efficient energy system.

Given these limitations, there is a need for advanced systems such as Digital Twin technology that is capable of continuously monitoring power plant performances, simulating operational conditions, and picking up real-time data.

Digital Twin Technology Integration

The industrial revolution introduced powerful emerging technologies powered by intelligent process controls and have redefined how the industry can monitor, analyze, and optimize systems. One technology that can utilize its potential to accurately monitor a power plant is the Digital Twin technology.

Digital Twin (DT) technology is the virtual representation of a physical system that enables real-time monitoring of data from real-world operations and it allows simulation, prediction, evaluation through sensors, and optimization of the system.[16] While DT technology is originally for aerospace and manufacturing industries, it is now being explored in the energy sector, from smart grids, wind turbines, and thermal power plants as means to improve the reliability of the system.[17]

Despite the global progress towards smart energy systems, DT technology has limited implementations in power plants, most especially in developing countries. In the Philippines, advanced data analytics or digital monitoring frameworks are still not yet widely integrated into renewable power plants. The absence of potential smart energy systems restricts plant operators to identify early abnormalities, analyze fuel properties, or predict the potential failure before it occurs which directly affects the plant's efficiency.

Introducing a Digital Twin technology enables an early abnormality detection through its real-time data harvesting and simulation-based program.[18] Furthermore, the sensor-based predictive analysis improves the reliability and reduce the possible number of unplanned downtimes. [19] This provides an opportunity to establish a continuous monitoring system to support a more efficient biomass fuel for the power plant. As energy systems in the Philippines are vulnerable to climate which can influence the quality of rice husk, Digital Twin offers a more intelligent power generation.

The effectiveness of a Digital Twin depends on the continuous and accurate data harvesting from the physical system, thus making real-time moisture sensing an essential component.

Real-Time Moisture Sensing and Fuel Quality Monitoring

Fuel quality is a critical factor in the efficiency of biomass powerplants especially in those that relies on agricultural residues like rice husk. It was mentioned that rice husk performs optimally at 14% moisture content to produce a complete combustion behavior.[5] High deviations on this requirement indicates that the rice husk is too dry or too wet which leads to an incomplete combustion, increased fuel combustion due to fast burning, and rapid wearing on the plant's equipment.

For the Philippines, maintaining the ideal fuel moisture is a challenge due to typhoons which causes high humidity, fogging, and flooding that exposes the rice husk to extreme weather conditions.

Without the precise and continuous monitoring, the power plant risks its efficiency because wet or dry rice husks results in incomplete combustion and reduced output.[20] Real-time moisture sensing technology provides a solution to this operational gap as it enable immediate detection of inconsistencies in the fuel.

For HyperGreen's 12MW power plant, incorporating a real-time moisture sensing technology into a digital twin framework will shift the traditional monitoring to an intelligent power plant management. By continuously capturing the moisture along the fuel pathways, the sensors will provide the Digital Twin with an actual operational data.

However, monitoring itself does not resolve the inconsistencies in fuel quality. Physical intervention is needed to prevent efficiency loss and this is provided through an automated robotic arm reprocessing.

Smart Robotic Arms for Picking and Reprocessing

Robotics are redefining the modern industrial systems to provide higher precision and operational safety. Particularly, a robotic arm is a programmable mechanical device capable of physical motion and exhibits locomotion through interconnected joints and links that is driven by actuators and motors guided by sensors to have a controlled physical motion in a defined workspace.[21] Since this emerged, automation is often used in today's society to assist people in doing their jobs and improve work efficiency. As these robots make tasks simpler, it is used in many ways ranging from assembly to industrial practices due to their ability to execute repetitive, hazardous, and high-precision tasks with accuracy.

The robot's movement is determined by its Degree of Freedom (DOF), and the higher the DOF, the more movement the robot can do. To resemble the flexibility of a human arm, an articulated robot is designed with six DOF to provide higher reach from the base because it provides a high degree of flexibility and movement.[22] This geometric configuration makes a robotic arm suitable for tasks that requires precise manipulation such as picking, sorting, and material handling.

