UNIVERSITI MALAYSIA SARAWAK
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**Faculty of Engineering**

# A Framework for Green Energy Resources Identification and Integration Supported by Real-Time Monitoring, Control, and Automation Applications

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# A Framework for Green Energy Resources Identification and Integration Supported by Real-Time Monitoring, Control, and Automation Applications

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**DECLARATION**

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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## ABSTRACT

Sarawak is transitioning to green energy adoption, yet progress is hindered by a lack of comprehensive spatial data to identify optimal locations, inadequate optimization techniques for effective integration of these sites, and insufficient robust Industrial Internet of Things-based real-time monitoring and automation strategies to manage the intermittent nature of green energy resources. To address these challenges, a novel Geographical Information System-based fuzzy Technique for Order Preference by Similarity to Ideal Solution coupled with filtration algorithms was proposed. This two-layered approach effectively filters potential green energy sites. The first layer identified 23 optimal wind energy sites and 138 optimal hydro energy sites. The second layer employed spatial data and the fuzzy Technique for Order Preference by Similarity to Ideal Solution algorithm to refine potential solar energy sites, yielding the top 100 optimal locations. The proposed method demonstrated a 69.01 % alignment when validated against the weighted sum method. Following site identification, an improved Geographical Information System-driven fuzzy Traveling Salesman Problem-Binary Integer Programming algorithm was proposed to integrate these sites into a reliable ring-based system topology, aiming to achieve a zero-carbon footprint. The process involved clustering by divisions and designing optimal electrical power line routing for each cluster, prioritizing minimum total distance, elevation difference, and average ground flash density. Validation against conventional methods and state-of-the-art algorithms confirmed the superior performance of the proposed approach. Additionally, an Industrial Internet of Things-based system utilizing servers, cloud platforms, and Supervisory Control and Data Acquisition systems was developed for real-time monitoring, control, and automation to address green energy intermittency. Hardware prototypes using Raspberry Pi and Industrial Internet of Things components were interfaced with SCADA systems to validate real-world applicability. Experimental results confirmed the effectiveness of the proposed methodologies. In conclusion, the proposed methodologies demonstrate the potential to overcome barriers to green energy implementation, fostering sustainable development in Sarawak. This research offers practical insights for policymakers, energy stakeholders, and researchers advancing green energy initiatives.

**Keywords:** Fuzzy, green energy resources, geographical information system, integrated green energy systems, industrial internet of things

***Satu Kerangka untuk Pengenalpastian dan Penyepaduan Sumber Tenaga Hijau Disokong oleh Aplikasi Pemantauan, Kawalan dan Automasi Masa Nyata***

## *ABSTRAK*

*Sarawak sedang beralih kepada penggunaan tenaga hijau, namun perkembangannya terhalang oleh kekurangan data spatial yang komprehensif untuk mengenal pasti lokasi optimum, teknik pengoptimuman yang tidak mencukupi bagi penyepaduan efektif tapak-tapak ini, serta strategi pemantauan masa nyata dan automasi berasaskan Internet Perindustrian Perkara yang kurang kukuh bagi mengurus sifat berselang-seli sumber tenaga hijau. Bagi mengatasi cabaran ini, satu metodologi baharu Sistem Maklumat Geografi berasaskan teknik kabur untuk Technique for Order Preference by Similarity to Ideal Solution digabungkan dengan algoritma penapisan telah dicadangkan. Pendekatan dua lapisan ini berjaya menapis tapak tenaga hijau yang berpotensi. Lapisan pertama mengenal pasti 23 tapak tenaga angin optimum dan 138 tapak tenaga hidro optimum. Lapisan kedua menggunakan data spatial dan algoritma kabur untuk Technique for Order Preference by Similarity to Ideal Solution untuk memperhalusi tapak tenaga suria berpotensi, menghasilkan 100 lokasi solar optimum teratas. Kaedah yang dicadangkan menunjukkan tahap keselarasan sebanyak 69.01 % apabila disahkan terhadap kaedah jumlah berwajaran. Selepas pengenalpastian tapak, algoritma Masalah Jurujual Perjalanan-Pengaturcaraan Sistem Angka Perduaan yang dipacu oleh Sistem Maklumat Geografi yang dipertingkatkan dicadangkan untuk menyepadukan tapak-tapak ini ke dalam topologi sistem berasaskan gelang yang boleh dipercayai, bertujuan mencapai sifar jejak karbon. Proses ini melibatkan pengelompokan mengikut bahagian dan merekabentuk laluan talian kuasa elektrik optimum untuk setiap kluster, dengan keutamaan diberikan kepada jumlah jarak minimum, perbezaan ketinggian, dan purata ketumpatan kilat tanah.*

