

Technical program

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Paper abstracts

The paper abstracts presented here encompass ten key themes that collectively reflect the interdisciplinary scope of the Energy Informatics Academy Conference. These themes capture the latest research and innovation trends driving the digital energy transition across buildings, industries, and communities.

- Building Energy Forecasting & Modeling
- Context-Aware Digital Innovations for Energy Transitions
- Cybersecurity & Communications in Digital Energy Systems
- Data Centres, AI & Sustainable Energy Footprints
- Digital Infrastructure & Interoperability for Energy Systems
- Digital Innovation for Resilient Low-Carbon Industry
- Energy Storage & Circular Resource Management
- Local Energy Communities, Microgrids & Distributed Energy Resources
- Methods, Governance & Responsible Digitalization in Energy
- Thermal Storage and Flexibility in Buildings

Building Energy Forecasting & Modeling

Explainable Boosting Machine for Energy Consumption in Buildings

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Abstract. The formulation of advanced management strategies in applications involved with the energy market is recommended to avoid imbalances between the demand for power and the supply that may result in potential system failures. However, the uncertainties of the demand behavior as a result of the non-linear patterns may complicate the formulation of an optimization plan that reduces the energy costs as much as possible. Hence, forecasting methods from the artificial intelligence and machine learning areas should be considered to learn non-linear patterns in the training phase in order to obtain accurate predictions for unseen data. Some forecasting methods can be enumerated including Artificial Neural Networks, K-Nearest Neighbors and XGBoost. Understanding the reasons behind the obtaining of higher or lower forecasting accuracy is not easy for data scientists and machine learning professionals. Hence, the Explainable Artificial Intelligence area arises as a field that generates explanations, for example, of the input features' contribution to the forecasting performance. Some of these methods are the following: Local Interpretable Model-Agnostic Explanations (LIME), SHapley Additive exPlanations (SHAP), impurity-based feature importance and Explainable Boosting Machine (EBM). This paper analyzes the input features (past consumptions and sensors) that contributed more or less to the forecasting performance for an office building with the support of the impurity-based feature importance and the Explainable Boosting Machine methods.

Keywords: Energy sector, Explainable Artificial Intelligence, Explainable Boosting Machine, Machine Learning.

Intelligent IoT Device Powered by AI-based Models for Forecast and Classification

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Abstract. The proliferation of internet of things solutions has been gaining importance, which are now widely adopted in residential and commercial buildings. These solutions can benefit from the adoption of artificial intelligence models to create intelligent solutions and provide supported actions and decisions to assist users and building operators. The evolution of technology, hardware, and software enabled the capability of having artificial intelligence models deployed in the edge layer and on the internet of things' devices. However, further studies to test these capabilities are needed to validate the feasibility of having artificial intelligence-based models near the devices, resources, and users. The proposed solution presented in this paper will assess the feasibility of having in the same microcontroller three machine learning models while being able to read and measure multiple signals from sensors and communicate the sensor's data and the models' outputs to a streaming communication protocol. In this work, two neural networks will be used for temperature forecast and CO2 forecast, and a random forest model will be used to classify, with true or false, the occupancy of a room. All the data will be communicated using the message queuing telemetry transport protocol. The results seem very promising, and the microcontroller was able to perform the given tasks.

Keywords: Internet of Things Devices, Machine Learning, Tiny Machine Learning, Edge Computing.

Scalable estimation of energy savings via demand-temperature modeling in commercial buildings

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Abstract. This paper presents a data-driven approach for estimating energy savings potential in commercial buildings by modeling the relationship between electricity demand and outdoor temperature. Designed for early-stage assessments, the method requires only minimal input: annual energy use, building type, and location, eliminating the need for detailed physical models or high-resolution data. Buildings are categorized by type, and for each category, typical demand-temperature profiles are developed for both pre- and post-implementation of advanced control systems. These profiles capture characteristic shifts in energy use as a result of operational improvements. To evaluate a new building, its energy profile is compared with these reference models, allowing the estimation of potential savings under similar control strategies. Validation with real-world data across diverse building types and climates demonstrates the method's reliability and scalability, making it well-suited for screening large building portfolios.

Keywords: Energy flexibility, Energy savings, Consumption profiles, Building potential, Energy audit, Demand-side management

Data-Driven Simplified RC-Based Thermal Modeling of Indoor Temperature Dynamics

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Abstract. Accurate and computationally efficient models of indoor temperature dynamics are essential for building energy management and control. This paper proposes a simplified thermal model of a building floor, formulated through thermal balance equations and identified using only data recorded from the building management system. The physical structure of the system is represented as an RC circuit, with thermal capacity and thermal resistance estimated via two complementary optimization strategies: a metaheuristic method (PSP) and a deterministic approach (SQP). Simplification assumptions are introduced to improve prediction performance while preserving physical interpretability. A stepwise methodology is employed to progressively refine the model and align it with measured temperature dynamics. Results demonstrate that the proposed approach effectively reproduces the thermal behavior of the building, providing a practical trade-off between model simplicity, accuracy, and applicability for real-time control and optimization tasks in building energy systems. With the proposed identification approach, R2 scores of up to 0.84 and 0.86 were reached using respectively SQP and PSO algorithms.

Keywords: Building RC-model, indoor temperature prediction, stochastic optimization, deterministic optimization.

CLASH: An energy-aware service for building load forecasting computation

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Abstract. This work presents CLASH (Computational Load Assessment daSHboard), a software service that operationalizes the methodology proposed by [1] for assessing the computational and energy costs of building load forecasting. CLASH extends the original approach by providing a service with an API and interactive dashboard for configuring the featured applications parameters, running the complete prediction pipeline, and visualizing the trade-offs between accuracy, execution time, and energy consumption. The backend implements REST endpoints that wrap the forecasting scripts, including context creation, outlier handling, dataset splitting, and prediction execution, while enabling parameter control through JSON configuration or API calls. Users can define the context periods (hourly or 5-minute periods), the context moments (All day moments; Only activity times; Only night periods; Only night periods), and the processing unit (CPU/GPU). Additionally, users can upload datasets, and trigger both complete and stepwise forecasting. The frontend dashboard allows intuitive parameter selection, execution sequencing, and results exploration, including forecast outputs and computational metrics. As such, CLASH enables direct comparison of forecasting scenarios, highlighting cases where increased model accuracy incurs high computational or monitoring energy costs, confirming and extending the findings of the original study. Initial tests show that end-users can dynamically evaluate forecasting strategies, balancing predictive performance with sustainability considerations. By embedding green computing principles into a ready-to-use, API-accessible service, CLASH bridges the gap between research methodology and practical deployment. It empowers researchers to make informed, sustainability-oriented forecasting decisions without manual script execution or code modification.

Keywords: Building energy management, computational sustainability, intelligent buildings, load forecast, dashboard

Digital Infrastructure & Interoperability for Energy Systems

Geometry-Driven Automatic Placement of IoT Sensors in Digital Twins for Smart Building Energy Management

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Abstract. Accurate digital representation of sensor locations is essential for the creation of operational digital twins in smart buildings. This paper introduces a geometry-driven method for automatic digital placement of IoT sensors within Building Information Models (BIMs), requiring no semantic metadata or manual annotation. The method analyses the three-dimensional geometry of rooms, walls, and openings to infer plausible and rule-based sensor positions that reflect real-world installation practices. Unlike optimization-based approaches that seek coverage or cost efficiency, the present work focuses on geometry-only reasoning for visual and spatial alignment between physical sensors and their digital counterparts. The algorithm is implemented in a browser-executable environment using three.js, enabling real-time visualization of sensor layouts directly from mesh-based BIMs. Validation in a live office building with more than 300 sensors demonstrates that the computed placements reproduce actual installation patterns for all regular rooms. The results confirm the feasibility of geometry-only methods for automated, metadata-agnostic sensor visualization in digital twin environments supporting energy and indoor climate management.

Keywords: Building Information Model (BIM), Digital Twin, Internet of Things (IoT), Geometry-Based Sensor Placement, 3D Mesh Analysis, Smart Building Energy Management

A Visual Diagnostics Framework for District Heating Data: Enhancing Data Quality for AI-Driven Heat Consumption Prediction

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Abstract. High-quality data is a prerequisite for training reliable Artificial Intelligence (AI) models in the energy domain. In district heating networks, sensor and metering data often suffer from noise, missing values, and temporal inconsistencies, which can significantly degrade model performance. This paper presents a systematic approach for evaluating and improving data quality using visual diagnostics, implemented through an interactive web-based dashboard. The dashboard employs Python-based visualization techniques, including time series plots, heatmaps, box plots, histograms, correlation matrices, and anomaly-sensitive KPIs such as skewness and anomaly detection based on the modified z-scores. These tools allow human experts to inspect and interpret data anomalies, enabling a human-in-the-loop strategy for data quality assessment. The methodology is demonstrated on a real-world dataset from a Danish district heating provider, covering over four years of hourly data from nearly 7000 meters. The findings show how visual analytics can uncover systemic data issues and, in the future, guide data cleaning strategies that enhance the accuracy, stability, and generalizability of Long Short-Term Memory and Gated Recurrent Unit models for heat demand forecasting. The study contributes to a scalable, generalizable framework for visual data inspection and underlines the critical role of data quality in AI-driven energy management systems.

