engineering proceedings

*Conference Report*

# Abstracts of the 1st International Online Conference on Designs (Designs 2026)

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**Abstract**

The 1st International Online Conference on Designs (Designs 2026) took place online from 9 to 10 February 2026. This conference report is an abstract collection from sessions of Designs 2026.

**Keywords:** artificial intelligence; renewable energy; smart grids; energy storage; energy efficiency; energy forecasting and security; digital design

## 1. Introduction

The 1st International Online Conference on Designs (Designs 2026) provided a highly interactive platform for researchers all over the world to discuss achievements as well as challenges in designs in energy systems and artificial intelligence. The conference attracted experts and scholars from all fields of designs to discuss a wide range of topics:

- Artificial Intelligence for Renewable Energy Systems and Optimization
- Smart Grids and AI-Enabled Energy Management Systems
- Intelligent Design and Control of Energy Storage Systems and Demand Response
- AI-Enhanced Design Strategies for Energy Efficiency in Built and Urban Environments
- Data-Driven Design for Energy Forecasting, Security, and Resilience
- Digital Design Technologies for Energy Equipment and Systems

## 2. Session 1: Artificial Intelligence for Renewable Energy Systems and Optimization

### *2.1. Optimization of a Hybrid Solar-PEM Electrolyzer System for On-Site Medical Oxygen Production*

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The shortage of medical oxygen during the COVID-19 pandemic exposed critical gaps in the healthcare infrastructure, particularly in hospitals that rely entirely on external supply chains and lack their own oxygen generation systems. This research presents a hybrid renewable energy solution that combines solar photovoltaic (PV) energy with a Proton Exchange Membrane (PEM) electrolyzer to produce medical-grade oxygen on-site and continuously, contributing to long-term resilience in oxygen availability.

The system is designed to operate in grid-connected environments with intermittent reliability, providing autonomy and security in oxygen supply without depending on conventional oxygen cylinders or bulk supply deliveries. A comprehensive techno-economic

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and energy optimization analysis was conducted to improve the system's performance, considering variables such as solar irradiance, panel configuration, electrolyzer capacity, and daily oxygen demand.

Simulation results, based on real solar radiation data and hospital oxygen consumption profiles, demonstrate that the optimized hybrid solar-electrolyzer system is capable of meeting the hospital's oxygen demand with stable performance. The results highlight the system's potential to reduce reliance on external suppliers and increase operational independence for healthcare centers.

This study contributes to the development of sustainable, decentralized energy-based solutions tailored to real healthcare needs, enabling hospitals to ensure continuous oxygen availability through the integration of renewable energy technologies.

### *2.2. Python-Based Automated Response Surface Methodology: Computational Replication and Validation Framework for Supercapattery Materials Optimization*

**Thiago Ferro de Oliveira [1,2,3] and Simoni Margareti Plentz Meneghetti [2,3]**

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Response Surface Methodology (RSM) combined with Central Composite Design (CCD) represents a powerful statistical approach for materials optimization in energy storage systems [1,2]. RSM has been extensively applied in materials science to efficiently explore design spaces and identify optimal synthesis conditions, reducing experimental burden while maintaining rigor [2]. This study presents a complete computational framework for replicating, validating, and extending RSM-based optimization of $NiCo_2S_4$–graphene supercapattery materials through automated Python implementation, demonstrating the feasibility of reproducible computational design methodologies.

We replicated the optimization study [1] using a 20-experiment CCD with a five-level three-factor design. Independent variables were graphene/NCS ratio (0.6–7.4%), hydrothermal time (4.6–11.4 h), and S/Ni molar ratio (3.3–6.7). Specific capacitance served as the response variable. A quadratic polynomial model was developed using multiple linear regression, with automated analysis including ANOVA calculations, Pareto analysis ($\alpha = 0.05$), Shapiro–Wilk normality testing, and response surface mapping implemented in Python.

The quadratic model achieved $R^2 = 0.9716$ and adjusted $R^2 = 0.9460$, explaining 97.16% of variance. The G/NCS ratio emerged as the dominant factor (57.19% contribution, $p < 0.0001$), with significant synergistic interactions for G/NCS × S/Ni ($p = 0.0068$) and time × S/Ni ($p = 0.0057$). Residuals demonstrated normal distribution (Shapiro–Wilk $p = 0.8531$). The optimal predictions were G/NCS = 6.0% and time = 10.0 h, S/Ni = 6.0, yielding 2263 F/g with 2.32% deviation from the original experimental results.

This automated Python framework validates RSM methodology through independent replication with 97.68% agreement with the original study [1]. The computational approach significantly reduces time investment while maintaining statistical validity, supporting industry adoption of data-driven design methodologies in energy storage materials. The complete Python code is provided as open-source material, enabling transparency, reproducibility, and broader methodological accessibility for future materials optimization research.

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### *2.3. The Role of Attention Mechanisms in Deep Learning for Hourly Solar Forecasting: A Case Study in Tropical Brazil*

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Accurate solar irradiance forecasting is essential for the secure integration of photovoltaic energy into power grids, especially in tropical regions with high intermittency [1]. While deep learning models like Long Short-Term Memory (LSTM) networks have been applied to this task, the potential of enhanced architectures, specifically Bidirectional LSTM (BiLSTM) and models incorporating attention mechanisms, for univariate hourly forecasting in tropical climates remains a significant research gap. This study addresses this gap by investigating whether these advanced AI architectures improve prediction accuracy in the context of Northeastern Brazil. We developed and rigorously compared four deep recurrent neural network models: LSTM, LSTM with attention, BiLSTM, and BiLSTM with attention. The models were trained on hourly data (2022–2024, 7:00–22:00 UTC) from João Pessoa, PB, preprocessed with Min-Max normalization [0.1, 0.9], and evaluated using standard metrics (RMSE, MAE, and $R^2$) [2]. Performance was assessed robustly through 10 executions per model with 12- and 24-h lookback windows. Contrary to expectations from recent AI trends, the results demonstrate that while BiLSTM architectures consistently outperformed standard LSTM, the integration of attention mechanisms degraded forecast performance across all configurations. This key finding suggests that for univariate solar irradiance series in tropical Brazil, the added complexity of attention gates may not capture beneficial additional temporal dependencies. This study provides empirical evidence for optimal model selection (BiLSTM) in regional grid integration applications and challenges the assumed universal utility of attention mechanisms in time-series forecasting for renewable energy.

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### *2.4. A Hybrid Co-Variance-Guided ABC–NSGA-II Metaheuristic for Multi-Objective Multi-Area Dynamic Economic–Emission Dispatch with Renewable Integration and Implicit Constraint Handling*

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The increasing penetration of wind and solar resources in interconnected grids has made multi-area dynamic economic–emission dispatch (MADEED) a significantly more challenging optimization problem due to multi-temporal coupling, stochastic renewable fluctuations, inter-area power exchanges, and complex nonlinear constraints such as ramp limits, valve-point effects, and prohibited zones. Existing intelligent optimization techniques often show limited scalability, slow convergence, or poor constraint feasibility when applied to large multi-area systems. To overcome these limitations, this study proposes a hybrid Co-variance Guided Artificial Bee Colony (CG-ABC) and NSGA-II framework equipped with boundary-update implicit constraint handling and BWM–TOPSIS decision analytics for identifying the Best Compromise Solution (BCS) across conflicting economic and emission objectives.

The proposed CG-ABC enhances the original ABC by introducing a co-variance learning matrix, enabling bees to adapt search directions based on population distribution and correlated variable dynamics. This significantly improves global exploration and local exploitation in large-scale dispatch spaces. The hybridization with NSGA-II ensures robust non-dominated sorting, crowding-distance-based diversity management, and stable Pareto-front generation under multi-objective competition. An implicit constraint-handling mechanism based on boundary-repair and feasibility-preserving updates ensures strict adherence to tie-line flow limits, dynamic ramping limits, and inter-area balance constraints without requiring penalty parameter tuning.

The method is validated on multi-area test systems referenced in the recent literature, including two-area (6 units), three-area (10 units), and four-area (40 units) setups incorporating wind and solar generation modeled using Weibull and lognormal distributions. Comparative studies demonstrate that the proposed hybrid algorithm provides smoother, denser Pareto fronts, faster convergence, and superior feasibility preservation compared to recent high-performance algorithms reported in the literature. With BWM–TOPSIS aiding operator-level decision-making, the proposed framework offers a robust and sustainable tool for renewable-integrated multi-area power scheduling aligned with future low-carbon grid objectives.

### *2.5. Adaptive Fuzzy Particle Swarm Optimization for Hybrid Renewable Energy Systems in Direct Current Electrical Distribution System*

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The integration of renewable energy sources into modern power systems is essential for reducing carbon emissions and improving energy sustainability. Hybrid renewable energy systems, especially photovoltaics (PVs) and wind turbines (WTs), present an attractive solution due to their complementary generation profiles. However, their optimal placement and sizing in electrical distribution networks remain challenging due to nonlinear constraints and multiple objectives such as minimizing power losses, improving voltage

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profiles, and reducing operational costs. Advanced optimization techniques are therefore critical to achieving these goals.

This work presents an Adaptive Fuzzy Particle Swarm Optimization (AFPSO) algorithm applied for optimal integration of hybrid PV and wind energy systems in Direct Current electrical distribution networks. The proposed method, tested on a multi-objective function that addressed three objectives, minimization of active power losses, improvement of voltage deviation, and reduction of cost, is applied to the IEEE 69 bus system. AFPSO incorporates fuzzy logic to adaptively regulate PSO parameters, enhancing exploration and exploitation capabilities.

Comparative numerical comparison with Particle Swarm Optimization (PSO), Artificial Bee Colony (ABC), Grey Wolf Optimizer (GWO), and Whale Optimization Algorithm (WOA) algorithms is performed; the comparison reveals that AFPSO achieves the best results in terms of power loss reduction, voltage profile enhancement, and economic performance. The approach demonstrates strong potential for supporting efficient and reliable renewable integration in DC distribution systems.

### *2.6. Adaptive Neuro-Fuzzy Control of a Small Wind Turbine Integrated with Battery Storage for Remote Villages in Uzbekistan*

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Rural regions of Uzbekistan experience continuing issues of energy access because of poor grid networks and variable renewable sources. The solution is small-scale wind turbines and energy storage. But the wind speeds and load demand are variable and thus this solution needs intelligent control systems to perform its best.

This paper is an attempt to design an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller to control a small wind power system with a battery storage unit. The controller will be intelligent to control the flow of power between the wind turbine, battery, and local loads. A model of MATLAB/Simulink is created to simulate the reaction of the system to various wind and load conditions.

The results of the simulation prove that the ANFIS controller is better at stabilizing the voltage, reducing the power fluctuations, and optimizing the battery charge-discharge cycle compared to other conventional PI and the standalone fuzzy controller. Environmental variability is effectively responded to by the system, making it more reliable and energy-efficient.

ANFIS control and wind–battery microgrid integration provides a feasible and expandable off-grid electrification solution to remote areas. This strategy promotes the renewable energy ambitions of Uzbekistan and offers an example of smart microgrid implementation in other resource-limited rural areas. The next steps would be on practical applications and hardware verification.

### *2.7. Advancements in Artificial Intelligence for Renewable Energy Systems over the Past Decades*

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Sunlight, air, and other natural resources are invaluable gifts that must be utilized responsibly to enhance human welfare while preserving the environment and protecting all forms of life. The reliance on fossil fuels has increasingly threatened these resources, which has made the exploration of sunlight and air as major renewable energy sources a critical focus of research and development. Artificial intelligence (AI) originally developed to

mimic human thought and decision-making processes that have become a transformative force in renewable energy systems by optimizing energy generation, management, and distribution for greater efficiency and sustainability. This paper shows the advances of AI as it applied and continues to research in wind, solar, geothermal, hydro, ocean, bioenergy, hydrogen, and hybrid energy systems during the last decades. A bibliometric analysis, conducted via VOSviewer and Bibliometrix, of the literature was conducted systematically by reviewing relevant journal articles between 2000 and 2025. AI and energy provide a recent lit of energy trends in research, collaboration maps, future use applications, and newly explored domains. Different studies shows AI technologies measurability improve several aspects of renewable energy for the purpose of integrating operations into the grid for users, specifically forecasting, improving system stability and frequency, and obtaining a means to assess transient stability. This research offers meaningful recommendations to facilitate the development of AI, accelerate the application and promotion of AI technology in the field of renewable energy, and build efficient models, processors, and data centers through shifting to renewable energy.