A controller serves as the robot's brain that is crucial to operate a robot and it ranges from basic microcontroller platforms to advanced industrial control systems.[23] As robotics continues to advance, their integration to the industrial setting supports a more efficient and data-driven operations.

Leveraging a robotic arm in the HyperGreen's 12MW Biomass power plant for picking and reprocessing will serve as the physical response to the real-time data interpreted by the Digital Twin. This automated intervention ensures an intelligent operation within the plant.

These technologies work together in integration. The Digital Twin interprets the data harvested by the moisture sensor, and the robotic arm will execute the action needed, creating an intelligent closed-loop system.

Building on these challenges and technological opportunity, this paper aims to introduce a technology that could reshape the operational efficiency in HyperGreen's 12MW rice husk-fired biomass powerplant.

A Digital Twin technology incorporated by an automated moisture sensing for the rice husk and a robotic reprocessing arm engineered to segregate and reprocess overly wet or dry rice husk before it enters the combustion chamber. This aims to address an overlooked challenge in biomass powerplants which is fuel quality inconsistency. This study bridges renewable energy and emerging technologies in one unified framework while supporting the future digitalization initiatives of the Philippines.

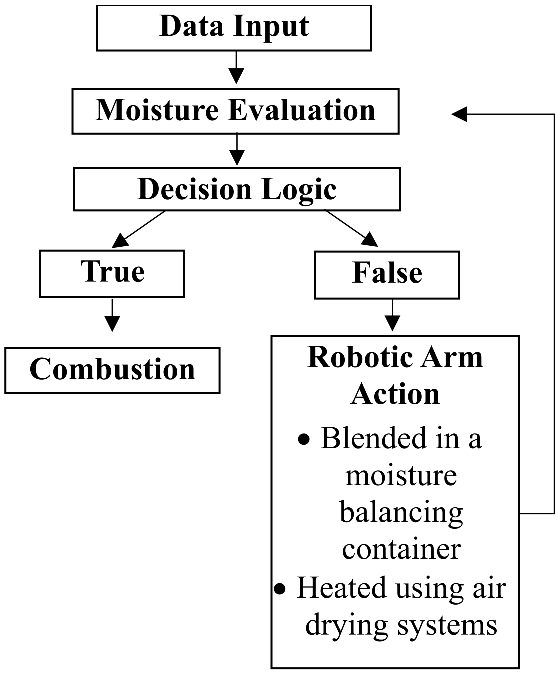
I. METHODOLOGY

This study utilizes a design-based approach to develop a technically grounded roadmap focused on guiding the future implementation of a Digital Twin integrated with an automated moisture-sensing system and a robotic reprocessing arm for HyperGreen's 12MW Rice-Husk Fired Power Plant in Taal, Bocaue, Bulacan. It will focus on the conceptual modelling, system architecture design, and logical integration of the components.

The system provides:

1. Monitoring of the rice husk moisture continuously with high accuracy.

Figure 1: System Architecture



2. Integration of moisture sensor's data.
3. Classification of rice husk based on its deviation from the set acceptable moisture range.
4. Automated reprocessing of the unsuitable rice husk for combustion using a robotic arm.
5. An interface for monitoring and control for the supervisors.
6. Operation in a closed-loop manner to ensure stability.

The Digital twin serves as the virtual representation of the physical biomass plant and has four interconnected layers: the physical plant, the real-time sensing, data processing and decision logic, and the interface of the operation. It ensures that moisture is monitored at important and critical transition points, acting as the brain of the system by receiving moisture sensor inputs, interpreting the data, and commanding the robotic arm's response.

Physical Plant Layer

The real-world operation of the biomass power plant including the storage areas of rice husk, feeding mechanisms, combustion chamber, power generation components, and silos is replicated. The real-time readings are received from these points.

This defines the system boundaries and ensures that all fuel related processes are captured in the virtual environment. It has its subsystems to provide a separate representation of the critical places where the sensor needs to perform.