Keywords: visual diagnostics, district heating, data quality, dashboard, AI forecasting, smart meter data

Bridging Rapid Simulation and Real-Time Execution: A Software-in-the-Loop Testing Platform for OCPP-Based EV Charging Station Management Systems

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Abstract. Electric vehicle (EV) charging management systems require scalable and standards-compliant coordination across distributed infrastructures. However, current testing approaches often lack the flexibility to support both accelerated development workflows and high-fidelity real-time validation. This paper presents a dual-mode Software-in-the-Loop (SiL) testing platform for validating EV Charging Station Management Systems (CSMSs) that communicate using the Open Charge Point Protocol (OCPP) 2.0.1. The platform enables the same CSMS software to be evaluated across discrete-time and wall-clock-time modes without modification, supporting rapid scenario testing and protocol-accurate verification. A case study involving 126 home charging stations in Denmark evaluates two smart charging strategies under real-world electricity pricing and demand conditions. Results show that discrete-time testing enables rapid performance evaluation, while wall-clock execution maintains protocol fidelity with minimal time drift. The platform offers a robust and reusable method for validating EV charging software and can support future applications involving distributed energy resources (DERs), smart grids, and cyber-physical energy systems.

Keywords: Software-in-the-Loop (SiL) Testing, Charging Station Management System (CSMS), Open Charge Point Protocol (OCPP 2.0.1), Smart Charging, Validation and Verification (V&V), Simulation, Electric Vehicle (EV) Charging, Energy Management System (EMS), Smart Grid, Distributed Energy Resources (DER)

Interoperable Energy Management Systems and Multi-Vector Flexibility Control in Building Clusters: Opportunities, Challenges, and Pathways for Scalable Integration

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Abstract. This review synthesizes the state of interoperable Energy Management Systems (EMS) and multi-vector flexibility in building clusters, ports, and industrial zones. We cover communication standards (e.g., OpenADR, IEC 61850), semantic models (BRICK, SAREF), control architectures (centralized, hierarchical, federated), and enabling assets (BESS, heat pumps, PtX). We highlight how interoperable EMS orchestrate distributed energy resources, enable demand-side flexibility, and interface with markets. Drawing on EU pilots (e.g., InterConnect, Platone, FlexCoop), we discuss techno-economic trade-offs, regulatory constraints, and lifecycle considerations. This review contributes a cross-domain synthesis spanning technical, regulatory, and socio-economic dimensions; integrates multi-vector flexibility with industrial and port case narratives; foregrounds interoperability testing/certification; and introduces compact synthesis tools. We outline pathways that link standards harmonization, data-driven validation (digital twins), and human-centred adoption to scalable deployment.

Keywords: Interoperable EMS; Multi-vector flexibility; Building clusters; Ports; Industrial parks; Demand response; Digital twins; Semantic interoperability.

Performance Benchmarking Platform for Building Energy Management Systems

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Abstract. The wide range of methodologies employed in Energy Management Systems (EMS), spanning rule-based strategies, heuristic approaches, optimization algorithms, model-based frameworks such as Model Predictive Control (MPC), and data-driven techniques including machine learning and reinforcement learning, necessitate a thorough evaluation of their performance and adaptability. Yet, despite the diversity of methods, there is a lack of systematic benchmarking across paradigms, which leaves stakeholders without clear guidance on selecting suitable control strategies. This paper conducts a comprehensive benchmarking of these methodologies to identify the most effective approaches, highlighting their strengths, limitations, and potential for driving future innovations. By focusing on critical performance metrics such as energy efficiency, bill reduction, and scalability, this work aims to provide valuable guidance to stakeholders in selecting and implementing optimal energy management solutions for the smart buildings and energy grids of the future. Our experimental results show that reinforcement learning methods, particularly PPO and DQN, consistently outperform rule-based and MPC approaches in terms of both electricity bill reduction and PV self-consumption, demonstrating their strong potential for future iEMS deployment.

Keywords: Building EMS, Battery Management System, Reinforcement Learning

Cybersecurity & Communications in Digital Energy Systems

Energy and time-Optimized Encryption involving Hybrid Architectures from AES and ChaCha20

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Abstract. The increasing deployment of resource-constrained devices in modern energy infrastructures—such as smart grids, renewable microgrids, and IoT-enabled power systems—demands encryption solutions that balance strong security with low computational overhead. While AES offers robust security, it is energy-intensive on low-end hardware. Conversely, ChaCha20 provides efficient performance on embedded systems but lacks the long-standing cryptographic assurance of AES. This paper introduces a hybrid encryption model, CHaE, which strategically integrates AES and ChaCha20 to leverage the strengths of both algorithms. The proposed hybrid replaces the MixColumns operation in AES with the ChaCha20 stream cipher, enhancing diffusion and nonlinearity while maintaining structural integrity. Implemented and evaluated in Python, CHaE demonstrates superior randomness across all 14 NIST statistical tests, outperforming both standalone AES and ChaCha20 in 11 tests. Additionally, it achieves significantly faster encryption times—up to $8.1\times$ faster than AES and $1.7\times$ faster than ChaCha20 for medium sized data—while maintaining near-ideal Shannon entropy. These results affirm that CHaE is a highly secure, efficient, and energy-optimized encryption solution suitable for real-time applications in resource-constrained IoT and smart grid environments.

Keywords: Hybrid Encryption, IoT security, resource-constrained, WOT, AES, ChaCha20.

Lightweight Moving Target Defense for Robust Intrusion Detection in Smart Grids

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Abstract. Smart grids rely heavily on network protocols, e.g., classic Modbus TCP for substation communications, yet conventional learning-based intrusion detectors overfit to spurious correlations and crumble under adversarial or distributional shifts. In this work, we introduce a lightweight Moving Target Defense (MTD) proxy that randomizes the Modbus slave address on each TCP session. In our proof-of-concept experiments, a Random Forest detector under MTD maintains 95% detection accuracy while, in the eXplainable Artificial Intelligence (XAI) sense, its reliance on the address field drops, and payload-related features gain prominence. We further demonstrate that simple deterministic checks and dynamic honeypots can complement MTD to protect integrity, availability, and confidentiality with minimal or no machine learning. Our results highlight that even modest MTD interventions can substantially harden smart-grid intrusion detection systems against both inadvertent shifts and targeted evasion.

Keywords: Smart Grid, Artificial Intelligence, Security.

Energy-Informatics Driven Self-Calibrating TDMA Algorithm for Energy-Efficient and Reliable Wireless Body Sensor Networks (WBSN)

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Abstract. It is becoming more common to use Wireless Body Sensor Networks (WBSNs), which are groups of sensors that can sense, process, and communicate to more accurately monitor remote or mobile subjects at reduced costs in many fields, such as healthcare, environmental monitoring, and smart infrastructure. Sensors, referred to as nodes in these networks, manage four essential functions: gathering, transmitting, receiving, and processing data. Consequently, they must utilize resources efficiently, optimizing memory usage, CPU cycles, and above all, energy consumption to extend network lifetime and ensure reliable data transmission. In this paper, we present an energy informatics-driven model that characterizes and optimizes energy loss patterns in typical WBSN deployments, integrating its diverse energy components within a unified framework. This model provides a systematic approach for evaluating and enhancing the energy efficiency of sensor-based applications by simplifying component interactions and identifying critical energy-saving opportunities. The goal is to develop an Energy Mapping Architecture tailored for WBSN applications, encapsulating both fundamental and application-specific energy components, and modeling how these elements interact to impact the total system consumption. We propose a Self-Calibration TDMA (SC-TDMA) method that adaptively minimizes energy waste and queue overheads by dynamically adjusting node transmission schedules based on real-time network conditions. The proposed energy-efficient topology management strategy is benchmarked against conventional TDMA approaches, demonstrating its capacity to establish reliable, low-latency links between nodes with significantly reduced energy footprints. Extensive simulation experiments conducted on randomized WBSN scenarios validate that SC-TDMA algorithms substantially enhance energy efficiency, throughput stability, and communication reliability, affirming their suitability for next-generation energy informatics applications.

Keywords: Energy Informatics, Wireless Body Sensor Networks (WBSN), Energy-Efficient Communication, Self-Calibration TDMA, Network Lifetime Optimization, Adaptive Scheduling Algorithms.

Enhancing Dynamic Threat Detection in IoT Networks Through Context-Aware Adaptive Cybersecurity Algorithms for Energy and Informatics Optimization

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Abstract. The fast growth of IoT networks present harsh cyberspace issues, particularly in limited resources and evolving circumstances. To achieve this, a new context-aware adaptive cybersecurity framework is offered, which combines reinforcement learning and meta-learning to dynamically tune the process of detecting threats to devices, location, and time. The framework is tested on CICIDS2017 and IoT-23 datasets, with a detection accuracy of 95.9, a low latency of 5.46 ms, and high precision in detecting attacks like Mirai and Sybil than traditional, respectively. The solution offers a scalable, efficient, and real-time middleware to enhance the security of nonhomogeneous IoT environments, enabling more efficient defense of energy-conscious and informatics systems and infrastructure.

Keywords: Adaptive cybersecurity, Context-aware security, IoT threat detection, Energy-efficient algorithms, Informatics optimization, Smart grid security, Machine learning for IoT, Zero-day attack prevention.