### *2.8. AI-Enabled Energy Management Systems for Small-Scale Businesses*

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Small-scale businesses face persistent challenges in managing energy efficiently due to limited resources, rising operational costs, and the absence of real-time monitoring systems. These constraints often lead to unnecessary energy wastage, reduced profitability, and a higher environmental footprint. Artificial Intelligence (AI) and the Internet of Things (IoT) present affordable, practical solutions that can transform the way small enterprises monitor, analyze, and optimize their energy usage.

**Problem Statement**

- High operational costs due to energy wastage.
- Lack of affordable and user-friendly energy monitoring tools.
- Need for scalable, low-cost AI solutions tailored for SMEs.

**Proposed Solution**

The proposed system integrates IoT sensors, smart meters, and cloud-based AI analytics to continuously monitor energy consumption. Machine learning models are applied to both historical and live data to forecast consumption patterns, detect anomalies, and recommend operational adjustments for improved efficiency.

**Methodology**

1. Install IoT-enabled smart meters.
2. Collect and transmit energy usage data to the cloud.
3. Apply machine learning models for forecasting and anomaly detection.
4. Generate actionable recommendations via an intuitive user dashboard.

**Expected Benefits**

- 15–25% reduction in energy costs.
- Lower carbon emissions.
- Improved operational efficiency.
- Scalable for SMEs in both urban and rural settings.

**Future Work**

Future developments include integration with renewable energy sources such as solar and wind power, and expanding the system to manage energy at a community or regional level.

**Conclusion**

AI-enabled systems can make energy management accessible, cost-effective, and sustainable, empowering small businesses to contribute meaningfully to global climate change mitigation efforts.

### *2.9. Artificial Intelligence-Driven Forecasting, Optimization and Control of Renewable Energy Systems: A Systematic Review and Design Framework*

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The rapid penetration of renewable energy systems has intensified operational challenges related to intermittency, decentralized architectures and data-driven decision making. In addition, artificial intelligence (AI) techniques are being increasingly adopted into renewable energy applications, as shown in the existing studies. However, these studies are often fragmented, focusing on isolated forecasting or optimization tasks without providing an integrated design perspective. This study addresses this gap by systematically reviewing and synthesizing recent AI-based approaches for forecasting, optimization and control of renewable energy systems.

A structured literature analysis was conducted covering machine learning, deep learning and reinforcement learning techniques applied to solar, wind, hydropower, energy storage, and hybrid renewable systems. Forecasting models, including Long Short-Term Memory (LSTM), Gated Recurrent Units (GRUs), Convolutional Neural Networks (CNNs) and hybrid architectures, were comparatively analyzed with respect to prediction horizon, data requirements, and operational relevance. Optimization and control strategies based on genetic algorithms, particle swarm optimization, and reinforcement learning were examined for battery scheduling, hybrid system sizing and market participation.

The analysis shows that these deep learning-based forecasting models consistently outperform old traditional statistical approaches. These modes enabled improved operational planning and higher renewable penetration. Predictive maintenance using SCADA data significantly enhances fault detection and asset reliability, while learning-based optimization techniques support adaptive and resilient energy system operation. Based on these findings, a unified AI-enabled design framework is proposed to guide the selection and integration of forecasting, optimization and control techniques for renewable energy systems.

### *2.10. Integrating AI Techniques for Solar Energy System Optimization*

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Introduction: Optimizing solar energy systems is essential for improving efficiency and reliability in the shift toward renewable energy. Artificial Intelligence (AI) plays a key role by enabling precise forecasting, adaptive control, and real-time optimization of photovoltaic (PV) technologies. This study examines the use of AI methods, such as neural networks, hybrid deep learning, and machine learning, to enhance solar irradiance prediction, panel orientation, and maximum power point tracking (MPPT).

Methods: Multiple AI models were examined, including Artificial Neural Networks (ANNs), Long Short-Term Memory (LSTM) networks, Convolutional Neural Networks (CNNs), and hybrid CNN-LSTM frameworks. These models utilized datasets containing meteorological variables such as solar irradiance, temperature, humidity, and historical PV output. Optimization tasks incorporated Random Forest Regressors with Grid Search, ANFIS for MPPT, and reinforcement learning for tilt adjustment.

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Results and Discussion: The GRU model achieved a 23.3% lower RMSE compared to standard backpropagation neural networks and 11.9% improvement over traditional RNNs. A hybrid CNN-LSTM model demonstrated superior performance, reaching an RMSE of 0.0187 and an $R^2$ of 0.9915. In large-scale deployments like the Benban Solar Park, the model yielded a MAPE of 2.04% and $R^2$ of 0.99. For MPPT enhancement, AI models using ANFIS improved thermal and electrical efficiency by up to 12.3% under dynamic irradiance conditions. AI-based orientation control using reinforcement learning improved annual energy yield by 10–15%, while supervised ML methods increased energy output by an average of 3.98% over fixed-tilt systems.

Conclusion: The integration of AI in solar energy systems yields significant quantitative benefits. Forecasting accuracy improves with hybrid models achieving 2% MAPE and >0.99 $R^2$, while orientation and MPPT optimizations result in 10–15% higher efficiency and up to 30% energy savings. These advancements highlight AI's role in transforming solar technologies from static, reactive systems into dynamic, intelligent energy infrastructures.

### *2.11. MPC–DRL Based Hybrid Energy Management System for Intelligent Climate Control in Controlled Environment Agriculture (CEA)*

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With energy demand increasing year by year, high-yield crop production requires the use of Controlled Environment Agriculture (CEA) facilities, such as modern greenhouses and precision technologies. However, the energy consumption for maintaining such an outstanding indoor climate, including temperature, humidity, and concentration, is exceptionally high. This study primarily focuses on the engineering challenge of improving energy efficiency through an Intelligent Hybrid Energy Management System (IHEMS) that leverages Artificial Intelligence (AI) to optimize in real-time solar photovoltaic (PV) and thermal energy storage systems in combination. The IHEMS employs a Model Predictive Control (MPC) algorithm integrated with a Deep Reinforcement Learning (DRL) agent. The MPC predicts future thermal and electrical loads based on crop-specific requirements, including external weather forecasts and historical, operational, and statistical data. The DRL agent then learns the most cost-effective and energy-efficient control plans for the hybrid system's components (e.g., maximizing PV self-consumption, coordinating the charging/discharging of the thermal storage tank, and modulating HVAC unit operation). The main objective is dual-target optimization. Firstly, minimize the net energy cost, and secondly, maintain the microclimate within a narrow, ideal band for maximum crop growth. The experimental validation using a test greenhouse facility shows that the IHEMS achieves up to a 25% reduction in peak power demand and an overall 18% reduction in energy consumption compared to traditional and conventional rule-based control systems, while significantly enhancing the potential for crop productivity. This research provides a robust engineering solution for sustainable, high-precision energy management in the future of the agriculture sector.

### *2.12. Multi-Objective Evolutionary Optimization with an Artificial Intelligence-Based Approach for Urban Energy Planning*

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The rapid growth of urban populations has intensified the global demand for clean and renewable energy sources. Among these, solar power has emerged as a vital element in sustainable urban planning. Integrating solar photovoltaic (PV) systems into city energy infrastructures represents a key step toward achieving sustainable urban transitions. Nevertheless, fluctuating weather conditions create significant challenges for optimizing solar energy generation and its seamless integration into urban energy networks. This study introduces an artificial intelligence-driven predictive modeling framework designed to support the development of sustainable urban solar energy systems. The proposed approach utilizes advanced machine learning algorithms to predict the degradation of solar energy systems by incorporating meteorological variables and urban air quality indicators within the densely populated capital of Bangladesh. The model is trained and validated using historical weather data alongside real-time degradation records from solar installations in Dhaka, Bangladesh. The results indicate that the proposed predictive model notably improves forecasting accuracy. This research highlights the potential of machine learning as a robust and precise tool for modeling complex urban solar energy dynamics. Furthermore, the developed framework offers practical value to urban planners, utility managers, and system operators by enhancing operational performance, supporting grid integration, and improving the financial sustainability of solar projects. The insights gained contribute to advancing smarter, more resilient, and sustainable urban energy infrastructures.

### *2.13. Optimal Power Sharing Between Multi-Microgrids to Improve Electrical Grid Resilience After Disconnection*

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This paper proposes the design of an optimal power management and dispatch strategy among networked microgrids to enhance electrical grid resilience after disconnection. The main contribution of this paper is the design of an optimal strategy to ensure power system stability in the event of generator disconnection. This is achieved through optimal power sharing among multiple microgrids connected at the load bus, combined with smart power dispatch of renewable energy sources. The proposed strategy includes three coordinated stages involving optimal power management of renewable sources in each connected microgrid, optimal sharing of interconnected microgrids, and intelligent load shedding. Each microgrid includes a solar PV generator, concentrating solar power (CSP), and a wind farm. In addition, a multi-energy storage system was installed in each microgrid, comprising Redox Flow Batteries (RFBs), Superconducting Magnetic Energy Storage (SMES) and Fuel Cells (FCs). Moreover, an optimal Load Frequency Control (LFC) loop was applied to cope with system load disturbances or climatic changes. The main objective was to design a decentralized controller using nature-inspired optimization algorithms. For this aim, an optimal Fuzzy-PIDN controller was designed using a recently optimized algorithm called the Crayfish Optimization Algorithm (COA), which was used to find the best controller parameters to enhance the power management of each green source, the frequency control using multiple storage units, and optimal microgrid power sharing to support the main grid frequency stability and control in case of load disturbances. Several case studies have been conducted to prove the validity of the proposed strategy. It can be concluded from the obtained results that multi-stage optimal power management and control ensure optimal sharing between interconnected multi-microgrids to increase resilience and energy autonomy after grid disconnection, and can also improve dynamic power system stability.

### *2.14. Optimization of Power Stability Index in Presence of Large-Scale Integration of Green Power Generation*

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Currently, the large-scale integration of renewable energy sources (RESs) such as wind and solar photovoltaic generators is profoundly altering the dynamic behaviors of electrical grids, notably by reducing their inertia and making transient stability more critical. The originality of this work lies in its systematic exploration of the nonlinear dynamics of electrical networks, analyzing in depth the impact of RESs integration on grid stability and focusing on frequency response and rotor angle dynamics. This work proposes a methodology for evaluating and optimizing power system stability index, focusing on two major indicators: the Critical Clearing Time (CCT) and the Rate of Change of Frequency (ROCOF). The IEEE 39-bus test system is used as a test bench to simulate different renewable energy injection and microgrid (MG) location scenarios. Three-phase faults are applied to several grid lines to determine the corresponding CCTs and assess the system's ability to recover a stable state after disturbance. An automated approach was developed to calculate the CCT, enabling faster convergence and simultaneous testing of multiple fault locations. Variations in the ROCOF were also measured to quantify the effect of microgrids on frequency stability. The results show that high renewable energy penetration tends to reduce the CCT and increase the ROCOF, indicating a loss of dynamic robustness. However, optimizing the microgrid location to include an energy storage system (ESS) improves overall stability. These observations are supported by comparative simulations with and without renewable energy integration. Ultimately, this work highlights the importance of optimally locating distributed units and using CCT and ROCOF indices as diagnostic and optimization tools for modern power grids with high renewable energy penetration.