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Table 2: Physical Plant Subsystems

Physical Plant Subsystem	Purpose
Fuel Intake	Monitoring of rice husk's arrival and initial moisture.
Storage	Monitoring of the bulk of accumulated rice husks.
Feed Line Entry	Monitor the final moisture content before combustion.

At each stage, moisture may change due to environmental exposure, handling, and storage conditions.

Moisture Sensing Layer

The sensors feed the data into the Digital Twin and is focused on the moisture content. This will provide the accurate detection of the moisture of the rice husk taking the optimal target of 14% moisture requirement. Furthermore, the sensor also considers the ambient humidity, storage temperature, and the feed line conditions.

Near-infrared (NIR) moisture sensors were selected as the primary rice husk moisture detection instrument because it enables a non-destructive biomass analysis with a minimal sample while delivering high-precision, non-contact measurement in real-time.[24] It determines the moisture content based on the absorption characteristics of the water molecules across infrared wavelengths which reduces the contamination in the equipment.

NIR sensors satisfies the following:

1. High sensitivity to moisture fluctuations
2. Fast response
3. Dust resistance
4. Resistant to high temperatures to be suitable for biomass power plants
5. Durability under vibration

NIR sensors serve as the initial data acquisition process which captures moisture values in its different conditions. Incorporating this allows the Digital Twin to have a more reliable representation of the fuel conditions to improve the combustion efficiency.

These sensors are placed at the intake pathways: in the biomass entry point, silos, and feeding mechanisms or feed lines for combustion, to ensure the full coverage of where moisture is most likely to vary and ensure early detection before going further to process for combustion.

Table 3: Sensor Placements

Location	**Purpose**
Biomass entry point	Initial detection of moisture
Silos	Moisture tracking in terms of large volume
Feed Lines	Final evaluation before combustion

The sensor data are collected through IoT enabled gateways. Message Queuing Telemetry Transport (MQTT) is the most suitable option because it is a very light and fast IoT communication protocol used for sending continuous small data even in low-bandwidth conditions.[25]

Data Processing and Decision Logic Layer

The Digital Twin continuously receive sensor readings through IoT gateways and this layer performs real-time evaluation. The moisture content is evaluated based on the thresholds for the rice husk to predict if it is suitable to be fed in the combustion chamber.

Providing a tolerance of ±0.5, 13.5-14.5% is acceptable, and any detection that is outside of its range will be reprocessed. The moisture exceeding or deviating significantly leads to inefficient combustion affecting the fuel quality.

Once processed, the Digital Twin replicates the potential impacts in combustion and then commands are issued to the robotic arm for interventions.

Table 4: Moisture Reading Decision Logic

Moisture Reading	**Digital Twin Reading**	**Robotic Arm Action**
< 13.5% (too dry)	Low-moisture content	Isolated for blending in a blending container where moisture balancing mixing occurs
13.5-14.5%	Accepted Moisture Content	Pass the entry points as it is suitable for combustion
> 14.5% (too wet)	High-moisture content	Moved to the reprocessing section to be heated using air systems. • Once acceptable it is sent back to the feed line

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	• If still above the range, sent for additional drying

The decision logic performs the following:

1. Classify if the rice husk is within or outside the acceptable range for the optimal target.
2. Predicts if the deviation will affect the performance of combustion.
3. Generate the command to the robotic arm reprocessing.

Once the decision logic classifies the moisture condition and determines the required action to take, it proceeds to perform a predictive analysis to evaluate the expected influence of the detected moisture deviation to the power plant's efficiency. These predictive analyses are summarized in Table 6.

Table 5: Predictive Analysis

Parameter	Process
Boiler's Thermal Efficiency	Evaluates the expected heat addition based on the measured moisture level of the rice-husk.
Steam Generation	Predicts the quantity of steam that can be produced.
Usable Thermal Energy Conversion	Determines how efficiently the rice husk will convert into usable thermal energy.
Emission	Predicts the rise in carbon emissions due to the moist rice husk.

Robotic Arm Reprocessing Mechanism

Serves as the physical component that responds to the Digital Twin's decision when it identifies the rice husk to be too dry or too wet. It will execute the command and redirect the rice husk to the preferred corrective measure.