Energy-Aware Optimization and Performance Analysis of LoRaWAN for IoT, Edge Computing, and Smart Sensor Systems

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Abstract. Low Power Wide Area Network (LPWAN) technologies play a crucial role in enabling scalable Internet of Things (IoT) applications, especially where long-range connectivity, minimal energy usage, and cost efficiency are essential. LoRaWAN (Long Range Wide Area Network) has emerged as a prominent solution for connecting large numbers of low-power devices across wide areas. This paper provides an energy-focused performance analysis and optimization of LoRaWAN in the context of IoT, edge computing, and smart sensor systems. The study examines the impact of key physical layer parameters—Spreading Factor (SF), Coding Rate (CR), and Bandwidth (BW) — on both energy efficiency and network performance. Based on Semtech SX1276/77/78/79 chipset characteristics with a 3.3V supply, the energy consumption of end devices is quantified across Transmit, Receive, ON, Idle, and Sleep modes. Data rates per device are calculated, and optimal throughput configurations are determined via convex optimization using the CVX toolbox. The results reveal critical trade-offs among data rate, coverage, and energy use, providing actionable guidelines for designing energy-efficient IoT and edge computing deployments that utilize LoRaWAN.

Keywords: LoRaWAN, Energy Efficiency, IoT, Edge Computing, Smart Sensor Networks

Local Energy Communities, Microgrids & Distributed Energy Resources

Stochastic Generation of Synthetic Load Profiles for Renewable Energy Communities

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Abstract. This paper presents a data-driven stochastic framework for modeling electricity consumption profiles. The motivation arises from the need for realistic load simulations to support planning and performance evaluation in small Renewable Energy Communities (RECs), where individual consumption patterns, especially those of prosumers, directly impact shared energy dynamics. Unlike conventional approaches that assume stationary seasonal distributions or rely on opaque resampling techniques, the proposed method leverages change-point detection based on Shannon entropy to identify behaviorally consistent segments in historical time series. These segments inform the training of a temporally aware Bayesian Network for day-type generation, while hour, day type, and period-specific Markov chains capture consumption transitions. The framework is applied to a real-world REC in Veneto, Italy, composed of one small-to-medium enterprise (SME) and two residential users. The SME acts as a prosumer with a 21.2 kWp photovoltaic system. Starting from one year of hourly data per user, the model generates 1,000 synthetic load profiles and simulates community behavior using Monte Carlo analysis. Results show that accounting for consumption uncertainty significantly increases the variance in monthly and yearly energy balances, nearly doubling the uncertainty compared to simulations using only stochastic production.

Keywords: Synthetic Load Profiles, Energy Community, Uncertainty, Entropy

Safety-Constrained Dynamic Scheduling of Renewable Energy using Value-at-Risk Metrics

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Abstract. Renewable energy is playing a growing role in modern energy systems, while its intermittent characteristics pose significant challenges to the economic and safety operation of power grid. Markov decision process (MDP) models are widely used to study the dynamic scheduling of renewable energy systems, which can capture the stochastic nature of renewable energy and the dynamic characteristics of energy scheduling. In this paper, we propose a steady-state value-at-risk (VaR, also known as quantile)-constrained MDP model for the dynamic scheduling of renewable energy systems, aiming to achieve coordinated economic and safety management. This model optimizes the performance when the system attains steady state. Specifically, the objective is to minimize the long-run average cost for economic performance while ensuring safety by imposing a steady-state VaR constraint, which limits the power fluctuations exchanged between the main grid and the microgrid to below a specified threshold with high probability. Leveraging the duality between VaR and probability constraints, we reformulate the steady-state VaR-constrained MDP as a linear programming problem, which can be solved efficiently. Finally, we validate our approach by using a numerical experiment with real data of a microgrid with wind power.

Keywords: Energy management; value-at-risk; constrained Markov decision process; linear programming

Sobolev-Trained Neural Networks for Reduced-Order Electric Water Heater Modeling

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Abstract. Electric water heaters (EWHs) provide a flexible and widely distributed resource for demand response (DR) programs due to their controllable thermal storage capacity and high residential penetration. To fully exploit their flexibility in grid services, dynamic EWH models must be both accurate and computationally efficient to enable large-scale, real-time control for effective market participation. This paper introduces a Sobolev-trained neural network reduced-order model (STNN-ROM) for predicting EWH thermal dynamics, while preserving key stratification behavior under reduced spatial dimensionality. The model incorporates physics-driven features from a multi-zone differential equation model (MZ-DEM) for EWHs and employs derivative-informed Sobolev training with a recursive approach to enhance physical consistency, mitigate error accumulation, and improve generalization. The STNN-ROM is trained on simulation data generated by MZ-DEM and validated against real-world measurements, achieving acceptable accuracy while reducing computational cost by over 69% compared to the full-order MZ-DEM. These results demonstrate the proposed model's potential for real-time DR implementation and the coordination of aggregated EWHs' flexibility through scalable control frameworks for demand-side management.

Keywords: Electric water heater, Temperature prediction, Neural networks, Reduced-order model, Sobolev training

Learning Based Approach for Residential Electricity Usage Simulation (REUS)

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Abstract. Residential electricity consumption datasets are essential for applications such as smart grid management, home automation, renewable energy integration, infrastructure planning, and policy-making. However, obtaining high-resolution residential datasets remains challenging due to the high costs and complexities of sensor installation, monitoring, and maintenance, obtaining approvals and related human factors, among other issues. To address this issue with a focus on the Indian residential context, where such data is quite limited, we propose a Residential Electricity Usage Simulator (REUS), to generate synthetic residential electricity usage data. Our approach models electricity usage for 7 different categories of homes using data collected over one year at an hourly interval, from 65 residences. In addition to energy data, we also collected 18 different features for each home to improve our modeling. The data and features are preprocessed using feature selection with Probabilistic Finite State Machines (validated through Multiple Correspondence Analysis) and further refined through systematic data cleaning and imputation. We built simulation models using the popular Machine learning techniques such as Long Short-Term Memory networks, including Vanilla, Stacked, BiDirectional, and Encoder-Decoder LSTMs and Transformer model, including Vanilla Transformer and Temporal Fusion Transformer. In addition, statistical techniques such as Markov Chains of orders (0, 1, 2, 3) and ARIMA were used as benchmarks to evaluate the models' ability to generate a synthetic residential electricity dataset that is close to real data. Via extensive experimentation and analysis, our results show that (Bi-di) LSTMs capture the trends in electricity consumption more effectively (with the lowest RMSE) than the other models. Simulation and analysis of this nature enables broader, region-specific energy research, reducing the need for costly or intrusive data collection.

Keywords: Synthetic data generation, Household Electricity simulation, Data pre-processing, Residential electricity

Cost-optimal control of a hybrid heated energy community

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Abstract. Nowadays several hybrid systems e.g. heat pumps and district heating are utilized in energy communities. The study analyzed the impact of three control strategies on energy usage and costs in a small energy community heated with a hybrid heating system. The system comprises a low-temperature heating network powered by a dual source heat pump and a district heating network. The analysis was implemented by dynamic simulations based on the customized heating network model. The cost-effective control strategy based on hourly electricity prices and the estimated cost of district heating produced by utilizing waste heat from hydrogen production resulted in the lowest annual costs. The control strategies included a low-temperature heating-prioritized and two cost-effective control strategies based on different electricity and district heating prices. The results showed that the cost-effective control strategy based on hourly electricity prices and a price estimate of district heating brought up to 25% total costs reduction compared to the heat pump-prioritized control strategy.

Keywords: hybrid system, heating, cost optimal, energy community

Energy storage management with day-ahead and real-time planning with physical batteries

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Abstract. Energy sustainability is a necessary goal for human flourishing. One way to tackle this is by making good management of electrical equipment and maximizing the efficiency and performance of it. In this paper, an energy storage management system capable of managing stationary batteries from individual households by making use of information about other energy resources. These resources available to the community are photovoltaic panels, electric vehicles, stationary batteries and other domestic devices. This is done by integrating a mixed integer linear programming algorithm for day-ahead scheduling and a genetic algorithm for real-time scheduling in a multi-agent system for managing individually and collectively homes from an energy community. The data comes from a published dataset where real houses were used to extract the data. This system was tested in a hybrid environment where part of the simulation interacts and acts on real batteries. The results show the system is capable of scheduling the battery usage throughout the day and how that impacts the real battery.

Keywords: Electric Vehicles, Energy Storage Management, Evolutionary Algorithms, Hybrid Simulation, Machine Learning, Multi-Agent Systems, Physical Batteries.

EneCross: A Scenario-Based Simulation Platform for Local Energy Communities

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Abstract. This paper introduces *EneCross*, a modular, scenario-based simulation platform designed to support the planning and evaluation of local energy communities (LECs). The platform integrates building, photovoltaic (PV), and battery energy storage models with optimization-based control strategies and is implemented as a web-based client–server architecture to ensure both technical accuracy and accessibility for non-programmers. The platform is demonstrated through real-world case studies at the BAM Campus, where results highlight three main findings: (i) scaling PV capacity strongly improves self-sufficiency but reduces self-consumption due to higher surplus generation; (ii) battery sizing offers benefits but with diminishing returns beyond certain capacity thresholds; and (iii) network topology critically influences flexibility and cost outcomes under peak constraints. By enabling rapid scenario configuration, execution, and visualization, EneCross provides a practical decision-support tool for stakeholders to explore cost-effective and sustainable LEC designs under realistic operational conditions.

Keywords: Local Energy Communities (LECs), energy management platform, distributed energy resources (DER), scenario simulation.