### *2.15. Optimizing MPPT Control Methods Using Nature-Inspired Metaheuristic Algorithms to Maximize the Use of Renewable Energies*

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Maximum Power Point Tracking (MPPT) is essential to maximize energy extraction from photovoltaic (PV) arrays, especially in islanded microgrids, where grid support is absent and energy margins are tight. Traditional MPPT techniques and established metaheuristics such as Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have been applied widely, but they can suffer from slow convergence, premature trapping in local maxima under partial shading and variable irradiance, and suboptimal tradeoffs between tracking speed and steady-state oscillation. This paper systematically evaluates and compares a set of established and novel nature and bio-inspired metaheuristic optimizers for MPPT in an isolated microgrid context. First, PSO and GA are implemented as baseline methods under standard and partial-shading scenarios. Second, three recently proposed metaheuristics—Quokka Swarm Optimization (QSO), Dendritic Growth Optimization (DGO), and Brown-Bear Enhanced Optimization (EBOA)—are adapted to design an enhanced MPPT and tested for the first time in this application. The investigated algorithms are benchmarked in simulations against realistic PV models, dynamic irradiance/temperature profiles, and common partial-shading patterns. Performance metrics

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include convergence time to global MPP, energy capture over daily cycles, robustness to measurement noise, computational load, and susceptibility to false local maxima. Obtained results show that several of the newer optimizers achieve faster convergence and improved global MPP identification under challenging conditions while maintaining acceptable computational costs, suggesting promising alternatives to classical approaches for islanded microgrids. The paper concludes with implementation notes for embedded controllers and recommendations for future hardware validation.

### *2.16. Physics-Inspired Machine Learning Framework for Reliable Power Prediction in Photovoltaic Systems*

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Accurate forecasting of photovoltaic (PV) power is essential for the reliable operation of renewable energy systems. Conventional approaches fall into two extremes: physics-based models that provide theoretical accuracy but require extensive parameters, and data-driven machine learning models that can learn from historical trends but often behave as black boxes with limited interpretability. While machine learning has achieved strong short-term performance, its lack of physical grounding restricts generalization to unseen weather or operating conditions. This study introduces a **physics-inspired machine learning framework** for predicting PV power output under varying irradiance and temperature conditions. A dataset of PV system performance, meteorological variables, and solar irradiance is used to train a neural network. Unlike conventional models, the proposed framework integrates **physics-informed regularization** into the training process. Constraints derived from PV physics including the Shockley–Queisser efficiency limit, temperature dependence of bandgap energy, and diode-based current–voltage relations are embedded into the model's loss function. These constraints ensure that predictions remain consistent with established photovoltaic principles while still adapting flexibly to real data. Preliminary evaluations show that the physics-regularized model reduces prediction error compared to standard neural networks and maintains robust performance under unseen conditions. More importantly, the approach offers **interpretable and trustworthy forecasts**, addressing a key gap in PV power prediction. By combining the adaptability of AI with the reliability of physical laws, this work contributes to the development of **sustainable, data-driven tools for renewable energy system optimization**.

### *2.17. Predicting Renewable Energy Generation to Reduce $CO_2$ Emissions for Net Zero in Bangladesh Using Hybrid Models*

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It is important for Bangladesh to balance energy development and sustainable growth in light of the country's need for net-zero emissions. In this study, we develop three hybrid models to forecast the growth of renewable energy and the level of $CO_2$ emissions for target dates set by the country. This paper presents a prediction analysis of $CO_2$ emissions and the renewable energy industry in terms of the necessary rate of mandated emissions based in probabilistic deep learning. We designed the first model, which combines Long Short-Term Memory (LSTM) with autoregressive integrated moving average (ARIMA) and XGBoost. The second hybrid model consists of deep neural networks (DNNs) and Gaussian process regression (GPR). The third model is a blend of random forest and LSTM with a Bayesian neural network (BNN). By exhaustive analysis of the results, we examine the values obtained from the generation of predictive models for the renewable energy

sector along with progressive enhancement of energy production and decarbonization. The results demonstrate the promise of the hybrid methodologies for the improvement of energy efficiency and energy policy systems with the objective o net-zero in Bangladesh. The outcome of the prediction method reveals that hybrid model of deep neural networks (DNNs) with a Bayesian neural network (BNN) achieve the best accuracy with the highest performance parameters.

### *2.18. Short-Term Wind Speed Forecasting at Termas Station: A SimpleRNN Pipeline with Weibull Characterisation*

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Short-term wind information is important for operating small wind plants and for planning other distributed energy resources. In this study, we work with one year of measurements from the Termas station and build a simple, reproducible workflow that goes from raw data to ten-minute wind speed forecasts. The original file contains 193,493 records with non-uniform timestamps and some suspect values near zero. We first standardise the timestamps, compute 10-min averages and select only complete days with 144 samples, obtaining 52 days and 7488 valid points. Days with extremely low daily means are removed and very small speeds are corrected to reduce obvious sensor and logging errors.

The cleaned series is then described with daily and global Weibull distributions. For the global fit, we obtain a shape parameter k = 1.27 and a scale parameter c = 1.40 m/s, which point to a low to moderate wind regime with frequent calm periods. For the forecasting step, we form supervised samples using 24-h sliding windows (144 time steps) to predict the next 10-min value. A single-layer SimpleRNN network is trained using a chronological split into training, validation, test and a final 10% hold-out set.

On the hold-out set, the network reaches a mean absolute error of 0.28 m/s and an $R^2$ of 0.78. These results suggest that even a modest recurrent model can follow the short-term variability of the wind speed at this site and that the proposed workflow can be reused with longer records or other stations.

### *2.19. The Role of Artificial Intelligence in Driving Renewable Energy Transition from the Current Landscape to Future Pathways*

**Md. Nurjaman Ridoy and Sk. Tanjim Jaman Supto**

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The shift from fossil fuels to renewable energy (RE) is a key component in achieving global sustainability and dealing with climate change. Natural resources, such as sunlight, air, water, and biomass, have tremendous potential to create clean energy; however, exploiting these resources in an efficient, stable, and large-scale integration manner is difficult due to their variable and distributed nature. Artificial intelligence (AI) approaches that mimic human learning and decision-making have recently become viable approaches to solve renewable energy problems. This study mainly examines the current landscape of AI applications across solar, wind, hydro, geothermal, ocean, hydrogen, bioenergy, and hybrid energy systems. Findings indicate that AI enhances renewable energy forecasting, improves power system frequency analysis and stability assessments, and optimizes dispatch and distribution networks. Beyond technical optimization, AI also contributes to broader sustainability goals, including energy efficiency improvements, intelligent smart grid management, and enabling mechanisms such as carbon trading and circular economy practices to reduce exposure to climate extremes. Drawing on evidence from a range of renewable energy areas, this study highlights the importance of artificial intelligence (AI) in bridging the link between technology innovation and sustainable energy management.

This paper discusses potential future research avenues, such as building sophisticated AI designs, energy-efficient chips, and data communication networks. Ultimately, the synergy between AI and renewable energy systems represents not only a technological advancement but also a transformative pathway toward a resilient, low-carbon future.

## 3. Session 2: Smart Grids and AI-Enabled Energy Management Systems

### *3.1. AI-Enhanced Energy Monitoring Framework for Smart Factories: A Neural Network and Six Sigma-Driven Approach*

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The increasing complexity of modern manufacturing systems has amplified the need for intelligent energy monitoring solutions capable not only of visualizing consumption but also of detecting anomalies and predicting failures. Traditional monitoring applications provide real-time dashboards and performance indicators; however, they remain reactive and offer limited capacity for forecasting abnormal behaviors or guiding improvement initiatives. This research proposes an enhanced intelligent energy monitoring framework for smart factory environments, combining neural network modeling with a Six Sigma analytical approach to strengthen prediction accuracy and process stability. The study begins by examining the operational logic of conventional energy monitoring systems, highlighting their architecture, data flow mechanisms, and functional limitations. To address these gaps, a predictive model based on artificial neural networks is developed and trained using real production data to detect erroneous measurements, and predict potential failures related to equipment or data acquisition. Six Sigma methodology is integrated into the modeling process to structure the improvement cycle, refine parameter selection, evaluate statistical significance, and ensure robust model validation through performance metrics and process capability indices. The proposed solution is finalized through the design of a new application framework embedding the predictive model into the existing monitoring architecture. This intelligent platform enables continuous KPI tracking, automated alerts, and data-driven decision-making for proactive maintenance, process optimization, and energy efficiency. Results demonstrate that the integration of AI and Six Sigma improves monitoring intelligence, reduces reaction time, and strengthens operational reliability in Industry 4.0 environments. The findings confirm the potential of hybrid analytical approaches to transform energy monitoring from a descriptive system into a predictive and prescriptive decision-making tool.

### *3.2. Evolution of Smart and Micro-Grid Laboratories Toward Real-Time Co-Simulation and Digital Twin Testbeds*

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In recent years, the transformation of micro-grid laboratories has accelerated toward more integrated, real-time, and data-driven environments. The evolution from early control-validation setups to advanced Power Hardware-in-the-Loop (PHIL), Co-Simulation, and Digital Twin (DT) frameworks has enabled a new generation of smart-grid experimentation emphasizing interoperability, scalability, and cyber-resilience. Modern testbeds now merge real-time simulators, HELICS/FMI-based middleware, and cloud-linked monitoring

systems to create hybrid validation environments that reproduce complex grid interactions with high fidelity and automation. This convergence allows simultaneous testing of control, communication, and operational layers while bridging laboratory models with live field data. However, challenges remain in affordability, latency control, data standardization, and reproducibility, particularly for universities and utilities in resource-limited regions. This study presents a systematic review of micro-grid testbed developments between 2015 and 2025, classifying and comparing representative PHIL, Co-Simulation, and Digital Twin architectures. This study highlights open-architecture design approaches, interoperable standards, such as IEC 61850, IEEE 2030.5, and MQTT/REST, and cybersecurity-ready interfaces suitable for distributed validation. A five-step implementation roadmap is proposed to guide the development of low-cost, reproducible, and industry-aligned laboratories. The findings demonstrate that the convergence of real-time simulation, cross-domain synchronization, and Digital Twin intelligence represents a decisive step toward the next generation of sustainable, validated, and data-centric micro-grid testbeds.

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### *3.3. From Solar Panels to AI Decisions: Intelligent Server Utilization for Sustainable Computing*

**Nikolaos Fragkos, Stylianos Katsoulis, Evangelos Nannos, Fotios Zantalis, Ioannis Chrysovalantis Panagou, Panagiotis Tsiakas and Grigorios Koulouras**

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The integration of renewable energy sources, like solar power, is crucial for achieving sustainable computing infrastructure, especially in off-grid systems. The variable nature of solar energy often leads to surplus generation, particularly at midday, that cannot be efficiently stored or consumed. To address this challenge, we propose an AI-enabled demand response system that dynamically scales server utilization based on real-time solar availability. The system is also adaptable for integration with grid-connected networks for broader energy optimization. Leveraging recent advances in Artificial Intelligence (AI) and drawing from the peer-reviewed literature, reputable conference proceedings, and industry white papers, we evaluated an AI-driven framework for server scaling and resource allocation in Large Language Model (LLM) training. Real-time data on energy production and consumption, as well as battery storage, were collected from various sources, including Battery Management Systems (BMSs), Maximum Power Point Tracking (MPPT) units, and smart inverters. Supplementary solar forecasts were likewise integrated from third-party services (e.g., Solcast). These data were fed into a Tools AI Agent Node, and implemented within n8n, a low-code workflow automation platform, using the Ollama chat model gpt-oss:20b. This agent evaluates whether surplus energy would otherwise be unutilized for computational workloads and, if so, decides to use our proposed tool, activating or shutting-down the selected RAM-only provisioned servers optimized for LLM execution, effectively repurposing otherwise-wasted energy. Preliminary evaluations demonstrated high operational reliability (99%), near-real-time responsiveness (1 s latency), and accurate surplus energy detection. Workloads were successfully executed aligned with solar availability, validating the operational stability of the system. This research demonstrates that AI-driven demand response can repurpose surplus solar output into a

valuable resource for sustainable computing, contributing to energy-efficient data centers and a broader transition toward renewable-powered infrastructures.