Table 6: Role of Robotic Arm

Action	Task
Sorting	Separate the unacceptable rice husk from the accepted batches.
Reprocessing	• Place the wet husk to the drying system. • Place the dry husk to the moisture blending container.
Returning	Sending the reprocessed huck back into the feed line.

When the Digital Twin commands the need for reprocessing, the robotic arm automatically performs the required action without needing manual adjustments.

Operator Interface Layer

The interface layer provides the dashboard for operators to supervise the plant operation, parameters, alerts, and manually fix or override options for operational control and prevent its effect on the plant's efficiency.

This includes:

1. Visual of the real-time moisture data.
2. Alerts if the moisture is too high or too low.
3. Tracking of the robotic arm's activity.
4. Manual controls to override the system.
5. Predictive warnings based on historical trends.

Validation Approach

The validation approach of this study is centered on determining how the proposed system works as a functional unified framework. Since the study does not involve creating a physical prototype and deployment of a Digital Twin technology, the validation is done conceptually by ensuring that the three systems involved operate realistically as a complete automated process.

Functional Validation

This examines whether every part of the system logically influences the next, ensuring that the entire framework works as intended. The system is analyzed through the following sequence:

1. The sensors placed at the entry points provide enough data to track the moisture changes realistically.
2. The Digital Twin receives inputs in the correct order and does not rely on any data that is not received by the sensor.
3. The decision of the Digital Twin responds correctly to the acceptable moisture range if it is dry, acceptable, or wet.
4. The robotic arm will logically perform the accurate action depending on the moisture threshold given.

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This process validates that the system functions end-to-end and each system depends on real inputs and outputs.

Decision Logic Accuracy Evaluation

In validating how the system interprets and responds to sensor data, rice husks with different moisture contents are fed into the entry points to test the decision logic. Each rice husk is checked for:

1. Consistent moisture readings to the correct categories based on the study's defined acceptable range.
2. Correct command is sent to the robotic arm for each moisture content.

As the system produce consistent decision outputs in repeated trials with the same input, this ensures that the Digital Twin is stable and accurate.

System Responses Validation

This validation focuses on the system's response to different operational conditions experienced in Biomass power plants.

Table 7: Operational Conditions

Condition of Rice Husk	Response
Slight Moisture Changes (14.3% or 13.8%)	• Should allow passage if the moisture is still within the acceptable range. • Only triggers reprocessing if it crosses 14.5%. • Avoid stopping or malfunctioning to small fluctuations
Sudden Moisture Spikes (13% to 17%)	• The digital twin must immediately classify to "too wet." • The robotic arm must pick the rice husk and redirect it to the drying systems without the operator controlling it.
Sudden Unexpected Dryness	The robotic arm should instantly accept the command from the Digital Twin to pick up the rice husk and subject it to moisture blending.

In terms of predictive analysis, the Digital Twin must correctly reflect the effects of these changes to ensure that the system performs intelligently for the output of the power plant.

Closed-Loop System Consistency

This examines whether the loop remains stable.

1. The loop must be able to repeat indefinitely without breaking the cycle.
2. No component should require manual intervention to continue processing unless the operators decided to do so.
3. the Digital Twin must correctly update its system after every action and readings.

This validates that the system is not working individually but a fully coordinated automated system.

Operational Validation

This validation ensures that the system is practical and relevant to the actual operations of a rice husk-fired power plant.

The system will be compared to the existing plant such as the placements of the sensors and the robotic arm should be positioned where moisture changes, the plant is replicated precisely by the Digital Twin, and that moisture is one of the factors that influences the power plant's efficiency.

This validates that the proposed system is not only for theoretical but useful as a guide for modernizing rice husk-fired power plants.

This study is limited to the development of a conceptual unified framework of a Digital Twin, real-time moisture sensing, and robotic reprocessing for a rice husk power plant. There are no simulations, physical prototyping, and deployment of an actual Digital Twin platform, sensors, and robotic arms.