Energy Storage & Circular Resource Management

Designing an Intelligent Supply Chain for E-Waste Recycling in the Renewable Energy Sector: Applying Advanced Optimization Algorithms to Enable Circular Economy in Solar Panel and Wind Turbine Management

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Abstract. Renewable energy sources, solar panels or wind turbines produce large volumes of electronic waste (e-waste) when their lifecycle ends. Incorrect recycling of this e-waste results to severe environmental and economic issues brought about by toxic materials and unproductive recycling techniques. The e-waste management process in the renewable energy sector is now disunified, unfocused, and uncoordinated without data exchange in real-time. These constraints form obstacles to the optimization and sustainability of recycling supply chain. This paper fills these gaps by introducing a smart supply chain model that is composed using as much as possible optimization algorithms and artificial intelligence (AI) functions to ameliorate solar panels and wind turbines e-waste recycling. The primary implication of this study is introducing a detailed, data-based framework that facilitates the principles of circular economy by implementing closed-loop material cycles and by seeing as much as possible of the resource back to circulation. The mix of qualitative supply chain mapping with quantitative mathematical optimization as a mixed-method is solved using metaheuristic algorithms. Sensors based on IoT and AI-based sorting enhance data collection and decision-making, and vehicle routing plus inventory management is optimized to minimize cost and scale the environmental harm. Findings indicate a 75 percent recycling efficiency, 30 percent increase in collection levels, 15 percent decrease in cost of operations and a 20 percent loss in CO₂ emissions over pre-conditions. Such results indicate the applicability of the model in complementing sustainable and cost friendly recycling of e-waste within the renewable energy industry.

Keywords: Artificial Intelligence, Circular Economy, E-Waste, Optimization Algorithms, Supply Chain

Life Cycle Assessment of Solid-State Batteries with AI Enhanced Predictive and Recycling Models

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Abstract. Energy storage systems are known as important features of connecting green energy resources to new power grids. Lithium-ion and solid-state batteries are commonly applauded because of their high-power density and efficiency. Of these, solid-state batteries have gained recent interest on the basis of their possible environmental and performance advantages. Nevertheless, the current research is affected by such pitfalls as high costs of manufacturing, risk of data variability, narrowness of the sphere of artificial intelligence (AI) use, recycling process inefficiencies, and the absence of assessments to consider the sustainability of materials. The use of sophisticated AI algorithms allows conducting a full life cycle analysis (LCA) of solid-state and advanced battery energy storage systems in this paper, which adds value to the paper. To overcome the drawbacks of the past, multi-dimensional LCA data is being trained with deep learning, ensemble, and reinforcement learning techniques that enhance the model of predicting environmental impact and optimize the recycling process. Inventory, emission, and material composition data are merged with AIs to increase accuracy and insightfulness. The environmental impact of solid-state batteries in terms of carbon footprint is evaluated, and the dramatic positive effects are put forward in contrast to other systems. The carbon footprint and resource utilization is 2 minimized and the values range between 58.0 to 67.3 kg CO₂-eq/kWh depending on the cathode mix. It proves that AI-based approaches have substantial predictive capability and low root mean square error. The sensitivity analysis indicates that the impact factors of importance are energy intensity and material costs. More environmental impact effects are reduced when greener materials like biopolymer electrolyte and graphene are used. The hybrid recycling strategies are shown to be more efficient and less costly than conventional ones, thus enabled by optimized strategies, which align with the practice of the circular economy.

Keywords: Artificial intelligence, Battery energy storage, Life cycle analysis, Recycling strategies, Solid-state batteries

Integrating Energy Informatics and Optimization Algorithms for Corrosion Mitigation in Carbon Steel Boiler Tubes under Reverse Osmosis (RO) Water Conditions

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Abstract. The performance of industrial boilers is vital in the current dynamic environment of sustainable energy systems because they are the key to realizing reliable and efficient performance. This paper examines the corrosion and metal degradation of Carbon Steel Grade 200 Group A boiler tube in conditions of Reverse Osmosis (RO) water. Putting a prime focus on the interdisciplinary field of energy informatics, the study combines experimental, corrosion evaluation along with sophisticated methods of computational or machine intelligence known as Genetic Algorithms (GA) and Particle Swarm Optimization (PSO). These algorithms are used to optimize operating parameters and forecast the corrosion rates, resulting in a data-driven framework of decision support in the context of preventive maintenance of energy systems. The results are analyzed using informatics-based modeling with electrochemical cell testing, SEM microscopy, and mechanical property testing to determine the ideal combination of temperature (100 °C), pH (8), and corrosion is minimized at 1.1 per year. The study is beneficial to the field of energy informatics because it makes it possible to realize smart monitoring of corrosion, predictive maintenance, and life extension pathways of crucial infrastructure within power production systems.

Keywords: Energy Informatics, Corrosion Prediction, Reverse Osmosis Water, Boiler Tubes, Optimization Algorithms, Smart Maintenance, Predictive Analytics, Data-Driven Decision Support

Comparative Analysis of Short-Term and Long-Term Multi-Objective Optimal Planning for Solar PV and Battery Energy Storage System Integration in Distribution Systems

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Abstract. Nations worldwide are committing to net-zero emission targets, accelerating the integration of distributed energy resources (DERs) into power grids. However, improper planning of DER deployment may result in adverse impacts, including increased losses and voltage violations. This paper presents an optimal placement and sizing framework for solar PV and battery energy storage systems (BESS) in distribution systems (DS), comparing short-term (1 year) and long-term (10 years) planning strategies. The problem formulation simultaneously minimizes three objective functions: total power loss, total voltage deviation, and total system cost. The optimization is solved using Multi-Objective Particle Swarm Optimization (MOPSO), and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied for decision-making among Pareto-optimal solutions. The proposed model is validated on the IEEE 33-bus system under three cases: base case, short-term planning (1 year), and long-term planning (10 years). The selected cases evaluate how different planning horizons, accounting for overall load growth, influence the optimal placement and sizing outcomes. Results show that long-term planning reduces power loss by 50.89%, voltage deviation by 40.81%, and cost by 26.48% compared to the base case. Additionally, renewable penetration improves by 14.3% relative to short-term planning, confirming the benefits of coordinated PV–BESS integration for sustainable grids.

Keywords: long-term optimal planning, short-term optimal planning, solar PV, battery energy storage system, distribution system

Deep Learning for Lithium Battery Management Systems: A Systematic Literature Review

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Abstract. The rapid electrification of transportation and the global shift toward sustainable energy systems have underscored the critical role of Battery Management Systems (BMS) in ensuring the safety, efficiency, and reliability of lithium-ion batteries in electric vehicles (EVs), renewable energy storage, and portable electronics. This Systematic Literature Review (SLR) provides a comprehensive analysis of deep learning (DL) techniques applied to BMS, focusing on state estimation such as State of Charge [SOC], State of Health [SOH], fault diagnosis, optimization strategies and their implementation on resource-constrained embedded systems like microcontrollers. Adhering to the PRISMA framework, we systematically reviewed 52 studies published between 2018 and 2024, retrieved from IEEE Xplore and Scopus. The findings demonstrate that DL methods, particularly LSTM and CNN-LSTM, significantly enhance state estimation accuracy, achieving SOC errors as low as 1% MAE and SOH errors of 1%-2% RMSE, leveraging reliable datasets like NASA and CALCE. However, fault diagnosis and optimization remain underexplored, with only 3 and 7 studies respectively, lacking standardized metrics to quantify safety and efficiency improvements.

Keywords: Battery Management System, Deep Learning, Renewable Energy, Electric Vehicles

Data Centres, AI & Sustainable Energy Footprints

AI-Optimized Sustainable Cooling for Data Centers: A Hybrid Solar and Waste Heat Recovery System

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Abstract. This paper proposes a hybrid cooling system that utilizes the concepts of artificial intelligence (AI) to use solar energy and waste heat recovery (WHR) to improve the sustainability and efficiency of data centers. The data centers are estimated to use 1-2 % of global electricity and cooling systems use about 40 % of the total power. Traditional cooling systems like the computer room air conditioning (CRAC) units, chilled water systems are power-consuming and non-environmental. The main focus of earlier studies seems to be solar cooling or waste heat recovery in isolation and does not attempt to incorporate AI in significant combinations to optimize in real-time. The hybrid system manages to reduce these shortcomings by integrating photovoltaic (PV) panels, solar thermal collectors, absorption chillers, and an AI-controlled module. This new solution is the first hybrid cooling system that combines solar PV, solar thermal energy, and WHR with AI optimization and allows the real-time optimization of the energy consumption under changing workload and weather conditions. The system design is based on computational modeling, computational fluid dynamics (CFD), experimental validation and a 10 k W testbed. The outcome shows that 92.28 % of cooling needs are supplied by renewable sources, which puts grid reliance at 7.72 %. Its system will be energy efficient of 70-85 % given varying operational and climatic conditions with cost savings amounting to 40-60 % and carbon emission cut of 50-70%.

Keywords: Absorption, AI, cooling, hybrid, solar

Kubernetes Scheduling for Green-powered Microgrid Data Centers

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Abstract. Data centers are expected to consume 3 – 13% of the global electricity in 2030. Thus, different measures such as reducing the carbon footprint and utilizing renewable energy sources should be explored to limit the environmental impact of cloud computing. By configuring data centers as microgrids, able to operate both in connected and disconnected mode from the main grid, and by exploiting electrical storage and renewable energy production, carbon reductions might be possible. Default workload schedulers are not yet fitted with the capabilities of knowing the source of energy and thus cannot act accordingly. Therefore, we propose a way of using the Scheduling Framework for Kubernetes to implement two different green strategies, one focusing on renewable energy self-consumption, the other taking into account also the carbon intensity of the local main grid. Additionally, we propose a framework for simulating microgrids and nodes, where the effects of scheduling are observable. By simulating a large number of microgrids and configuring them with servers (also known in this paper as nodes), our plugin determines the best possible microgrid according to our green strategies to schedule a workload. We simulate workloads based on a real Azure worktrace, and we show that our proposed plugin can either improve self-consumption by 35.86%, or have a much smaller carbon footprint in comparison with the default Kubernetes scheduler. Further study could introduce different workload types and specific hardware requirements, a non-heterogeneous node specification or different, better-fitting renewable energy sources tailored to the geographical region. All code and data used in this study is available open source, more information under the Declarations section.