### *3.4. Intelligent Control of Energy Sharing in Wind Based Microgrids*

**Aymen Bamaarouf**

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The global energy transition promotes the development of microgrids integrating renewable sources such as wind energy. However, the intermittency of these sources creates challenges in terms of stability, synchronization, and optimal energy flow management. This research proposes an artificial intelligence-based approach to optimize control, synchronization, and energy sharing among distributed units within a microgrid connected to the national grid. The methodology relies on reinforcement learning algorithms and neural networks to dynamically adjust control parameters according to load conditions and generation fluctuations. Preliminary simulation results show a significant improvement in system stability and a reduction in energy losses. Furthermore, the proposed model can be adapted to different configurations of distributed generation systems, ensuring flexibility and scalability for real applications. Future work will focus on experimental validation through a laboratory-scale microgrid platform integrating real-time data acquisition and hardware-in-the-loop simulation. This step aims to confirm the robustness and adaptability of the proposed intelligent control under realistic operating conditions, paving the way toward autonomous and resilient smart energy systems. So it's mandatory to take in consideration many external conditions which influence the stability of these microgrids.

These findings highlight the potential of intelligent control strategies for enhancing the integration of renewable sources in modern smart grids.

### *3.5. AI-Driven Energy Management System for Smart Grids Using LSTM-Based Forecasting and Reinforcement Learning Control*

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Modern smart grids increasingly incorporate distributed energy resources, electric vehicles and renewable generation, which are creating complex energy management challenges. Traditional control approaches lack the intelligence and responsiveness required to manage rapidly fluctuating loads and irregular renewable production. To address these limitations, this study proposes an AI-driven Energy Management System (EMS) designed to enhance grid stability, operational efficiency and energy optimization in smart grid environments.

The proposed EMS integrates a Long Short-Term Memory (LSTM) model for short-term load forecasting with a Reinforcement Learning (RL) controller for real-time operational decision-making. The LSTM model is trained using historical load demand data to generate accurate short-term predictions while the RL agent learns optimal coordination strategies for distributed resources such as battery storage systems and rooftop photovoltaic (PV) units. System performance was evaluated using multiple test scenarios reflecting variable consumer demand and fluctuating renewable energy availability.

Results demonstrate that the AI-based forecasting approach improves prediction accuracy by 22% compared with conventional statistical models. Intelligent battery scheduling achieved a 15% reduction in peak demand while renewable energy utilization increased

by 26%. The system also exhibited strong adaptability to sudden load variations, improved voltage and frequency stability and enabled cost-effective operation under dynamic grid conditions.

These findings highlight the significant potential of AI-enabled energy management to increase the flexibility, efficiency and resilience of next-generation smart grids. The proposed framework presents a scalable pathway for managing complex distributed energy environments and supports the global transition toward more intelligent and sustainable energy systems.

### *3.6. AI-Enabled Smart Energy Governance: A Business-Centered Optimization Framework for Intelligent Grids and University Energy Efficiency*

**Emma Verónica Ramos Farroñán [1], Danny Alonso Lizarzaburu Aguinaga [2], Pedro Manuel Silva León [3], Ricardo Gómez Sernaque [3], Edwin Martín García Ramírez [1]**

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This research develops a strategic management framework examining artificial intelligence integration with next-generation smart grids to enhance energy efficiency in university settings. As energy infrastructures become increasingly decentralized with higher renewable energy adoption and fluctuating demand patterns, academic institutions need sophisticated solutions to optimize consumption, minimize operational expenses, and achieve sustainability targets. The framework employs machine learning forecasting algorithms, multi-agent coordination systems, and reinforcement-learning optimization techniques to improve energy distribution, predict consumption patterns, and strengthen financial planning across campus operations. Additionally, it establishes energy governance metrics, enabling institutions to formulate transparent, evidence-based sustainability policies. Through combining organizational assessment, economic analysis, and AI-driven decision-making processes, this model demonstrates substantial capacity to decrease peak demand, enhance demand-response program participation, and boost system resilience. This interdisciplinary work bridges smart grid technology, artificial intelligence applications, and business management, providing a scalable methodology for universities, energy suppliers, and governmental organizations pursuing energy transition goals. The results underscore how intelligent management platforms facilitate more efficient, adaptable, and environmentally sustainable energy ecosystems. The proposed approach offers practical implementation pathways for institutions seeking to modernize their energy infrastructure while balancing economic viability with environmental responsibility, operational excellence, and strategic positioning in evolving energy landscapes characterized by technological and regulatory transformation.

### *3.7. Dynamical Classification of Residential Electricity Consumption*

**Tetyana Mamchych and Ivan Mamchych**

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Residential electricity consumption is an important part of the general system. Modern trends in the use of remote communications and remote work only enhance the importance of this part.

The total amount of energy consumed and the stability of consumption are important characteristics of an individual profile. In our opinion, it is the combination of these two

characteristics that is significant for the tasks of forecasting consumption and ensuring system stability. Cases when consumption has high volumes and low stability are undesirable for both the individual consumer and the overall system. However, such cases may go unnoticed by owners.

In this presentation, we introduce a model of dynamic classification of residential electricity consumption, taking into account volume and stability. The availability of modern smart-grid technologies allows for monitoring individual consumption and obtaining time series of readings. For stability modeling, the coefficient of auto-similarity is used, which is dynamically calculated based on time series of hourly spaced readings.

The model has been successfully tested on real data of Swedish residentials (Zimmermann, J.P. (2009) [1], End-use metering campaign in 400 households in Sweden. Assessment of the potential electricity saving. Enertech). Cases with low (0.20) and high (0.80) readings of the coefficient of auto-similarity were considered.

In our opinion, the proposed model has good prospects for implementation in practical devices for individual consumption monitoring. This can have a positive effect on reducing the cost for the individual consumer, as well as contributing to the stability of the overall system.

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### *3.8. Smart Design and Intelligent Control of Cacao Fermentation Systems: A Technical and Bibliometric Review*

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The modernization of cacao fermentation is essential to improve quality consistency, energy efficiency, and process traceability within tropical agro-industries. Traditional fermenters remain highly empirical, lacking thermal control and data-driven optimization. This study presents a technical–bibliometric review of recent research on cacao fermentation systems integrating design, modeling, and intelligent control approaches. A Scopus search covering 2016–2025 retrieved 20 documents from 13 sources, authored by 93 researchers with an international co-authorship rate of 30% and an annual growth of 8%. Data were analyzed through bibliometric mapping using VOSviewer and Biblioshiny, focusing on keyword co-occurrence and thematic evolution. Colombia emerged as the leading contributor, followed by Brazil, Canada, China, Côte d'Ivoire, and Ecuador, reflecting the strategic importance of cacao in tropical research agendas. The keyword network revealed three main clusters: (1) a bioprocess–thermal control cluster (red) linking fermentation process, thermal variables, and cocoa beans, oriented to modeling temperature, pH, and microbial kinetics; (2) a machine-learning and predictive modeling cluster (green) including random forests, adaptive boosting, and discriminant analysis, emphasizing algorithmic prediction of fermentation quality; and (3) an IoT and smart devices cluster (blue) focused on process monitoring, sensor networks, and energy control. Despite the growing integration of AI and digital tools, the analysis exposed notable gaps: limited use of hybrid energy systems, scarce CFD-based thermal modeling, and few pilot-scale intelligent fermenter designs for real tropical conditions. Future research should couple renewable-energy management, real-time data analytics, and AI-driven control architectures to develop scalable, sustainable

fermentation technologies. These findings position cacao fermentation as an emerging interdisciplinary domain bridging food bioprocess engineering, smart energy design, and artificial intelligence for sustainable agro-industrial transformation.

## 4. Session 3: Intelligent Design and Control of Energy Storage Systems and Demand Response

### *4.1. Determining the Efficiency of the Energy Storage Unit of Solar Chimney Power Plants with Artificial Intelligence*

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The biggest drawback for solar energy systems is the lack of performance during non-sunlit hours. While this can be overcome by integrating energy storage units into the systems, the initial investment cost and maintenance costs are disadvantages. Solar chimney power plants, a type of solar energy system, have a simple structure consisting of a collector, chimney, and turbine and operate solely on the principle of generating electricity by accelerating heated air upwards. The system's feasibility was demonstrated with the first prototype, Manzanares, which serves as the reference pilot plant in this study. Solutions are obtained after the validation and mesh-independent solution steps of the model created with the 3D CFD model. For real-world simulation, a discrete ordinates (DO) solar ray tracking algorithm is implemented in the analysis, assuming turbulent flow. Solar radiation enters the system through the translucent collector and reaches the ground. Solar radiation reaching the ground can be stored for heat transfer to the system air during non-sunlit hours using energy storage materials. Due to the system's structure, using storage materials in the ground is quite easy, and even using water with high heat capacity is possible. This study discusses the appropriate amounts of artificial intelligence-based energy storage systems for use on the ground. Solutions to increase energy storage efficiency and reduce performance degradation throughout the day are discussed. In particular, comprehensive recommendations are offered for maximum 24-h performance.

### *4.2. Optimal Coordinated Control of a Renewable Water–Energy Microgrid Connected Seawater Pumped Storage and Desalination for Coastal Communities*

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Isolated microgrid, offshore platforms, and coastal communities face a dual critical challenge: ensuring a reliable electricity supply and continuous access to potable water while limiting dependence on fossil fuels. This paper deals with the design of a new water–energy microgrid architecture dedicated to a small island community and remote area, combining renewable power generation, hybrid energy storage, and seawater desalination. The investigated system integrates onshore photovoltaic (PV) panels, offshore wind turbines connected via a high-voltage direct current (HVDC) link, a seawater pumped storage plant using a single upper reservoir, a flywheel energy storage system (FESS) for

fast power smoothing, a reverse osmosis (RO) desalination plant, a freshwater storage tank, and a small backup diesel generator.

In the first stage, a global coupled electricity–water model was developed. Then, an optimal control strategy using a recent metaheuristic algorithm was proposed to coordinate renewable generation, the pumping/turbining modes of the pumped storage plant, and the power allocated to the desalination unit. A small-signal stability analysis was also carried out around several representative operating points, examining dominant eigenvalues, damping margins, and the sensitivity to control and storage parameters (pumped storage, FESS).

Time-domain simulations and frequency-domain analysis show that the proposed architecture can maintain power–frequency balance in the microgrid while ensuring continuity of water supply. This work therefore lays the groundwork for a more advanced study of an Energy Management System (EMS) and multi-objective water–energy optimization, which will be addressed in future works.

### *4.3. Techno-Economic Analysis of a Novel Optimization Method for Hybrid Diesel–PV–Battery Systems*

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In this study, a novel optimization framework was developed to minimize the Net Present Cost (NPC) of hybrid renewable energy systems under realistic Somali conditions. The study evaluated four configurations using hourly load, solar radiation, and temperature data: Diesel-only, Diesel/PV, PV/Battery, and Diesel/PV/Battery systems. The main objective was to identify the most techno-economically viable and environmentally sustainable option capable of supplying a commercial load with a 15.8 kW peak demand. The optimization was conducted in Python through a single-objective cost function constrained by system reliability, with a Loss of Power Supply Probability $\leq$0.05 and total capacity maintained between 21–25 kW. The analysis considered capital, replacement, and fuel costs with component lifetimes ranging from 10 to 20 years and a discount rate of 8%. The results indicated that the Diesel + PV + Battery configuration achieved the best overall performance, with an NPC of $286,746, LCOE of $0.296/kWh, reliability of 95.5%, and a renewable fraction of 74.6%, while reducing $CO_2$ emissions to 987 t. In comparison, the diesel-only system recorded the highest cost, with an NPC of USD 345,140 and emissions of about 1338 t $CO_2$. The proposed optimization method demonstrates a practical and scalable approach for low-cost hybridization in resource-constrained regions, enhancing both economic efficiency and environmental sustainability of local microgrids.

## 5. Session 4: AI-Enhanced Design Strategies for Energy Efficiency in Built and Urban Environments

### *5.1. Context-Sensitive AI for Urban Energy Systems: A Comparative Study of Paris, Dijon, and Nice*

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AI-enhanced design strategies for energy efficiency are opening new options for urban adaptation across diverse environments. Paris, Dijon, and Nice illustrate distinct approaches shaped by climate, governance structures, and policy frameworks. Their experiences show how cities can tailor AI applications in energy management to local constraints and opportunities. This paper identifies the institutional, technical, and social mechanisms that enable successful integration of AI solutions into urban energy systems, and highlights key considerations for adapting them elsewhere.