No on-site data collection was conducted and all the system behaviors, acceptable moisture range, and control systems are gathered from related literatures and are not measured experimentally. Therefore, real environmental factors such as changing humidity, exposure to rain, or contamination of rice husk are not evaluated and analyzed.

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These limitations classified this study as an implementation framework to guide future engineering development towards an advanced energy sector.

RESULTS AND DISCUSSION

This presents the outcomes of the development of the conceptual unified framework of the Digital Twin technology, real-time moisture sensing, and a robotic arm reprocessing for a rice husk-fired biomass power plant. Since the study does not involve any prototyping and deployment, the results will focus on the theoretical performance and system interactions of the proposed integrated systems.

The findings will describe how the framework operates under varying theoretical moisture conditions. Furthermore, it will also describe how the Digital Twin processes information, and how the robotic arm responds to the classified moisture content. The results that have been validated under different system conditions are interpreted to assess the reliability and connectedness of the systems.

Unified System Framework

The conceptual model demonstrates an end-to-end operational system process. The real-time sensor data harvested by the moisture sensors is processed by the Digital Twin to enable a real-time and intelligent command for rice husk handling to be done by the automated robotic arm. The theoretical system shows that the unified framework is capable of:

1. Classifying the rice husk's moisture level accurately based on literature based acceptable range which is 13.5-14.5%.
2. Providing an accurate Digital Twin-based prediction that identifies fuel quality risks from moisture variations including their expected impacts on the boiler's efficiency, content of steam, and emission levels.
3. Commanding the robotic arm reprocessing to perform the accurate action commanded by the Digital Twin based on the classification of moisture content.
4. Maintaining a continuous monitoring of the plant.

Integrating these three components shows that a closed-loop automation system is logical for a rice husk-fired power plant and can theoretically replace the traditional monitoring practices.

Moisture Classifications

The moisture content of the Digital Twin was determined theoretically using threshold-based values from literatures. The system consistently detects moisture levels from too dry, acceptable, and too wet.

1. The system classified theoretical moisture content below 13.5% as too dry and unfit for combustion.
2. Moisture value between 13.5% and 14.5% were consistently identified as acceptable and ready for a complete, and will not affect the fuel quality.
3. Moisture content that exceeds 14.5% is consistently classified to be too wet and unfit for combustion

These results shows that the framework's classification logic is functioning exactly as intended and the moisture content classifications are being read in a consistent manner.

Digital Twin's Predictive Analysis

Integrating the Digital Twin technology also aimed to provide a predictive analysis in terms moisture content. This model produces theoretical predictions that is aligned with the reviewed biomass combustion behavior without on-site data.

Table 8: Digital Twin Prediction

Moisture Content	Digital Twin Prediction
<13.5% (too dry)	• Too fast combustion. • Low emissions due to fast combustion rate. • Decreased boiler efficiency.
13.5-14.5% (acceptable)	• Complete combustion. • Stable thermal efficiency for an ideal turbine operation. • Fuel-to-energy conversion is maximized. • Low emissions as fuel is burned completely.
>14.5% (too wet)	• Incomplete combustion. • Low conversion efficiency. • Increased emissions due to

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	incomplete combustion. • Lower thermal efficiency

These results show that the classification logic of the framework and predictive responses are consistent with the known thermodynamic behavior of a biomass fuel. This states that the Digital Twin can accurately predict the operational outcome based on moisture contents picked up by the moisture sensors.

Execution of the Robotic Arm

Based on the commands of the Digital Twin, the conceptual model shows that the robotic arm executes the needed response:

1. Transferring wet or dry rice husk to the reprocessing sections:blending or the drying sections.
2. Returning the reprocessed rice husk back to the entry points.

This shows that the robotic arm performs the needed response and handling determined by the Digital Twin. If the moisture deviates outside of the acceptable range, the robotic arm redirects the batch to dry or to gain moisture while the acceptable rice husk is allowed to pass for combustion.

The robotic operations show that it follows a logical sequence, showing that the integrated systems can automate fuel segregation and processing in a rice husk-fired power plant. Strongly, this indicates that the robotic arm can effectively sort and contribute to fuel quality control for an efficient power plant output.