Keywords: Kubernetes Scheduling Framework · Microgrids, Microgrid Simulation, Cloud Computing, Renewable Energy, Kubernetes Plugin

Sustainable Data Centres: A Bibliometric Analysis of Research Trends, Patterns, and Future Directions

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Abstract. This study provides an in-depth bibliometric analysis of research on sustainable data centres, using the Scopus database and VOSviewer software. The objective is to identify the key research trends, leading publications, patterns and emerging themes in the field. This research examines a dataset of 238 documents from Scopus spanning from 2008 to August 2025. VOSviewer is used for data visualisation and analysis of keyword co-occurrences and citation relationships. This study reveals a growing interest in sustainable data centres, particularly regarding their environmental impact. Key findings include the identification of six distinct thematic clusters derived from keyword co-occurrence analysis and the delineation of influential sources, authors, and countries through bibliographic coupling analysis. Notably, China, India and the United States emerged as significant contributors and the journal “IEEE Transactions on Sustainable Computing” was identified as a leading publication. The analysis underscores the importance of exploring topics such as energy efficiency, environmental sustainability, and green computing. This study provides valuable insights into the evolution of sustainable data centres, identifies areas requiring further exploration, and establishes a robust foundation for subsequent interdisciplinary research. It emphasises the need for longitudinal research to determine the longterm impact of data centres on energy management, AI-based optimisations, and green computing, which can provide insights for fellow researchers, policymakers, and practitioners.

Keywords: Sustainable data centres, Green IT, Energy efficiency, Renewable energy, Bibliometric analysis.

The Energy Footprint of AI: Understanding and Mitigating the Impact of Artificial Intelligence Workloads on Data Centre Sustainability

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Abstract. The rapid proliferation of AI workloads, particularly those involving large-scale model training and inference, has significantly altered energy consumption patterns in data centres. This paper critically examines how the growth of AI is driving these transformations, explores the environmental consequences of escalating energy demands, and evaluates the technological and policy-based strategies being developed to mitigate their impact. Through a comprehensive review of hardware, infrastructure, algorithmic, and governance innovations, we highlight the need for interdisciplinary collaboration to align AI development with sustainability goals.

Keywords: Sustainable Computing, Carbon Footprint of AI, AI Data Centre, Energy Consumption

Methods, Governance & Responsible Digitalization in Energy

Geolocation-Based, Privacy-Aware Indoor Climate Data Access and Control in IoT-Enabled Smart Buildings

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Abstract. This paper presents a dynamic, privacy-preserving context-aware geofencing system designed to support indoor climate data access and control in IoT-enabled buildings. The approach addresses two interrelated challenges: safeguarding sensitive indoor climate data in compliance with the General Data Protection Regulation's (GDPR) data minimization and purpose limitation requirements, and enabling responsive environmental control based on user presence without relying on continuous tracking. During installation, each IoT device is registered via a mobile application that automatically collects spatial metadata, including GPS coordinates, which are clustered and aggregated into convex hulls representing building footprints. These geofences govern both data access and control logic, with evaluations occurring locally on users' mobile devices to preserve privacy. The system architecture integrates a Java-Spring-MongoDB backend with an Angular-based dashboard and supports real-time visualization using Leaflet, OpenStreetMap, and Three.js. Evaluations at two case study sites, a mid-sized Danish university building and a large Malaysian library, demonstrate accurate spatial modeling, responsive access control enforcement, and successful actuation of climate control systems based on geofence crossings. Results show that anticipatory thermal preconditioning and energy-saving setbacks can be triggered reliably by geofence events, confirming the viability of location-based automation as a privacy-aware control mechanism for smart buildings.

Keywords: Internet of Things (IoT), Energy Informatics, Smart Buildings, Geofencing, Access Control, GDPR Compliance, Climate Control.

Blockchain-Enabled Demand Response: Designing Consumer-Centric Electricity Markets with Smart Contracts

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Abstract. A blockchain-powered demand response system is suggested to mitigate the minimal consumer engagement and insufficient transparency in existing demand response (DR) programmers. The framework is deployed on Hyperledger Fabric, within which to automate settlements and secure data exchange between stakeholders the smart contracts are implemented. Simulation in MATLAB is employed to analyze the strategy, which demonstrates that the peak demand decreases by 15%, energy expenses decrease by 20%, and customer engagement reaches seventy percent. The findings indicate that the framework presented is appropriate to increase supply-demand adequacy and offer a scalable solution to energy markets in the future.

Keywords: Automation, Blockchain, Demand Response, Electricity Markets, Smart Contracts.

Ontology-driven generative adversarial networks for the design of renewable energy systems: A knowledge base approach

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Abstract. The design of Renewable Energy Systems (RES) involves the simultaneous consideration of technical, economic, and regulatory constraints. Traditional approaches often lack the flexibility required to efficiently explore the full range of possible configurations. Generative Adversarial Networks (GANs), as generative models, offer promising potential to automate this task. However, their purely data-driven nature makes them poorly suited to highly constrained domains such as RES. This paper proposes a hybrid methodology that combines the generative power of GANs with the rigorous structuring of knowledge through an energy domain ontology. The formalized ontology guides the generation of RES configurations by embedding domain specific rules, functional relationships, and physical constraints. The GAN is conditioned by this semantic information, ensuring that the generated configurations are more coherent and relevant. This work lays the foundation for a knowledge guided approach to RES configuration generation. It opens promising perspectives for automated, interpretable, and domain compliant design, pending future validation through concrete case studies.

Keywords: GAN, ontology, renewable energy systems, configuration generation, knowledge-driven design

Assessing The Effectiveness of Virtual Reality (VR) Integration in Electrical Engineering Education: A Fundamental Study on Student Practical Skill Development in Electrical Power System

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Abstract. This paper examines the integration of Virtual Reality (VR) technology in Electrical Engineering (EE) education, specifically focusing on its effectiveness in enhancing student practical skill development within Electrical Power System courses. Despite technological advancements in educational tools, Electrical Engineering Education continues to face significant challenges including declining student performance, limited access to specialized equipment, high laboratory costs, and difficulties in updating practical teaching modules. Traditional Physical-Based Laboratory (PBL) learning, while essential for developing hands-on competencies, is increasingly constrained by resource limitations and accessibility issues. This paper presents a detailed methodological framework employing mixed-methods research design across two sequential phases, designed to evaluate VR effectiveness through both quantitative performance metrics and qualitative user experience data. The proposed infrastructure requirements, technical specifications, and implementation protocols are thoroughly examined to establish feasibility parameters for institutional adoption. This fundamental study contributes to the theoretical understanding of immersive technology integration in engineering education by providing a structured approach for evaluating VR's pedagogical impact. The research framework offers valuable insights for curriculum designers, educational technologists, and institutional decision-makers considering innovative approaches to practical skill development in electrical engineering programs. By addressing the theoretical foundations of VR-enhanced learning, this study lays the groundwork for empirical research that could demonstrate how immersive technologies can democratize access to high-quality engineering education while improving student engagement and competency development outcomes.

Keywords: Virtual Reality, Project Based Learning, Higher Education, Electrical Engineering, Engineering, Electrical Power System, Practical Skill Development

How Buildings are Textualized for Large language Models Processing: a Preliminary Study

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Abstract. Large Language Models-based AI Agents (LLM Agents) are capable of replicating human-like intelligent behaviors such as reasoning, planning, decision-making and executing actions across various environments. Recent studies have demonstrated the effectiveness of applying LLM Agents to building energy systems, enhancing automation, streamlining information processing, and supporting decision-making processes while reducing the need for manual intervention and domain-specific expertise. However, the fundamental challenge of how physical building systems are properly textualized so that LLMs can process them remains largely unaddressed. This paper analyzes how various LLM applications in the building and energy domains represent and textualize their physical system targets, based on a preliminary review of recent literature. The study reveals that most current applications rely on custom, simple, unstructured text-based representations. In contrast, a number of existing works have adopted ontology-based representations, which introduce formal semantic graphs that can help integrate heterogeneous information. Building on this observation, the paper highlights ontology-based approaches as a promising direction for enhancing LLM-building interactions.

Keywords: LLM Agents, Smart Building Energy Systems, Agentic systems

Investigating User Awareness and Consent Practices for Individual Privacy in Smart Building Environments

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Abstract. Smart buildings increasingly integrate advanced technologies to enhance functionality and user experience, making robust privacy regulations essential to safeguard individual rights. This project investigates the current landscape of privacy laws and ethical guidelines governing smart buildings by examining both local and international regulations. As smart technologies continuously collect vast amounts of user data through sensors and IoT devices, significant privacy concerns arise—necessitating a comprehensive study of user awareness and consent practices. The research involves a detailed review of existing privacy regulations, an assessment of user knowledge through questionnaires, and the development of recommendations to improve consent practices. The study focuses on respondents in Malaysia, specifically everyday users of office and residential buildings, to reflect real-world awareness and expectations. The primary objectives are to: (a) identify and evaluate the rules and regulations shaping consent practices in smart buildings, (b) analyze user awareness and perceptions regarding privacy and their rights, and (c) propose guidelines to enhance consent practices within these environments. Findings from this study provide a clearer understanding of current user awareness levels in the Malaysian context and offer practical recommendations to strengthen privacy and consent mechanisms in smart building settings.