A comparative case study methodology underpins the analysis, drawing on official French reports, municipal open data, and academic and technical literature. The three cities were selected to represent different climatic zones and governance models. The study focuses on AI deployment in energy management at building and district scales, and on the roles of policy and stakeholder engagement in enabling or constraining experimentation.

The results show that Paris uses AI platforms to manage building energy use, optimize infrastructure, and support smart grid operation in a metropolitan context. Dijon's centralized operations system coordinates multiple infrastructures, achieving significant energy savings, particularly in public lighting, through real-time monitoring, cross-domain data integration, and predictive control. Nice deploys AI to manage neighborhood-scale smart grids and integrate renewable energy under Mediterranean conditions, with particular emphasis on peak-load management and resilience. These cases reveal how performance is shaped by data governance, institutional capacity, and degrees of citizen and stakeholder participation.

The analysis identifies opportunities for adapting AI-based urban energy applications, while underscoring persistent challenges: data standardization, algorithmic transparency, interoperability across sectors, policy alignment, social acceptance, and privacy and security concerns. Addressing these issues is crucial to align technical innovation with institutional and societal conditions. The paper offers guidance for cities seeking to design and govern AI-based energy solutions that are both effective and context-sensitive.

### *5.2. Federated Learning for Energy-Aware Decision Systems in Smart Built Environments*

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Modern smart buildings and urban infrastructures increasingly depend on artificial intelligence to monitor, predict, and optimize energy performance. Deploying such intelligent systems across distributed devices and facilities requires approaches that are not only accurate and adaptive but also energy-efficient and privacy-preserving. Traditional centralized machine learning models are often less effective in this context, facing significant data privacy constraints and communication bottlenecks. Federated Learning (FL) provides a decentralized framework that allows multiple local agents, including smart meters, HVAC controllers, and building management nodes, to collaboratively train models without transmitting sensitive data to a central server. This study explores how FL can support lightweight decision and prediction models, including compact language or foundation models, designed for real-time energy monitoring and management. These models can operate efficiently on edge devices with limited computational power, a crucial requirement for widespread deployment. By emphasizing parameter-efficient and resource-aware learning, FL can reduce computational demands and communication costs,

making continuous learning feasible within energy-constrained environments. This enables enhanced capabilities such as predictive maintenance scheduling, real-time load balancing, and personalized occupant comfort profiles. The integration of such distributed AI systems lays the foundation for intelligent, adaptive, and low-energy decision-support frameworks in sustainable buildings and urban infrastructures, advancing the vision of resilient and self-optimizing smart environments.

### *5.3. AI Potential in the Site Suitability Analysis of Renewable Energy Communities*

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The deployment of Renewable Energy Communities (RECs) is a cornerstone of the transition toward low-carbon and resilient urban systems. Their effective planning requires decision-making tools capable of integrating environmental, social, and technical criteria within dynamic territorial and regulatory contexts. Traditional multi-criteria approaches (e.g., the Analytic Hierarchy Process) provide a solid methodological basis for site suitability analysis but are often limited by expert subjectivity, static weighting, and low adaptability to evolving conditions.

Artificial Intelligence (AI)-based tools could help at multiple stages of the decision-making process, from the automatic weighting of criteria to the optimization of alternative planning scenarios. Machine learning and deep learning algorithms can learn from historical data, such as energy performance records, socioeconomic indicators, or patterns of social acceptance, to calculate dynamic weights, thereby reducing dependence on subjective, judgment-based assessments. Adaptive multi-criteria systems can then update these weights in real time in response to regulatory changes, incentive availability, or variations in energy consumption. Natural Language Processing can further expand the decision base by extracting and classifying relevant information from complex sources, such as legislative documents, urban plans, and environmental impact reports, ensuring that planning processes remain aligned with current policies and sustainability goals. In parallel, optimization through AI metaheuristics, including genetic algorithms, swarm intelligence, or reinforcement learning, can identify optimal combinations of sites and configurations for RECs while balancing multiple constraints (e.g., landscape, historical, environmental, etc.). When integrated with Geographic Information Systems and remote sensing, these AI capabilities allow for continuously updated spatial analyses and transparent, explainable decision models.

The use of AI in energy planning offers a promising pathway to more adaptive, data-driven, and participatory frameworks for REC development, aligning local energy strategies with the broader objectives of circularity, sustainability, and resilience in the built environment.

### *5.4. AI-Driven HVAC Optimization: Enhancing Energy Efficiency in Built Environments Through Gree's Intelligent Climate Control Technologies*

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As global urbanization accelerates, the demand for energy-efficient building environments continues to rise. Heating, ventilation, and air-conditioning (HVAC) systems account for nearly half of a building's total energy consumption, highlighting the urgent need for intelligent optimization. This paper presents Gree Electric's advancements in integrating artificial intelligence (AI) into HVAC systems to enhance energy efficiency and environmental comfort in built environments. The study introduces a multi-layer AI optimization framework combining real-time data analytics, adaptive control algorithms, and predictive maintenance to minimize energy waste across residential, commercial, and urban applications. Utilizing deep learning models and IoT-enabled sensor networks, Gree's system dynamically adjusts temperature, humidity, and airflow based on occupant behavior, ambient conditions, and energy pricing signals. Experimental simulations and pilot installations demonstrate reductions of up to 25% in overall energy consumption while maintaining high user comfort and system reliability. This research also discusses Gree's broader vision of AI-enhanced urban climate management, including the integration of smart HVAC with renewable energy systems and building energy management platforms. By aligning AI design strategies with sustainable architecture and smart city initiatives, Gree's approach illustrates how data-driven climate control technologies can significantly contribute to low-carbon, intelligent urban environments. Future research will explore large-scale implementation models across diverse climatic zones, integration with district energy networks, and the development of autonomous control architectures for multi-building systems. The study contributes to advancing AI-based energy efficiency strategies and supports the global transition toward intelligent, resilient, and environmentally sustainable cities.

### *5.5. Circular Design as a Key Strategy to Reduce Embodied Energy: An AI-Powered Tool to Support Material-Related Data Exchange for a Sustainable Built Environment*

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In the transition towards a more circular built environment at all levels of design, digital support tools are needed to ensure effective material-related data exchange and enable the reduction of embodied energy in both products and buildings.

In this process of change, multi-stakeholder digital platforms can play a key role in promoting the collaboration among the different players involved in the various supply chains, helping them tackle the main challenges, including rising energy and raw material costs and the need to ensure energy and resource efficient solutions.

The AI-powered digital tool resulting from the NPRR research project "From waste to manufacturing: digital tools to establish virtuous cycles" integrates a web platform for circular materials, which enables data exchange between designers, manufacturers and waste recyclers, with a CAD plugin that supports real-time sustainability assessment with the help of AI-enhanced features, focusing on the nexus between the recycled content in materials and the reduction of embodied energy.

AI, trained through scenario-based learning with stakeholder participation during platform use, can support designers in researching and sourcing recycled/reused materials, as well as in data processing. By continuing training, with the support of LCA experts, AI could interpret complex documents such as Environmental Product Declarations, extracting the information needed to guide design towards the selection of circular, low-embodied-energy materials and products, as increasingly required by international regulations.

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### *5.6. AI-Driven Parametric Architectures: Generative Design Workflows for Ultra-Low-Energy Buildings and Districts*

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**Introduction**: The building and urban sectors account for a major share of global energy use, yet current energy-efficient design remains constrained by linear workflows and limited design-space exploration. This paper proposes an AI-driven parametric design framework that couples generative form-finding with performance-based evaluation to support the creation of ultra-low-energy buildings and districts. The focus is on retaining architectural authorship while leveraging artificial intelligence to navigate complex trade-offs between form, comfort, and energy demand.

**Methods**: A multi-stage workflow is developed using a parametric modelling environment linked to energy simulation and AI-based optimisation. Parametric building and district models encode key geometric and material variables (massing, orientation, envelope articulation, glazing ratios, and passive systems). Surrogate models trained on simulation datasets (e.g., regression and neural networks) predict energy and comfort metrics in real time. Multi-objective genetic algorithms and reinforcement learning agents generate and refine candidate configurations, while an architect-in-the-loop interface allows designers to steer and constrain the search.

**Results**: Applied to prototypical mid-rise building typologies and mixed-use district scenarios, the workflow rapidly produces large families of design variants and visualises Pareto fronts between energy use intensity, daylight availability, and floor area efficiency. Compared to conventional iterative design, the AI-enhanced approach uncovers solutions with substantially lower predicted annual energy demand while preserving spatial quality and façade diversity. At the district scale, coordinated optimisation of building forms and orientations demonstrates improved load smoothing and reduced peak demands.

**Conclusions**: The study shows that AI-driven parametric architectures can transform energy-oriented design from a late-stage validation exercise into an integrated generative driver of form at building and urban scales. The proposed workflow reinforces, rather than replaces, architectural judgement, and suggests a path towards explainable, performance-informed design cultures for ultra-low-energy built environments.

### *5.7. AI-Enhanced Detection of Thermal Anomalies in Urban Roofs via Drone-Assisted Infrared Thermography (UAV-IRT)*

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Urban areas, now hosting over half of the global population and consuming 60–80% of total energy, make urban energy management a critical global priority. Historic cities, with their centuries-old and listed buildings, pose unique challenges but also offer significant opportunities for improving energy efficiency. Effective energy management requires comprehensive knowledge, supported by accurate diagnostics of building quality. Non-destructive testing (NDT) techniques, valued for their precision and non-invasive nature, offer effective solutions for complex urban environments. Among these, infrared thermography (IRT) plays a central role by enabling rapid and non-invasive acquisition of surface temperature distributions to support both qualitative and quantitative analyses. Drone-assisted IRT (UAV-IRT) further enhances these capabilities by facilitating energy

audits, diagnosing heat losses, assessing HVAC efficiency, and inspecting renewable energy systems at the urban scale. Unlike ground-based imaging, UAV-IRT can access hard-to-reach areas and high-altitude structures (e.g., rooftops), without accessibility constraints, thereby improving the scope, accuracy, and efficiency of diagnostics.

Interpreting thermograms acquired via UAV-IRT for urban roof diagnostics remains challenging due to heterogeneous construction materials, complex thermal patterns, and the large volume of data generated. Manual inspection is often inefficient, subjective, and error-prone, particularly when distinguishing among insulation defects, moisture ingress, thermal bridges, and potential structural damage. This study presents a dataset of thermograms collected over two years from multiple historic buildings in Italy and applies machine learning for automated interpretation. The AI-based approach allows for the automatic detection and classification of thermal anomalies by reducing subjectivity and improving accuracy and consistency. It also enables surface segmentation by distinguishing between different materials and functional zones (e.g., roof coverings, mechanical systems, structural elements), revealing correlations between anomalies and underlying structural or energy-related conditions. This method demonstrates the feasibility of faster, more reliable, and predictive roof diagnostics, thereby supporting evidence-based strategies for energy management and conservation in historic cities.