System Response Under Different Moisture Conditions

Table 9: System Behavior under Varying Conditions

Moisture Conditions	Response
Inputs that read 13.8%, 14.3%, 15%	• The system correctly keeps the rice husk in the acceptable range until it exceeds 14.5% • At 15%, the system quickly shifts into the “too wet” classification and activates the robotic arm for drying and reprocessing.
Sudden Moisture Spike (12% to 15%	• The classification instantly changes from “too dry” to “too wet” • The robotic arm is immediately commanded by the Digital Twin.
Sudden Unexpected Dry Rice Husk (14% to 10%)	The robotic arm accepts the command of the Digital Twin to send the rice husk to the moisture blending section.

These results confirm that the system remains programmed to its needed response quickly under varying conditions.

Closed-Loop System

The study ensures that the system operate in a continuous automated monitoring cycle of:

1. Sensors measure the incoming rice husk for its moisture content.
2. The Digital Twin processes the data from the sensor, make predictions, and send the command to the robotic arm.
3. The decision logic triggers the robotic arm’s actions.
4. The reprocessed rice husk re-enters the entry points with moisture sensors.
5. The data for moisture readings stored in the Digital Twin is updated and the loop restarts.

This confirms that every part of the loop works with the information it needs, showing that the entire loop in the framework can function smoothly as designed. As the operational logic is established, the framework is expected to influence the multiple aspects of plant operations and fuel-quality management.

1. Improved fuel quality through the integration of moisture sensors, Digital Twin, and robotic arm.
2. Higher combustion efficiency due to the stable and reliable moisture control.
3. Reduced manual labor.
4. Improved plant safety as reduced human intervention reduces contact to unsafe environments.
5. Implementation of proactive maintenance as predictive analysis is already present.

These key findings show that the proposed framework to HyperGreen’s 12MW Rice Husk-Fired Power Plant has a potential to modernize its operations.

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Interpretation of Results

The results indicate that by utilizing a comprehensive conceptual framework:

1. The system works logically and reliably.
2. Provides a solid foundation for future implementation.
3. Supports the main objective of the study to address the fuel quality of HyperGreen's 12MW Rice Husk-Fired Power Plant to improve the plant's efficiency.

Generally, the conceptual results show that the proposed system is a practical framework that can be developed in the energy sector.

CONCLUSION

This study developed a conceptual unified framework integrating Digital Twin technology, real-time moisture sensing, and robotic arm reprocessing for HyperGreen's 12MW Rice Husk-Fired Power Plant to help their fuel quality control. The framework showed how advanced monitoring and automated handling systems can theoretically manage the rice husk quality to increase combustion efficiency and overall plant output.

Through the process of integrating the moisture sensor to Digital Twin and robotic arm response, the study provides a structured guide for future engineering development in the rice husk biomass sector.

The results show that moisture content thresholds derived from literature reviews can effectively be classified into "too dry", "acceptable", and "too wet" and be a basis to the Digital Twin's decision-making process. The Digital Twin technology provides theoretical predictions that are consistent with the moisture classifications and its effect on the boiler performance, steam generation, emissions, and overall output. The robotic arm mechanism for reprocessing shows that an automated rice husk handling is possible as it responds intelligently to the Digital Twin's commands. Collectively, these systems form a logical closed-loop system that supports real-time quality assurance in biomass operations.

As the study is conceptual and does not include real-world testing, the results is centered on theoretical behavior and performance. The validation processes show that the framework can theoretically maintain a good fuel quality with varying moisture inputs caused by different conditions and temperatures while still responding effectively to sudden changes.

These outcomes demonstrate that the framework can be used as a reference for researchers and engineers seeking to modernize biomass fuel monitoring.

The study contributes a framework that can guide the rice husk-fired power plants in the Philippines. As biomass power plants in the country continue to improve for higher efficiency and digitalization, the proposed system offers a comprehensive roadmap about unifying Digital Twin technology to real-time moisture sensing and robotic arm reprocessing into daily power plant operations.

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