Keywords: Smart Buildings, Privacy Regulations, User Awareness, Consent Practices, Privacy Properties

Digital Energy Systems and Data Privacy: A Review of Legal and Ethical Considerations in Building and Grid-Level Applications

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Abstract. Digital technologies are playing a growing role in how energy is managed, both within buildings and across large power systems. These systems often rely on collecting and analyzing detailed data from users, devices, and networks to improve performance, service quality and enhance customer satisfaction, but while these developments support greater energy efficiency and adaptability, they also introduce serious concerns about data privacy, surveillance and ethical responsibility. This paper explores the legal and ethical implications of data use in digital energy systems, focusing on applications at both the building and grid levels, the review compares global data protection laws such as the GDPR and CCPA with those in Southeast Asia, including Malaysia's PDPA, to highlight gaps in how these regulations apply to energy data. Ethical concerns such as consent, data control and fairness are also discussed, especially in regions with limited resources and the analysis shows that effective governance of digital energy systems must account for local context, cultural values, and the readiness of legal institutions. This study adds to ongoing debates about how to promote innovation in the energy sector while safeguarding individual rights and ensuring equity during digital transformation.

Keywords: Digital Energy Systems, Data Privacy, Smart Grids, Cybersecurity, Ethical and Legal Frameworks.

Context-Aware Digital Innovations for Energy Transitions

From Models to Meaning - Understanding the Human Dimensions of Optimization in Energy System Modelling through Autoethnography

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Abstract. This paper explores how ethical, social, and interpretive dimensions shape the use of optimization in real-world decision-making with a focus on energy-related applications. By drawing on ten years of the author's experience working on interdisciplinary projects across academia, industry, and education, the objective is to investigate how abstract models acquire meaning in real-world decision-making contexts relevant to energy informatics such as electric vehicle charging, battery systems, energy system planning, sustainable logistics. Using an autoethnographic approach the study shows that modeling is not just technical but deeply interpretive. Decisions are influenced by values like efficiency, fairness, and accountability, and by the need to balance technical simplicity with complex stakeholder needs. The findings highlight how models, rather than offering purely objective answers, are embedded in dynamic interpretive processes, gaining meaning and authority through storytelling, framing, and negotiation. Ethical tensions frequently emerge between technical elegance and social responsibility, or between model simplicity and stakeholder complexity, and are often managed informally, through persuasion and compromise. By positioning modeling as a situated, meaning-making practice, this paper connects operations research and ethnographic approaches, in a way that has never been done before, and it offers a novel insider account of the human and ethical efforts involved in turning mathematical formulations into actionable decisions.

Keywords: energy system modelling, mathematical optimization, operations research, autoethnography, ethics, justice, pedagogy, decision making, participatory modelling.

A Comparative Assessment of Nuclear Energy's Contribution to Malaysia's 2050 Carbon Neutrality Goals

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Abstract. Malaysia has committed to achieving net-zero emission by 2050, as outlined in the National Energy Transition Roadmap (NETR). While nuclear energy is not currently part of the energy mix under the National Energy Policy 2022–2040, its inclusion could significantly contribute to decarbonization. This study evaluated nuclear power's potential role in Malaysia's energy transition using the reference approach to estimate carbon emission in 2050 and compared these results with NETR projections. CO₂ emission from fossil fuels was calculated to determine the residual CO₂ emission. The number of nuclear power plants needed to offset the residual CO₂ emission was then calculated for analysis. The levelized cost of electricity (LCOE) was assessed using the IAEA simple INPRO Nuclear Energy System (NES) simulator for different discount rates and deployment scenarios. Results indicated that under the reference approach, 34 reactors would be required to offset residual emission after accounting for land use, land-use change, and forestry (LULUCF) sinks, whereas using NETR projections would require 18 reactors. However, construction timelines and licensing constraints pose significant challenges in deploying this huge number of nuclear reactors. A more realistic build rate of one reactor every three years from 2035 would result in six reactors by 2050, avoiding 10.45 Mt CO₂ annually. LCOE values range from \$0.04/kWh to \$0.10/kWh, depending on discount rate and deployment scale, demonstrating economic competitiveness of nuclear energy. Unfortunately, six nuclear power plants by 2050 are still not enough to achieve net-zero emission even with carbon capture and storage (CCS) projections from NETR being considered.

Keywords: Nuclear Energy, Carbon Neutrality, Malaysia, Levelized Cost of Electricity, Reference Approach, NETR.

Bridging the Urban–Rural Divide: A Review of Context-Aware Smart Homes with Insights from Semi-Rural Malaysia

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Abstract. This paper presents a comprehensive review that incorporate context-aware computing, with a focus on their application in smart home environments within semi-rural areas of Malaysia. As smart home technologies become increasingly accessible, there is a growing need to personalize services based on users' contextual information—such as location, activity, preferences, time, environmental conditions, and occupant physical status—to improve usability, energy efficiency, and occupant well-being. We explored the evolution of context-aware systems, analyzing current models, data collection strategies, and context modelling techniques relevant to smart homes. Special attention is given to challenges unique to semi-rural Malaysian settings, including inconsistent internet connectivity, cultural acceptance, infrastructure limitations, and readiness to embrace. Through a rigorous literature review, this paper identifies gaps in current approaches, particularly in multi-user environments, cold-start scenarios, and the integration of real-time sensor data. This work aims to provide a foundation for researchers and developers to design and implement contextually intelligent recommendation frameworks that are both technically feasible and culturally sensitive in underrepresented regions.

Keywords: Context-aware, smart homes, sustainability, energy efficiency, connectivity, semi-rural space.

Digital Innovations, Resilience and Solidarity in the EU Energy Sector

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Abstract. This short paper explores the European Union's evolving energy governance in the context of resilience, solidarity, climate neutrality, digital innovations and geopolitical instability. Anchored in Article 194 TFEU, the Union's energy policy is increasingly shaped by the need to ensure resilient energy markets and solidarity among Member States while navigating the disruptive potential of digital technologies. Recent initiatives, such as Digitalising the Energy System Action Plan, reflect a strategic shift toward integrating artificial intelligence, smart grids and cybersecurity into energy infrastructure to support a more resilient energy sector. This short paper offers a policy-oriented perspective on resilience in the European Union's energy governance, with particular attention to resilience obligations embedded in regulatory frameworks on the digitalisation of the energy markets and the inherent tensions with the principle of energy solidarity.

Keywords: European Union/EU, energy policy, regulation, resilience, solidarity, digitalisation, artificial intelligence/AI, data governance.

Data Innovation in the Energy Sector: Can Regulatory Fragmentation Support Resilience?

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Abstract: The European Union has positioned digital innovation as a cornerstone in the green energy transition and in its strategy to achieve climate neutrality by 2050. Through initiatives such as the Digitalising the Energy System Action Plan from 2022 and the upcoming Strategic Roadmap for Digitalisation and AI in the Energy Sector in 2026, the EU aims to foster a resilient, efficient and consumer-centric energy system. The challenge is how or whether it is actually possible for the EU to achieve this goal through the current regulatory approach, where the EU continues to adapt more legislation. This abstract and presentation explores how the EU's evolving regulatory landscape supports digital innovation to act as a stabilising force in uncertain energy futures. The following two points will serve to elaborate further on this: First, it is necessary to analyse the current regulatory landscape relevant for entities in the energy sector. This analysis is relevant to determine what is needed to support a smart and efficient green transition that also aligns with the primary target of security of supply. Second, use of data across the energy sector must support a more resilient energy system. The EU encourages AI deployment in grid optimisation, demand forecasting, energy efficiency and integration of wind and solar energy. Resilience helps maintain a stable and reliable energy supply, even during disruptions such as extreme weather events, cyberattacks, equipment failures or geopolitical tensions. The EU is building a Common Energy Data Space to support secure, standardised data sharing. But balancing consumer control with privacy remains a challenge. Our research wants to uncover whether the current regulation of data use supports the path towards a resilient energy system.

Keywords: energy regulation, resilience, climate targets, energy data, dataspace digitalisation, AI, data innovation.

Decarbonizing Asphalt Production in Iceland: An AHP Evaluation of Green Fuels

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Abstract. The industrial sector faces significant pressure to transition from fossil fuels to renewable energy sources to meet ambitious climate targets. This paper addresses this challenge within the context of Iceland's asphalt production industry, an energy-intensive process currently reliant on fossil fuels at a plant operated by Colas Iceland. The primary objective is to evaluate the feasibility of replacing Marine Gas Oil (MGO) with locally produced green fuels for heating and drying aggregates. A multi-criteria decision-making framework, the Analytic Hierarchy Process (AHP), is employed to systematically compare five fuel alternatives: biodiesel, hydrogen, methane, wood pellets, and methanol. The evaluation is based on four key criteria identified in collaboration with the industrial partner: fuel availability, cost, infrastructure requirements, and environmental impact from combustion emissions. The AHP analysis, grounded in operational data from Colas, reveals that wood pellets are the most favorable option, primarily driven by their significant cost advantage. Biodiesel and methanol emerge as strong secondary candidates, requiring minimal infrastructure modifications but at a higher price point. This study provides a practical, data-driven methodology for industrial stakeholders to navigate the complexities of green energy transition.

Keywords: Green Energy, Decarbonization, Asphalt Production, Analytic Hierarchy Process (AHP), Multi-Criteria Decision Analysis.