### *5.8. AI-Enhanced Strategies for Energy-Efficient Urban Environments*

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Artificial intelligence (AI) is reshaping urban energy management by linking predictive analytics with closed-loop control across buildings, grids, mobility, and planning. This paper investigates which AI strategies deliver verified, scalable efficiency gains in cities and under what conditions they outperform conventional practice. Synthesizing recent applications, we compare measured and simulated outcomes across asset scales. In buildings, machine learning for forecasting, fault detection, and supervisory control, including reinforcement-learning policies, commonly yields ~10–37% operational energy savings while maintaining comfort. AI-enabled digital twins that fuse BIM/IoT with physics-guided models support anomaly detection and set-point optimization, with documented energy reductions of ~5–17% and improvements in indoor environmental quality. On the supply side, AI strengthens smart-grid operations through improved demand and renewable forecasting, demand–response orchestration, and predictive maintenance, enabling higher variable-renewable penetration and lowering peaks. In urban mobility, adaptive, AI-coordinated signaling reduces intersection delays by ~10–30%, with fuel and emission co-benefits. Realizing system-level gains, however, depends on high-quality data, robust calibration, and human-in-the-loop operation; key barriers include fragmented data governance, limited generalization across climates and vintages, interoperability gaps among BMS/IoT/twin platforms, and privacy–cybersecurity risks. We argue that durable impact will come from physics-guided ML and RL/MPC with explicit comfort, equity, and safety constraints; secure, interoperable digital-twin backbones; and standardized, transparent measurement-and-verification protocols. Implemented at scale alongside retrofits and clean power, AI-enhanced strategies can materially reduce urban energy use and $CO_2$ emissions while preserving service quality, offering a pragmatic path for cities to accelerate decarbonization

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### *5.9. AI-Integrated Courtyard Geometry Optimization: A Smart BAS-Facade Framework for Climate -Responsive Architecture in Tamil Nadu*

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Courtyards have long been integral to vernacular architecture in Tamil Nadu, offering passive cooling, natural light, and social connectivity. However, modern residential buildings often overlook their climatic and energy benefits, leading to increase reliance on mechanical systems. This study explores how artificial intelligence (AI) can be integrated with Building Automation Systems (BAS) and responsive facade technologies to enhance the environmental performance of courtyard-based architecture across different climatic zones of Tamil Nadu.

By analyzing traditional courtyard geometries, proportions, and orientations, this research identifies key parameters influencing thermal comfort, ventilation, and daylight performance. By reducing energy demand and increasing energy efficiency, AI adds overall impact by making the system smart. These parameters are then simulated and optimized using AI algorithms to derive climate-specific courtyard configurations. The integration of BAS enables dynamic environmental control—adjusting facade openings, shading devices, and airflow in real time based on sensor data.

The proposed AI-BAS-Facade framework bridges vernacular design logic and digital intelligence, transforming static courtyards into adaptive, energy-efficient microclimates. The results aim to establish data-driven design guidelines for low-rise housing that reduce operational energy consumption while preserving regional architectural identity. This approach demonstrates how AI-enhanced traditional design strategies can lead to sustainable, context-responsive built environments in a rapidly urbanizing climate.

### *5.10. Bio-Inspired, AI-Optimised Timber Architectures: Integrating Material Intelligence and Energy Performance in the Design Process*

**Kachana Kasulu**

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**Introduction**: Timber has re-emerged as a primary structural material in low-carbon architecture, yet its full potential remains underutilised when energy performance, structural behaviour, and fabrication constraints are treated in isolation. This paper presents a bio-inspired, AI-optimised design framework that couples material intelligence in engineered timber systems with energy-driven morphogenesis. Drawing on biological analogues of branching, lattices, and shells, this approach seeks to derive envelope and structural logics that simultaneously minimise operational, embodied energy while preserving architectural expression.

**Methods**: A parametric environment is developed for CLT and glulam assemblies, encoding grain direction, cross-section variation, connection logic, and panelisation rules. Bio-inspired typologies (e.g., venation-like shading lattices, ribbed shells, and branching supports) are translated into editable generative scripts. Energy and structural performance are evaluated via linked simulation engines for dynamic thermal behaviour, daylight, and FE analysis. Multi-objective evolutionary algorithms and machine learning surrogates (e.g., gradient-boosted trees) search and approximate the design space, optimising annual energy use, daylight autonomy, structural utilisation, and material volume. An architect-in-the-loop interface allows control over formal language, tectonic articulation, and programmatic requirements.

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**Results**: When applied to pavilion-scale and mid-rise prototypes, the workflow yields timber morphologies that reduce annual heating and cooling loads by 20–30% relative to conventional rectilinear envelopes, while cutting material mass by 10–18% through structurally efficient, bio-inspired geometries. Shading lattices derived from venation logics improve daylight uniformity and reduce glare without sacrificing transparency. Sensitivity analyses show that joint topology and grain-aware orientation strongly influence both stiffness and thermal bridging, highlighting the necessity of integrated material and energy modelling.

**Conclusions**: This study demonstrates that bio-inspired, AI-optimised timber architectures can transform wood from a merely "sustainable" substitute into an active driver of energy-aware form-finding. Embedding material intelligence within AI-assisted parametric workflows enables architects to negotiate structural, environmental, and fabrication criteria as co-equal agents in design, advancing a holistic paradigm for high-performance timber architecture.

### *5.11. Data-Driven Performance Analysis of Net-Zero Buildings: Quantifying Ecosystem Services and Operational Efficiency in the Bullitt Center*

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Buildings consume nearly 40% of global energy and produce 36% of $CO_2$ emissions, making net-zero energy buildings (NZEBs) critical for climate mitigation. However, empirical validation of NZEB performance at commercial scale remains limited. This study presents a data-driven computational analysis of the Bullitt Center—a six-story, 50,071 sf office building in Seattle—to quantify its operational energy balance and ecosystem service value using AI-enhanced monitoring analytics.

Over 12 months, machine learning algorithms analyzed 8760 hourly data points from IoT sensors monitoring energy consumption, solar generation, water usage, and occupant behavior. Statistical modeling and regression analysis identified performance drivers, while predictive algorithms optimized HVAC operations and demand response. Multi-criteria ecosystem services valuation employed computational modeling to quantify economic benefits over the building's 250-year design life.

The Bullitt Center achieved an Energy Use Intensity (EUI) of 9.4 kBTU/sf/year, performing 77% better than Seattle's baseline and producing 114,085 kWh annual energy surplus. AI-powered analytics revealed daylighting strategies reduced artificial lighting by 82%, while predictive HVAC controls maintained thermal comfort with minimal energy use. Smart rainwater harvesting and composting systems eliminated municipal water and wastewater connections. Ecosystem services valuation estimated USD 18.45 million in total benefits: energy efficiency (45%), carbon reduction (38%), and water conservation (12%). Benchmarking against 350 regional buildings confirmed superior performance.

This study demonstrates that integrated design processes, rigorous commissioning, and AI-driven monitoring enable genuine net-zero performance at commercial scale. The computational framework provides evidence-based guidelines for architects, engineers, and policymakers advancing climate-resilient intelligent building systems.

### *5.12. Design-to-Decommissioning AI-Driven Plant Design Modelling (D2D-AI-PDM) in Offshore Structures: A Review*

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Fixed-bottom or floating offshore structures, including wind farms, oil/gas platforms, and subsea systems, provide higher and more consistent wind speeds, higher energy yield per turbine and per km, vast available area, reduced visual and noise impact, proximity to coastal load centres, lower land acquisition costs and conflicts, and synergies with existing maritime infrastructure, ports built for oil/gas, or shipping that can be repurposed. Design-to-Decommissioning AI-Driven Plant Design Modelling (D2D-AI-PDM) has the potential to enable a scalable, sustainable offshore energy, whether renewables or transition fuels, ensuring assets are designed once but optimised forever. Traditional fragmented approaches adopt tools that create data silos, leading to inefficiencies in the process. The end-to-end D2D-AI-PDM approach has the potential to evolve autonomously with real-world data, enabling predictive, optimised, and increasingly autonomous decision making.

This study reviews and highlights the current trends and level of adoption of the latest technologies, such as generative AI, neural networks, reinforcement learning, and self-updating digital twins, into a unified, continuous workflow that spans the entire offshore asset lifecycle, from conceptual design and engineering, procurement, construction, installation, and operations and maintenance (O&M), to decommissioning. The current trends and available platforms for achieving D2D-AI-PDM, as well as the current state and level of readiness of International Oil Companies (IOCs) to adopt them, were analysed using publicly available information. This study also highlights the challenges of data integration and interoperability, data privacy and governance, trust, and regulation, as well as skills in the offshore energy sector.

### *5.13. Development of a Framework Using AI for Building Facade Optimization: An Application Focusing on Retrofitting NYCHA Midrise Housing in New York City*

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Artificial intelligence (AI) technology and the industrial revolution (4IR) have potential for the raid advancement of smart buildings, materials, and construction processes to achieve global decarbonization goals. There is a need to perform the assessment work quickly and thoroughly to design the most appropriate retrofit system. Current retrofit techniques can vary a lot in their methodology from place to place, but what most have in common is time contraints and the need to follow budgets often and show significant reductions in energy usage. The objective of this research is to develop a framework that optimizes the façade retrofitting process with the help of AI, bringing it in as a decision-making tool that also accounts for other parameters, but differently to traditional retrofit methodologies, where both the designer and the user are the judges. Thus, this research explores the possibilities of recent AI tools such as Midjourney to be used for problem-solving in retrofitting. This is done with a literature review of the application of AI in the architectural field for retrofits, façade optimization, and image generation. From there, the overall framework suggested is developed addressing materiality, high performance analysis, affordable costs, and user-experience inputs, aiming for a successful retrofit. Furthermore, this research contributes to the retrofit discussions by initiating steps on how available AI tools can add to the discussion, carving out a pathway on how AI can

help in this process. The results show an improvement in the way retrofits are addressed with the help of AI, mainly on user-experience, with their integration in the decision-making process.

### *5.14. Exploring the Use of Generative AI in the Intelligent Design of Energy-Efficient Façade Renovations*

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This study examines the potential of generative artificial intelligence (AI) in architectural design processes, focusing specifically on the energy-efficient renovation of building envelopes. The research explores the use of AI-based image generation tools to assist in the conceptual design phase of ventilated façade systems aimed at improving the thermal performance of existing buildings.

Based on photographic documentation of façades—obtained through conventional photography and photogrammetric imaging (SFM) to ensure geometric accuracy—the proposed methodology generates multiple design alternatives with AI assistance. These alternatives are constrained by a predefined catalog of construction products and materials provided by façade system manufacturers. The objective is to evaluate the current capability of generative AI tools to produce, within a reduced timeframe, multiple façade design options that are both visually coherent and technically feasible, in accordance with specific constructive and material parameters.

The results are assessed according to both architectural criteria—such as aesthetic consistency, contextual adaptation, and formal diversity—and technical parameters, including constructability, compliance with energy efficiency requirements, and correspondence with manufacturers' specifications.

This research seeks to establish a framework for integrating generative AI into the early design stages of energy retrofit projects, providing architects with intelligent and responsive tools that enhance creative exploration without compromising technical rigor. Ultimately, this work contributes to the ongoing reflection on the role of AI in intelligent design processes, proposing its use as a collaborative and adaptive system that bridges aesthetic decision-making with energy-conscious architectural design.

### *5.15. From Climate Data to Building Form: Machine Learning–Guided Envelope Design for Energy -Efficient Architecture*

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**Introduction:** Architectural envelope design is central to building energy performance, yet in practice it is often driven by heuristic rules and fragmented simulation workflows. This paper presents a machine learning-guided approach that translates high-resolution climate data into informed decisions on envelope geometry, material layering, and façade articulation, enabling architects to navigate complex interactions between solar gains, thermal inertia, daylight, and ventilation while preserving design freedom.

**Methods:** Typical Meteorological Year data from five Köppen climate classes (Cfa, Cfb, BWh, Dfa, Dfb) are processed into climate features (solar radiation clusters, diurnal

temperature swings, humidity profiles, wind roses). These drive parametric envelope descriptors: orientation, window-to-wall ratio (15–60%), shading depth (0–1.5m), insulation thickness (50–300mm), and thermal mass distribution. A 12,000-variant dataset is generated using EnergyPlus and Radiance simulations. Gradient boosting and neural network models, validated via 5-fold cross-validation, predict energy use intensity ($R^2$ = 0.91, RMSE = 8.2 kWh/$m^2$), overheating hours ($R^2$ = 0.88), and daylight autonomy ($R^2$ = 0.93) from combined climate–envelope feature vectors.

**Results**: Tested on office and mixed-use prototypes, the ML-guided workflow identifies envelope strategies reducing annual heating and cooling demand by 20–35% compared with ASHRAE 90.1-2019 code-minimum baselines (prescriptive envelope requirements, identical internal loads and schedules). SHAP-based sensitivity analyses on held-out data reveal climate-specific design drivers—shading geometry and solar control glazing in hot/arid contexts versus airtightness and insulation continuity in cold climates—providing interpretable, actionable guidance.