*Pengesahan terhadap kaedah konvensional dan algoritma terkini membuktikan keunggulan pendekatan yang dicadangkan. Selain itu, sistem berasaskan Internet Perindustrian Perkara yang menggunakan pelayan, platform awan, dan sistem Kawalan Penyeliaan dan Pemerolehan Data dibangunkan untuk pemantauan masa nyata, kawalan, dan automasi bagi menangani sifat berselang tenaga hijau. Prototaip perkakasan menggunakan Raspberry Pi dan komponen Internet Perindustrian Perkara dihubungkan dengan sistem sistem Kawalan Penyeliaan dan Pemerolehan Data untuk mengesahkan kebolehgunaan di dunia sebenar. Keputusan eksperimen mengesahkan keberkesanan metodologi yang dicadangkan. Kesimpulannya, metodologi yang dicadangkan berpotensi mengatasi halangan pelaksanaan tenaga hijau, sekaligus menyokong pembangunan mampan di Sarawak. Penyelidikan ini memberikan pandangan praktikal kepada pembuat dasar, pemegang kepentingan tenaga, dan penyelidik dalam memajukan inisiatif tenaga hijau.*

**Kata kunci:** *Kabur, sumber tenaga hijau, sistem maklumat geografi, sistem tenaga hijau bersepadu, internet perindustrian perkara*

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| | |
|---|---|
| ABC | Artificial Bee Colony |
| AC | Alternating Current |
| ACO | Ant Colony Optimization |
| AES | Advanced Encryption Standard |
| AFSA | Artificial Fish Swarm Algorithm |
| AGC | Apollo Guidance Computer |
| AHP | Analytical Hierarchy Process |
| AI | Artificial Intelligence |
| ANP | Analytical Network Process |
| API | Application Programming Interface |
| AR | Assurance Region |
| AS | Automatic Switch |
| ASRS | Automated Storage and Retrieval Systems |
| BA | Bat Algorithm |
| BB | Branch and Bound |
| BF | Brute Force |
| BFOA | Bacteria Foraging Optimization Algorithm |
| BIP | Binary Integer Programming |
| BOCR | Benefit, Opportunity, Cost, and Risk |
| BRKGA | Biased Random-Key Genetic Algorithm |
| CETSP | Close Enough-Traveling Salesman Problem |
| CGTSP | Clustered Generalized Traveling Salesman Problem |
| COPRAS | Complex Proportional Assessment |

| | |
|---|---|
| CPLEX | Constraint Programming Linear Programming with Extensions |
| CS | Cuckoo Search |
| DAQ | Data Acquisition |
| DC | Direct Current |
| DE | Differential Evolution |
| DEA | Data Envelopment Analysis |
| DEMATEL | Decision Making Trial and Evaluation Laboratory |
| DEMs | Digital Elevation Models |
| DP | Dynamic Programming |
| ELECTRE | Elimination and Choice Translating Reality |
| EM-MOPSO | Elitist-Mutated Multi Objective Particle Swarm Optimization |
| EP | Evolutionary Programming |
| EPC | Engineering, Procurement, and Construction |
| ES | Evolutionary Strategies |
| FA | Firefly Algorithm |
| FIS | Fuzzy Inference System |
| FST | Fuzzy Set Theory |
| FTSP | Family Traveling Salesman Problem |
| GA | Genetic Algorithm |
| GDP | Gross Domestic Product |
| GERs | Green Energy Resources |
| GEs | Green Energy Locations |
| GFD | Ground Flash Density |
| GHI | Global Horizontal Irradiance |
| GIS | Geographical Information System |