Thermal Storage and Flexibility in Buildings

Predictive Control in Buildings – A commercializing view of the Norwegian building industry

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Abstract. This study investigates the adoption of predictive control methods in the Norwegian building industry, focusing on their current usage and the gap between academic research and industry practices. A survey of 59 companies, with a 54.2% response rate, revealed that 75% of participants use predictive control methods beyond outdoor temperature compensation, with 54% employing them regularly. Results show that the methods are predominantly applied to heating, cooling, and ventilation systems, with heating being the most common. While predictive control methods are widely adopted, advanced strategies like Model Predictive Control (MPC) remain underutilized. Only 9.3% of participants reported using MPC, and just 34.4% were familiar with it. This highlights a significant gap between academic advancements and industry implementation. Most predictive control methods integrate with existing infrastructures by adjusting PI/PID controller setpoints, reflecting a practical approach to innovation. The study concludes that while predictive control methods are gaining traction, significant potential remains untapped. Bridging the gap between research and practice requires targeted outreach, education, and practical demonstrations to accelerate the adoption of advanced control strategies, ultimately fostering sustainable and efficient building operations.

Keywords: Predictive control, energy efficiency, Model Predictive Control, building automation, Norwegian building industry.

Data-driven thermal models for smart energy management in heating system

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Abstract. Forecasting the thermal behavior of flexible heating assets is essential for real-time energy management in heating systems. While thermal dynamics are complex, the optimization algorithms within EMS require low-order models with minimal computational load to make rapid, real-time decisions. To bridge this gap, this study develops and validates low-order, data-driven models for a heat pump, an electric boiler and the indoor temperature of an office building. These models are designed for integration into the Digital Twin EMS of an industrial site. The e-boiler is characterized by its efficiency frequency distribution, which is centered at 85%, allowing it to be represented by a constant value. For the heat pump, a third-order polynomial captures how the COP depends on the outdoor temperature with a MAE of $\text{COP} = 0.41$. Indoor temperature dynamics are described with a discretized first-order model whose constant parameters are identified via four-minute nighttime regression; daytime disturbances are estimated either from training data or a three-day rolling profile. The developed indoor-temperature dynamic model predicts office temperatures with an overall MAE below a $0.3\text{ }^{\circ}\text{C}$ threshold, which humans cannot perceive. The resulting low-order models are suitable for integration into model-predictive algorithms that schedule the operation of the heating system.

Keywords: Data-driven model, Energy management systems, Digital Twin.

Building Energy Model Calibration as a Service

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Abstract. This thesis explores the feasibility of building energy model (BEM) calibration as a commercial service within engineering consultancies. BEMs are widely used to evaluate energy improvements in commercial buildings, yet their accuracy is often constrained by data availability and model uncertainty. To address this, a flexible calibration workflow was developed, integrating Monte Carlo sampling, surrogate modelling, and Bayesian optimisation.

The workflow was validated across three case studies: two real-world office buildings in Melbourne and Madrid, and a synthetic dataset designed to simulate realistic operational noise and variability. Results showed that calibration improved alignment between simulated and metered data, with hourly CVRMSE values ranging from 33 to 136. Key factors influencing calibration success included accurate floor area, correct mechanical system topology, and access to disaggregated or sub-metered demand data. To support standardisation across diverse data scenarios, a novel building data grading system was introduced, informed by industry knowledge of typical client data availability.

Commercial applications of calibrated models were also tested. These included comparative analysis of ECM predictions using no model, an uncalibrated model, and a calibrated model, as well as a simplified thermal model calibrated to assess grid-responsive thermal storage strategies based on local energy tariffs.

The study concludes that while BEM calibration offers clear technical and commercial potential, its viability as a service depends heavily on data accessibility and workflow scalability. Future work should focus on validating calibrated model predictions with post-retrofit data and exploring cloud-based or app-based deployment to enhance usability and adoption.

Keywords: Building energy model calibration, building energy modelling, energy improvement, commercial energy demand, Monte-Carlo, surrogate modelling, Bayesian, machine learning, EnergyPlus.

Adaptive Transformer Q-Networks for Energy and Comfort Optimization in Smart Buildings

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Abstract. Modern smart buildings operate in dynamic environments where achieving an optimal balance between energy efficiency and occupant comfort is complicated by partial observability, stochastic occupancy patterns, delayed actuator responses, and the coupled dynamics of thermal, air quality, and lighting systems. This growing complexity has motivated the increasing adoption of data-driven control methods, in which learning algorithms can complement or even surpass traditional model-based strategies. Reinforcement learning (RL) provides a model-free approach capable of deriving control policies directly from data. However, many RL architectures rely on recurrent neural networks (RNNs), such as long short-term memory (LSTM) networks, which often struggle to capture long-term dependencies due to hidden state compression. Transformer-based agents, such as the Deep Transformer Q-Network (DTQN), mitigate part of this limitation by using self-attention to selectively focus on relevant historical information. Nevertheless, their performance may degrade in highly non-stationary environments if temporal focus is not adapted dynamically. To address this issue, we propose an Adaptive Deep Transformer Q-Network (Adaptive DTQN) for non-stationary building control tasks. Adaptive DTQN operates at the level of individual attention heads, dynamically re-weighting their contributions based on real-time statistics such as attention entropy and token-level variance, thereby enabling the network to flexibly adjust its temporal focus as conditions evolve. We evaluate Adaptive DTQN in a simulated multi-variable smart building environment with hidden regime changes, realistic actuator delays, and stochastic occupancy. Results demonstrate that Adaptive DTQN consistently achieves robust performance across reward, comfort, and stability metrics, while keeping energy use within acceptable bounds, maintaining a favorable trade-off under changing temporal dependencies and underscoring its potential for real-world building automation.

Keywords: Smart building control, Reinforcement learning, Transformer Q-Network, Adaptive attention, Partial observability

Impact of Environmental and Operational Factors on Radiator Supply Water Temperature in Smart Buildings: Flexibility, Comfort, and Demand-Side Management

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Abstract. The temperature of the radiator supply water is a crucial factor in smart buildings, directly influencing energy efficiency, thermal comfort, and heating billing costs. This study examines how various environmental and operational factors, such as solar radiation, ventilation flow rate, occupancy heat gains, wind, and outdoor temperature history, affect radiator performance in a six-story commercial building in Sweden, rather than solely correlating supply temperature with outdoor conditions as conventional methods do. A computer model was created utilizing TRNSYS to simulate the building, its thermal energy system, and interactions with the district heating network. Simulation results indicate that solar radiation is the predominant contributor during transitional and warmer months, decreasing heating demand and radiator supply temperature by as much as 70%. Conversely, occupancy-related internal gains and ventilation significantly impact performance during colder periods, although wind and historical external temperature exhibited minimal influence. Integrating these dynamic parameters into supply temperature control systems results in substantial enhancements of comfort while saving up to 13% of annual radiator heating demand. The results indicate that radiator supply temperature serves as a significant mechanism for demand-side management, allowing buildings to enhance internal efficiency and comfort while functioning as flexible, interoperable assets within district heating networks and future smart grids. The research emphasizes the significance of digital modeling in measuring flexibility and formulating performance indicators that facilitate the incorporation of buildings into energy markets and policy structures aimed at decarbonization.

Keywords: Digital modeling, Smart HVAC, Demand-side management, Flexibility; Comfort, Energy efficiency, Smart buildings

Data-Driven Framework for Climate-Resilient Heritage Commercial Building Connected to District Heating

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Abstract. This study introduced a data-driven framework for the design, control, and resilience assessment of a low-temperature radiant heating and high-temperature cooling system in a heritage commercial building connected to a district heating network. The solution integrates a modular underfloor heating and cooling system with return-flow district heating, a reversible heat pump, and a building-integrated photovoltaic system. Circuit-level modeling and validation against manufacturer data show uniform thermal output with a mean absolute percentage error below 4%. Resilience is assessed under cold-wave and heat-wave scenarios using a validated simulation model. Control strategies include preconditioning with 1–5 h offsets, which exploit building thermal inertia to maintain comfort during extreme events. Results demonstrate how a data-driven approach enables accurate hydraulic and thermal design, effective renewable integration, and scenario-based resilience analysis in a constrained heritage context.

Keywords: Data-Driven Framework, Low-Temperature Heating, High-Temperature Cooling, District Heating Network, Resilience Assessment, Heritage Building, Renewable Integration

Standardizing Building Mass Flexibility through Digital Models and Control

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Abstract. The transition to renewable-based energy systems requires buildings to evolve from passive energy consumers into active, digitalized flexibility assets. Thermally Activated Building Mass (TABM) offers significant potential by using the inherent thermal inertia of structural components as distributed storage. IEA ES Task 43, Standardized Use of Building Mass as Storage for Renewables and Grid Flexibility (2023–2025), addresses the technical and informatics foundations necessary for TABM to become a scalable flexibility technology. Across four subtasks, the Task advances digital and systemic integration. Subtask B focuses on simulation models and co-simulation interfaces to assess flexibility potential and validate predictive control strategies using weather and price forecasts. It also develops supervisory control concepts and digital twins for building and district-level optimization, with explicit attention to data privacy and secure IoT/BMS interoperability. Subtask D prepares standardized Key Performance Indicators (KPIs) for energetic, economic, and ecological evaluation, including storage capacity, CO₂ savings, comfort compliance, and demand-response readiness. These informatics-oriented outputs are complemented by Subtask A (construction/material archetypes for digital models) and Subtask C (business models, user-centric data frameworks, and regulatory mapping). The emerging results confirm that TABM can shift daily loads, reduce costs, and provide sector-coupling benefits. More importantly, they show how digitalization—through predictive control, interoperable data exchange, and KPI-based benchmarking—enables TABM to participate in energy markets as a recognized flexibility resource. Task 43 thereby contributes to the energy informatics community by linking physical storage with cyber-physical systems and standardized data-driven frameworks for future market integration.