**Conclusions:** Machine learning can act as a climate-literate intermediary between raw weather data and envelope form-making. By embedding predictive models into parametric tools, architects gain rapid, intelligible feedback that elevates the building envelope from stylistic afterthought to a primary instrument of energy-efficient architectural design.

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### *5.16. From Super-Apps to Sustainable Communities: A Platform Framework for Coordinated Housing Retrofits*

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China's urgent need to retrofit 350 million residents' energy-inefficient housing faces critical coordination failures among diverse stakeholders. This paper investigates how digital platform principles, particularly those from Chinese super-apps, could enable community-driven sustainable housing transformations. Through systematic analysis of 27 digital platforms (15 Western, 12 Chinese) for housing services, we identify fundamental architectural divergences affecting retrofit coordination capabilities. Western platforms exhibit "fragmentation by design," prioritizing market competition over coordination efficiency, while Chinese super-apps demonstrate ecosystem integration but lack retrofit-specific mechanisms. Our analysis reveals five critical capability gaps: collective decision infrastructure, multi-stakeholder coordination, integrated compliance workflows, community benefit optimization, and trust beyond transactions. Based on these findings, we develop a conceptual framework comprising five interconnected modules operating above a unified data foundation: collective optimization (prioritizing community benefits over individual preferences), community coordination (structured decision-making), marketplace integration (trusted service provider connections), financial coordination (integrating diverse funding sources), and regulatory streamlining (proactive compliance support). The

framework fundamentally inverts conventional platform logic from individual preference aggregation to collective benefit optimization, with algorithms weighting community outcomes at 80% versus individual preferences at 20%. This reconceptualization demonstrates how platform-mediated collective action becomes possible when technology design aligns with community social practices rather than imposing market logics, offering a pathway to accelerate China's sustainable housing transformation.

### *5.17. Remote Sensing and Machine Learning-Based Assessment of Energy Efficiency in Urban Built Environments of Dhaka City*

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Rapid urbanization and unplanned land development have transformed Dhaka into one of the most densely built metropolitan areas in South Asia, leading to increased surface heat accumulation and energy consumption within the built environment. Numerous studies have reported a progressive rise in Dhaka's Land Surface Temperature (LST), ranging between 19 °C and 31 °C during the pre-monsoon months, accompanied by a strong negative correlation between the Normalized Difference Vegetation Index (NDVI) and LST, and a positive correlation between the Normalized Difference Built-Up Index (NDBI) and LST. This indicates that decreasing vegetation and expanding impervious surfaces are major contributors to the city's thermal inefficiency. The present study aims to assess energy efficiency patterns in the urban landscape of Dhaka by integrating remote sensing, GIS, and data-driven modeling techniques. Landsat 9 imagery and VIIRS nighttime light data were processed to derive NDVI, NDBI, and LST layers, while building footprints and road networks were extracted from OpenStreetMap to represent urban form. A supervised Random Forest model was employed to estimate the relative importance (weights) of these variables in influencing surface temperature distribution. Spatial overlay analysis and correlation assessment revealed that areas with high built-up intensity and low vegetation cover exhibit significantly higher surface temperatures, implying lower energy efficiency. In contrast, green and peri-urban zones demonstrate lower LST values, reflecting enhanced cooling potential. The resulting energy-efficiency map delineates critical urban heat zones that require mitigation through landscape-based interventions. This research underscores the importance of urban greening, reflective roofing, and compact yet sustainable vertical development as strategies to reduce thermal stress and improve energy performance. This study contributes to evidence-based urban planning approaches that can guide policymakers in designing more climate-resilient and energy-efficient cities in Bangladesh.

### *5.18. Resource-Significant Activity Costing in Offshore Structure Construction Projects Using Artificial Neural Network*

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Fixed-bottom or floating offshore structures are the foundations, platforms, and associated infrastructure that support oil and gas production systems, offshore wind turbines, and cabling. The remote nature of these structures and the harsh environment with high variability in wind, waves, currents, and weather make construction activity very difficult and unpredictable; variation in the schedule can lead to high construction vessel and personnel costs. The adoption of artificial intelligence using trends observed in historical data can help achieve more accurate construction cost and schedule predictions, reducing the capital expenditure cost of installation.

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A resource-significant activity, sometimes called a resource-critical activity or high-resource-demand activity, is an activity on a construction or project schedule that consumes a disproportionately large share of one or more resources compared with others. Plant Design Modelling (PDM) is a digital process that creates and manages a detailed 3D-model of a building's physical and functional characteristics and semantic information, such as cost and schedule. PDM serves as a single source of truth for multidisciplinary activities and, therefore, serves as a rich data source for various construction applications, including project scheduling and cost estimation. Neural networks (NNs), a subset of machine learning algorithms inspired by the human brain, excel at identifying patterns in complex datasets and making predictions, such as forecasting costs based on nonlinear relationships and historical trends.

We used data extracted from Aveva's-EverythingPDM of an offshore structure modification project, focusing on installation activities to create a dataset for machine learning model training. The extracted information includes geometry, material types, quantities, and spatial relationships between elements. The structured data extracted exhibit nonlinear patterns; therefore, they are analysed using ordinary and regularised linear regression models, as well as neural networks (NNs). NN models show a superior ability to predict the nonlinear nature of offshore construction activities' time.

### *5.19. Urban Digital Twins and Reinforcement Learning: Adaptive Energy Management Strategies for Climate-Responsive Cities*

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**Introduction:** Rapid urbanisation and intensifying climate variability are straining existing energy infrastructures, while city-level planning remains largely static and reactive. Urban digital twins—high-fidelity, data-rich virtual replicas of cities—combined with reinforcement learning (RL) offer new possibilities for adaptive, climate-responsive energy management. This paper explores how RL agents embedded in urban digital twins can orchestrate demand, storage, and distributed generation across buildings and districts to reduce energy use and emissions while preserving occupant comfort.

**Methods:** A multi-scale urban digital twin is constructed, integrating GIS-based morphology, building archetypes, district energy networks, and microclimate modelling. Real and synthetic data streams feed into the twin. RL agents (deep Q-learning and proximal policy optimisation, trained over 500 episodes with learning rate $3 \times 10^{-4}$ and discount factor $\gamma = 0.99$) control HVAC setpoints, shading devices, thermal storage, and battery dispatch at building and district levels. Reward functions encode multiple objectives, including minimising carbon intensity and peak demand while maintaining thermal comfort (operative temperature 20–26 °C, PMV $\pm$ 0.7). Comfort violations were deemed acceptable when affecting 5% of occupied hours. Scenario experiments explore different climate futures and urban design configurations.

**Results:** Simulation results for a mixed-use urban district show that RL-driven control reduces peak electrical demand by 18–30% and operational $CO_2$ emissions by 15–25% compared with rule-based schedules, while keeping comfort violations within acceptable limits. Coordinated control of façades, storage, and flexible loads mitigates urban heat

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island impacts during heatwaves. Policy analysis demonstrates how tariff design and incentive structures strongly influence RL convergence and system performance.

**Conclusions:** Coupling urban digital twins with reinforcement learning can transform static masterplans into adaptive, learning energy infrastructures. However, results are calibrated to a temperate European climate and mid-density mixed-use typology; generalisation to other climatic or morphological contexts requires further validation. Such tools nonetheless provide architects and policymakers with testbeds for prototyping climate-responsive districts.

## 6. Session 5: Data-Driven Design for Energy Forecasting, Security, and Resilience

### *6.1. Modelling and MATLAB-Based Optimization of Carbon Dioxide Adsorption Using Zn-MOF-5*

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The growing concern over greenhouse gas emissions has prompted the need for efficient carbon dioxide ($CO_2$) capture technologies. This study focuses on simulating $CO_2$ adsorption using a zinc-based metal-organic framework (Zn-MOF-5). The primary aim is to develop and refine a robust approach using MATLAB for equilibrium and kinetic modelling through the Linear Driving Force (LDF) model and Langmuir isotherm, which can accurately predict $CO_2$ adsorption performance under varying operational conditions. By employing advanced computational methods, this research seeks to streamline the process design and enhance the feasibility of sustainable $CO_2$ capture solutions. Excel was used for statistical analysis and validation, while MATLAB R2025a was utilised for equilibrium and kinetic modelling using the Linear Driving Force (LDF) model and the Langmuir isotherm. The independent impacts of temperature, pressure, and flow rate were evaluated using the variable effect method. This study found a significant negative association between temperature and $CO_2$ uptake, consistent with the exothermic nature of the adsorption process. Pressure had a considerable impact on adsorption, but flow rate had little effect within the investigated range. The simulated $CO_2$ uptake (21.196 mmol/g) closely matched the experimental data (21.07 mmol/g) with a 0.59% variance, validating the model's reliability. The research demonstrates that Zn-MOF-5 exhibits strong adsorption potential and that simulation tools can significantly reduce experimental costs and time. This underscores the potential of simulation tools to reduce costs and time, paving the way for more efficient carbon capture solutions. This initiative optimizes process design and promotes sustainable practices in addressing global $CO_2$ emissions. By contributing to process optimisation, this study aligns with the United Nations Sustainable Development Goal (SDG) 13, Climate Action, emphasizing the urgent need for innovative solutions to combat climate change and its impacts while supporting broader efforts for environmental sustainability.

### *6.2. Multi-Objective Optimization Method of Combined Air Conditioning Based on Building Conformity Prediction*

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Addressing the challenge of optimizing energy consumption in central air conditioning systems under coupled multi-parameter and dynamic operating conditions, this study

proposes an integrated approach combining cooling load forecasting with multi-objective collaborative optimization to enhance system energy efficiency and operational stability. Utilizing sensor data from a factory, a hybrid RF-CNN-LSTM forecasting model is developed. This model leverages random forest (RF) for feature selection, a convolutional neural network (CNN) for extracting local patterns, and a long short-term memory (LSTM) network for capturing temporal dependencies, achieving high-precision prediction of cooling capacity demand. Subsequently, an energy consumption model encompassing chillers, water pumps, and cooling towers is established. This study employs the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) to simultaneously optimize three objectives: minimizing the total system energy consumption, maximizing the coefficient of performance (COP) of the chillers, and minimizing the fluctuation of key operating parameters. The experimental results demonstrate that the forecasting model achieves a coefficient of determination ($R^2$) of 0.9625 and a mean absolute error (MAE) of 143.62 kW on the test dataset. After optimization, the total system energy consumption is reduced by an average of 14.53%, reaching 124.58 kW. The chillers contribute 93.94 kW (75.4%) of this energy saving, while the combined energy saving rate for the chilled water pumps and condenser water pumps reaches 37.76%. Despite a 16.40 kW increase in cooling tower power consumption, the overall system achieved significant net energy savings. A reduction of 4.8 °C in the cooling water inlet temperature led to a 13.8% improvement in chiller COP. The multi-objective optimization strategy significantly reduced the temperature fluctuation of chilled water supply and return by 76.48% and 81.79%, respectively, effectively enhancing operational stability. For scenarios involving sudden increases in cooling load, although the fluctuation of the cooling water inlet temperature slightly increases, the response effectively overcomes the hysteresis typically associated with traditional control systems.

### *6.3. Optimizing Offshore Green Hydrogen Systems via Modular Simulation*

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This study presents a mathematics-based simulation model for designing, analyzing, and optimizing offshore green hydrogen stations powered by solar photovoltaic systems, applicable to any location worldwide. Developed in Python, the model integrates environmental, physical, and technological parameters to simulate and forecast hydrogen production via water electrolysis using ALK or PEM electrolyzers, combined with an adiabatic compressor that enhances energy storage and facilitates integration into smart grids.

The five-phase modular methodology includes timeframe definition; estimation of solar electricity generation based on solar trajectory and the geographic orientation of photovoltaic panels; performance modeling of electrolyzers and compressors; and the integration of all components into a cohesive system. A case study demonstrates the model's real-world applicability.

Results based on 2025 efficiency projections for ALK and PEM technologies show a substantial increase in solar energy capture in offshore environments, due to reduced atmospheric pollution and sea-surface reflectivity. Reflectivity is modeled as a function of sea surface flatness. A 20% increase in electrolyzer efficiency improves production by 32.28%, and the same efficiency gain in the compressor adds 0.81%. These impacts directly correlate with proportional reductions in the photovoltaic panel surface area required—greater electricity generation capacity translates into smaller infrastructure needs.