Keywords: Building mass flexibility, thermally activated building systems, predictive control, digital twin, demand response, energy informatics, grid flexibility, renewable integration

Digital Innovation for Resilient Low-Carbon Industry

A Data-Driven Framework for Clustering and Decision-Support in Energy-Intensive Industrial Melting Operations

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Abstract. Energy-intensive manufacturing processes, such as induction melting, suffer from limited visibility into operational variability, hindering efforts to optimize energy use and productivity. Existing studies primarily focus on structural improvements or single-variable analysis, offering little support for dynamic, data-driven decision-making. This paper addresses this critical gap by proposing a novel framework that integrates full-cycle segmentation, unsupervised clustering, and multi-criteria decision-making (MCDM) to systematically discover, evaluate, and benchmark operational patterns in industrial melting. Unlike prior work that isolates temperature or energy profiles, the proposed method fuses high-frequency power, weight, and temperature signals to identify melting cycles using correlation-informed segmentation. K-means clustering is applied to full-process feature vectors, enabling interpretable groupings based on melting rate and energy-specific consumption. These clusters are then evaluated using an ensemble of MCDM techniques (SAW, TOPSIS, VIKOR) across both performance and operational dimensions. The framework is validated on a 16-month dataset from a Danish foundry, comprising over 3,400 melting cycles. Results reveal five distinct operational patterns and show that standardizing operations toward the top-performing cluster can reduce energy consumption by 9.3% and process time by 29%. Scientifically, this work contributes a unified pipeline for multi-sensor industrial process analytics, combining segmentation, unsupervised learning, and decision-support under a real-world context. Practically, it offers a scalable tool for identifying energy-efficient best practices and supports data-driven operational optimization in smart manufacturing environments.

Keywords: Energy Efficiency, Induction Furnace, K-means Clustering, Unsupervised Learning, Multi-criteria decision making.

Towards operational platforms for Power-to-X plants and waste heat reuse management

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Abstract. Power-to-X (P2X) technologies are gaining increasing attention in the digitalization of the energy sector. This is due to the special characteristics of these technologies, such as high energy consumption, flexibility in operation, and the capability to serve different sectors. In this paper, the recently introduced concept of operational digital platforms (ODPs) is adapted to the P2X technologies to facilitate their interactions with electricity markets (day-ahead and balancing markets) and manage waste heat reuse of these facilities. To demonstrate the effectiveness of the proposed ODP, it is applied to three different P2X technologies, i.e., electrolyzers, data centres, and heat pumps, and the results are discussed. The smart grid architecture model (SGAM) is also used to describe the focused zones and domains of the ODP in the smart grid architecture and its role in SGAM layers. Test results prove the proposed method's success in managing the P2X plants' operation.

Keywords: Power-to-X, data centres, electrolyzers, waste heat management, power bidding.

Uncovering Causal Drivers of Energy Efficiency for Industrial Process in Foundry via Time-Series Causal Inference

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Abstract. Improving energy efficiency in industrial foundry processes is a critical challenge, as these operations are highly energy-intensive and marked by complex interdependencies among process variables. Correlation-based analyses often fail to distinguish true causal drivers from spurious associations, limiting their usefulness for decision-making. This paper applies a time-series causal inference framework to identify the operational factors that directly affect energy efficiency in induction furnace melting. Using production data from a Danish foundry, the study integrates time-series clustering to segment melting cycles into distinct operational modes with the PCMCi+ algorithm, a state-of-the-art causal discovery method, to uncover cause-effect relationships within each mode. Across clusters, robust causal relations among energy consumption, furnace temperature, and material weight define the core drivers of efficiency, while voltage consistently influences cooling water temperature with a delayed response. Cluster-specific differences further distinguish operational regimes: efficient clusters are characterized by stable causal structures, whereas inefficient ones exhibit reinforcing feedback loops and atypical dependencies. The contributions of this study are twofold. First, it introduces an integrated clustering-causal inference pipeline as a methodological innovation for analyzing energy-intensive processes. Second, it provides actionable insights that enable foundry operators to optimize performance, reduce energy consumption, and lower emissions.

Keywords: Causal inference, Time-series analysis, Energy efficiency, Induction furnace, manufacturing processes.

Predictive Maintenance of Electrical Switchgears Using Calibrated Logistic Regression

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Abstract. The reliability of switchgear assets is critical for ensuring continuous power delivery in electrical distribution networks. However, aging equipment and recurring defects often lead to costly interruptions if failures are not detected early. This paper presents a data-driven predictive maintenance framework for switchgears based on logistic regression, emphasizing robust preprocessing and probability calibration to achieve reliable defect forecasting. Historical defect records from Tenaga Nasional Berhad (TNB) in Kelantan, covering the period 2020–2024, were consolidated into a defect matrix representing 42 switchgears across 17 inspection cycles. The modeling task was formulated as a binary classification problem to estimate the probability of defect occurrence in the final cycle (C17) and to forecast a hypothetical next cycle (C18). Initial experiments achieved an accuracy of 92.86%, misclassifying only three units. A Leave-One-Cycle-Out (LOCO) analysis revealed that excluding Cycle 15 improved model robustness, increasing accuracy to 95.24% and F1-score to 0.889. Further probability calibration using ROC and calibration curves identified an optimal threshold of 0.332, ensuring both accurate binary decisions and reliable probabilistic predictions. The findings demonstrate that even a simple model such as logistic regression, when supported by rigorous data preparation and calibration, can provide actionable insights for predictive maintenance scheduling. This study highlights the importance of probability calibration and threshold tuning in industrial applications, offering TNB a cost-effective and interpretable predictive maintenance solution for enhancing asset reliability.

Keywords: Predictive Maintenance, Switchgear Defects, Logistic Regression, Power Distribution Systems.

Hybrid Machine Learning Framework for Electrical Substation Defect Analysis and Predictive Maintenance

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Abstract. The management of electrical infrastructure maintenance has evolved significantly with the integration of artificial intelligence and machine learning technologies. This paper presents a comprehensive hybrid framework combining rule-based defect prioritization with machine learning-based failure prediction for electrical substation maintenance optimization. Using historical defect data spanning 2023-2024 from Malaysia's Pantai Timur region encompassing Kelantan, Terengganu, and Pahang states, we developed a two-phase system: (1) a transparent multi-criteria rule-based engine for immediate defect triage, and (2) ensemble machine learning models for monthly failure forecasting. The rule-based component processes switchgear defects using business logic derived from equipment type, defect location, and severity indicators. For predictive capabilities, we compared XGBoost and Random Forest classifiers on severely imbalanced data (88.40% zero-defect months), achieving ROC-AUC scores of 0.7562 and 0.7631 respectively. The Synthetic Minority Over-Sampling Technique (SMOTE) was integrated within cross-validation pipelines to address class imbalance while preventing data leakage. Feature importance analysis revealed temporal recency (months since last defect) as the dominant predictor, validating reliability engineering principles. The XGBoost model was selected for deployment due to superior cross-validation consistency and interpretability. This hybrid approach transforms reactive maintenance strategies into proactive intelligence systems, providing both immediate prioritization and strategic forecasting for optimal resource allocation in electrical infrastructure management.

Keywords: Predictive Maintenance, Electrical Substations, Rule-based Prioritization, Machine Learning, XGBoost, Random Forest, Ensemble Learning.

Genetic Algorithm-Based Arrhenius Kinetics and Energy Yield Assessment for Wood Pyrolysis

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Abstract. This study presents a kinetic and energy-informatics analysis of biomass pyrolysis, integrating experimental data with genetic-algorithm-optimized Arrhenius modeling to elucidate feedstock-specific conversion behavior. Three representative biomass types, nut shells and eucalyptus, were investigated to quantify how compositional differences influence reaction kinetics, product distribution, and energy recovery. Experimental data were fitted using a parallel–consecutive three-lump kinetic scheme describing primary and secondary devolatilization into gas, tar, and char. The GA optimization achieved excellent agreement with experimental results ($R^2 > 0.95$), yielding activation energies and pre-exponential factors consistent with the structural complexity of lignocellulosic components. Results reveal that nut shells, rich in lignin and aromatic polymers, exhibit slower decomposition dominated by stable char formation, while cellulose-rich eucalyptus undergoes rapid devolatilization, favoring gas and tar evolution. Energy yield analysis, based on lower heating values, indicates total recoverable energies of 19–25 MJ kg^{−1} biomass, corresponding to 5–7 kWh kg^{−1}. Sensitivity analysis demonstrated that gas yields are highly responsive to kinetic parameter perturbations, whereas char yields remain relatively stable, confirming the robustness of char-oriented systems under kinetic uncertainty. Beyond traditional kinetic interpretation, this work establishes a methodological bridge between reaction kinetics and system-level energy metrics. By embedding GA-optimized kinetic parameters within energy-informatics frameworks, the study enables predictive modeling of feedstock behavior, process optimization, and integration of pyrolysis within distributed, carbon-neutral bioenergy networks. The findings contribute to the digitalization of biomass-to-energy conversion and provide a transferable foundation for the development of data-driven, sustainable bioenergy systems.

Keywords: Biomass thermochemical conversion, Lumped kinetic modeling, Genetic algorithm fitting, Energy informatics, Bioenergy production, Gas–tar–char kinetics.