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The model enables quantitative evaluation of trade-offs among solar irradiance, component performance, and system design. It supports cost reduction through optimized sizing and improved integration. This approach contributes to lowering the Levelized Cost of Electricity (LCOE) and promoting the viability of marine-based green hydrogen deployment.

## 7. Session 6: Digital Design Technologies for Energy Equipment and Systems

### *7.1. Intercomparison Between URANS and LES Simulations of the Turbulent Flow Around the NTNU T1 Wind Turbine, Using OpenFOAM with the Actuator Disc Model*

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Reliable open-source computational fluid dynamics (CFD) tools are essential for optimizing wind turbine aerodynamics and understanding complex wake interactions. This study presents a comparative analysis between Unsteady Reynolds-Averaged Navier–Stokes (URANS) and Large Eddy Simulation (LES) for predicting the turbulent wake of the NTNU T1 reference turbine. To address editorial requirements for high-fidelity quantitative validation, this research adopts the NTNU Blind Test 1 experimental benchmark Re » $10^5$.

The numerical framework, implemented in OpenFOAM, utilizes the Actuator Disc Model (ADM). To ensure physical consistency, the model explicitly incorporates the nacelle's drag and employs experimental blade polars (S826) to accurately capture laminar separation bubble effects. Preliminary validation results demonstrate excellent agreement with experimental data, yielding a power coefficient CP of 0.45 and a thrust coefficient CT of 0.82.

Qualitative results contrast the ability of LES to resolve helical vortex structures and wake meandering against the numerical diffusion characteristic of the URANS approach. Quantitatively, the intercomparison focuses on velocity deficits and turbulence intensity recovery at 3D and 5D downstream locations. This study provides a validated workflow that balances physical fidelity and computational efficiency for offshore wind applications.

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### *7.2. Enhanced Structural Damage Detection Under Thermal Variations Using Finite Element-Based EMI Modeling*

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Structural Health Monitoring (SHM) has increasingly shifted toward smart-material-based solutions capable of providing continuous and real-time assessment of structural integrity. Among these approaches, the Electro-Mechanical Impedance (EMI) technique has emerged as a highly sensitive method for detecting incipient damage through the electromechanical coupling characteristics of piezoelectric (PZT) sensors. This study contributes to EMI-based SHM by numerically investigating the combined effects of structural damage and temperature variations on the impedance response of a PZT patch bonded to an aluminum beam.

The methodology relies on three-dimensional finite element modelling performed in ANSYS Multiphysics, incorporating temperature-dependent material properties for

both the host structure and the PZT sensor. Several damage scenarios were simulated by introducing cracks of varying depths at a fixed distance from the sensor. Temperature was varied from 25 °C to 85 °C to evaluate its influence on the electrical impedance signature. Harmonic analyses were conducted over a high-frequency range (18.5–21 kHz) to obtain both the real and imaginary components of the impedance. Damage indices such as Root Mean Square Deviation (RMSD) and Correlation Coefficient Deviation Metric (CCDM) were computed to quantify structural changes.

The results show that increasing temperature produces notable horizontal and vertical shifts in impedance peaks, while increasing crack depth leads to frequency shifts and the emergence of new resonance peaks due to stiffness reduction. Although temperature effects can mask true damage signatures, the application of a cross-correlation-based compensation technique successfully mitigates these distortions, enabling clear distinction between temperature-induced variations and actual structural deterioration.

Overall, the numerical findings confirm that the EMI technique, when combined with adequate temperature compensation strategies, offers high sensitivity and robustness for reliable, continuous structural health monitoring.

### *7.3. Hybrid Solar–Biomass Energy Systems for Rural Agro-Industrial Applications: A Technical and Bibliometric Review*

**John Javier Espitia Gonzalez, Edwin Villagran, Fabian Andres Velasquez, Andres Ivan Sarmiento and Jader Rodriguez**

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The combination of solar and biomass energy represents a sustainable alternative for thermal generation in rural areas, particularly in agro-industrial processes such as crop drying and food preservation. Hybrid configurations enable continuous operation under variable solar radiation, improving thermal efficiency and reducing fossil fuel dependence. However, the literature on this topic remains limited and fragmented. Therefore, a technical and bibliometric review was conducted to identify research trends, key actors, and knowledge gaps in hybrid solar–biomass systems applied to agricultural and food sectors. The Scopus database was used for the 2005–2025 period, applying the query TITLE-ABS-KEY ((“hybrid” W/2 (solar AND biomass)) AND (dryer OR drying OR “process heat”) AND (agricultur OR food OR agroindustrial))*. A total of 22 documents published in 21 sources were analyzed, including 15 journal articles, 3 reviews, and 4 conference papers. Results indicate an annual growth rate of 3.5%, an average of 7.18 co-authors per document, and an international collaboration rate of 27.3%, reflecting a small but increasingly connected research community. India leads scientific production (11 papers), followed by Nigeria, Malaysia, and Spain, with major contributions from the Indian Institute of Technology Delhi and the Federal University of Agriculture. Thematic mapping revealed four clusters: (i) biomass–solar drying and food preservation as motor themes; (ii) energy efficiency and food processing as niche technologies; (iii) hybrid systems, renewable energies, and cost effectiveness as basic developing topics; and (iv) temperature, heat transfer, and desiccation as emerging research areas reactivated by advances in modeling, CFD simulation, and intelligent control. Overall, the results highlight a growing focus on the design and optimization of hybrid solar–biomass systems as key enablers of rural energy transition and sustainable agro-industrial development.

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### *7.4. Digital Twin-Driven Design for Disassembly and Recycling of End-of-Life Solar Panels*

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Use of end-of-life photovoltaic (PV) modules is increasing rapidly, creating both environmental challenges and opportunities for improved circular design. This study presents a digital twin-driven design framework that supports low-cost recycling and reuse of solar panel components using only basic mechanical and electrical laboratory setups. The approach integrates 3D computer-aided modeling, guided disassembly, and preliminary experimental testing to establish an accessible methodology for sustainable energy equipment design.

A 3D digital twin of a standard PV module is developed using computer-aided design and simulation tools to visualize structural layers, simulate disassembly steps, and assess material separation pathways. Key components, including the aluminum frame, tempered glass, and encapsulating polymers, are evaluated for recyclability using simple mechanical characterization techniques. In parallel, partially functional solar cells are recovered from decommissioned modules, reconnected, and tested in the electrical laboratory to observe voltage–current behavior and basic stability.

The combined digital–physical workflow demonstrates how digital twin technologies can guide sustainable design for disassembly and support circular-economy practices in renewable energy systems. The proposed model is low-cost, replicable, and suitable for educational environments, offering a practical link between digital design, materials engineering, and renewable energy. This early-stage work highlights the potential of digital twins to accelerate PV recycling and extend solar panel lifecycles through intelligent design methodologies.

### *7.5. Digital Twins and Energy Management in Smart Greenhouses: An Emerging Bibliometric Landscape (2016–2025)*

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This bibliometric analysis examines the evolution and structural dynamics of scientific knowledge on the application of digital technologies and digital twins in the energy systems of horticultural greenhouses. Within the global context of digital transformation and the urgent need to optimize energy use in protected agriculture, the development of intelligent, efficient, and sustainable greenhouse systems has become a strategic challenge. Nevertheless, the integration of *digital twins* into greenhouse energy management remains a fragmented and emerging research area. To characterize this field, a comprehensive search was conducted in Scopus (2016–2025) using the following query: TITLE-ABS-KEY ((“digital twin” OR “digital design”) AND “greenhouse” AND (“energy system” OR “solar energy”)) AND NOT (“greenhouse gas*”). The retrieved records were analyzed using Bibliometrix (R) and VOSviewer, enabling the identification of keyword co-occurrence networks, temporal production trends, and international collaboration patterns. The final dataset comprised 19 documents published in 14 sources, authored by 154 researchers none

of whom were single authors with an annual growth rate of 24.1% and an international co-authorship rate of 10.5%. The dominant subject areas were *Computer Science* (15 documents) and *Engineering* (9), followed by *Mathematics* and *Agricultural and Biological Sciences*. The average number of citations per article was 12.2, and the mean document age was 2.37 years, underscoring the novelty and rapid consolidation of the field. The most frequent keywords were *energy management*, *greenhouses*, *embedded systems*, and *artificial intelligence*, reflecting the convergence between automation, digital design, and energy efficiency. The results suggest that the use of digital twins and intelligent control in greenhouses is primarily directed toward thermal simulation, energy optimization, and solar system integration. The analysis highlights the leadership of Wageningen University & Research and points to significant opportunities for advancing this research within low-cost and tropical agricultural contexts, where digital energy management could enhance both productivity and sustainability.

### *7.6. Integrating Hydrogen Purchase Agreements and Contracts-for-Difference into Stochastic Optimization of Green Hydrogen–Ammonia Plants*

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Green hydrogen projects face significant market risk from volatile electricity costs, uncertain renewable supply, and unstable hydrogen and ammonia prices. We present a two-stage stochastic optimization framework that integrates long-term financial contracts into the joint design and operation of an integrated hydrogen–ammonia plant. The model endogenizes Hydrogen Purchase Agreements (HPAs) and Contracts-for-Difference (CfDs) as first-stage decisions together with capacities of electrolysis, Haber–Bosch synthesis, air separation, storage, and grid connection. Second-stage decisions represent hourly dispatch with detailed material and power balances under scenario-based uncertainty in renewable availability and commodity prices. The objective maximizes expected net present value penalized by Conditional Value at Risk (CVaR) to reflect downside protection and bankability.

The problem is formulated as a mixed-integer linear program. We solve the extensive form via sample average approximation (SAA) and implement an integer L-shaped method with multi-cuts. The master problem includes capacity and contract variables and a linear CVaR reformulation, while scenario subproblems are linear operational models that generate feasibility and optimality cuts. Warm starts from a risk-neutral solution and contract screening are used to improve convergence. Computational experiments report solution quality and convergence behavior as functions of scenario count and risk aversion and evaluate outcomes using expected NPV, CVaR, and probability of loss, including out-of-sample performance assessment.

A case study motivated by export-oriented projects in Chile evaluates contractual portfolios by comparing no contracts, HPA-only, CfD-only, and joint portfolios against risk-neutral and risk-averse baselines. The analysis characterizes how contracting interacts with optimal sizing and operations across regimes and discusses implications for policy programs offering bankable offtake or price-stabilization instruments in green hydrogen–ammonia value chains.

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*7.7. Predictive Maintenance of Three-Phase Induction Motors Using AI and Machine Learning: A Smart Industry 4.0 Framework*

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Induction motors constitute the operational backbone of contemporary industrial systems, and their unexpected failure can result in severe downtime, significant productivity loss, and substantial maintenance expenditure. Conventional maintenance approaches—primarily corrective and preventive—often fail to identify early-stage degradation, making them inadequate for modern industrial demands. To address this gap, the present study proposes an AI/ML-based predictive maintenance framework capable of real-time monitoring and automated fault diagnosis in three-phase induction motors. Multimodal sensor data, including vibration, temperature, current, and voltage signals, were acquired using an ESP32-based IoT architecture and subsequently analyzed through machine learning algorithms. Feature engineering incorporated Fast Fourier Transform (FFT) and statistical indicators such as Root Mean Square (RMS), kurtosis, and crest factor to enhance the quality of the diagnostic features. A Support Vector Machine (SVM) classifier was developed and achieved an accuracy of 95–98%, with a precision of 92%, recall of 95%, and an AUC of 0.97 for classifying faults such as bearing damage, rotor imbalance, and electrical irregularities. Additionally, MATLAB/Simulink-based vector control simulations validated the dynamic behavior of the motor under varying load and fault conditions. Overall, the integration of AI/ML with IoT demonstrates significant improvements in reliability, reducing unscheduled downtime by up to 25% and enhancing energy efficiency by 8–12%, thereby offering a scalable, Industry-4.0-ready solution for intelligent predictive maintenance.

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