| | |
|---|---|
| GP | Genetic Programming |
| GPIO | General Purpose Input / Output |
| GSO | Glowworm Swarm Optimization |
| GWO | Grey Wolf Optimizer |
| HES | Hydro Energy Sites |
| HFLTS | Hesitant Fuzzy Linguistic Term Sets |
| HFS | Hesitant Fuzzy Sets |
| HMI | Human Machine Interface |
| IFS | Intuitionistic Fuzzy Sets |
| IGESs | Integrated Green Energy Systems |
| IIoT | Industrial Internet of Things |
| IP | Integer Programming |
| ISHDB | Internet of Things Smart Household Distribution Board |
| LabVIEW | Laboratory Virtual Instrument Engineering Workbench |
| Li-ion | Lithium-ion |
| LF | Load Following |
| LOA | Lion Optimization Algorithm |
| MA | Monkey Algorithm |
| MACBETH | Measuring Attractiveness by a Categorical Based Evaluation Technique |
| MCDM | Multi-Criteria Decision-Making |
| MILP | Mixed Integer Linear Programming |
| MLI | Multi-Level Inverter |
| MS | Manual Switch |
| NI | National Instrument |

| | |
|---|---|
| NN | Nearest Neighbor |
| NP | Nondeterministic Polynomial time |
| NTC | Negative Temperature Coefficient |
| OPC | Open Platform Communications |
| OS | Operating System |
| OWA | Ordered Weighted Averaging |
| PCNN | Pulse Coupled Neural Network |
| PDS | Parcel Delivery Services |
| PI-SVPWM | Proportional Integral-based Space Vector Pulse Width Modulation |
| PLC | Programmable Logic Controller |
| POWER | Prediction of Worldwide Energy Resource |
| PROMETHEE | Preference Ranking Organization Method for Enrichment Evaluation |
| PSO | Particle Swarm Optimization |
| PV | Photovoltaic |
| QL | Quality Learning |
| RC4 | Rivest Cipher 4 |
| RMS | Root Mean Square |
| SA | Simulated Annealing |
| SAW | Simple Additive Weighting |
| SCADA | Supervisory Control and Data Acquisition |
| SDGs | Sustainable Development Goals |
| SEB | Sarawak Energy Berhad |
| SES | Solar Energy Sites |
| SFLA | Shuffled Frog Leaping Algorithm |

| | |
|---|---|
| STATCOM | Static Synchronous Compensator |
| TDS | Technical Decision Support |
| TS | Tabu Search |
| TSP | Traveling Salesman Problem |
| TOPSIS | Technique for Order of Preference by Similarity to Ideal Solution |
| VIKOR | Multiple Criteria Optimization and Compromise Solution |
| WECS | Wind Energy Conversion Systems |
| WES | Wind Energy Sites |
| WLC | Weighted Linear Combination |
| WSM | Wireless Sensor Network |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background

Sarawak spans 124,450 $km^2$ with a population of nearly 3 million (Tang et al., 2023). It has warm, humid climate, with temperatures between 23 ℃ to 32 ℃ (Isia et al., 2022), offers significant potential for green energy. The state receives abundant solar radiation, averaging 4.21 $kWhm^{-2}$ to 5.56 $kWhm^{-2}$ (Kee et al., 2022) daily, and about 4.5 hours of sunshine per day (Arief et al., 2020), making it ideal for solar energy sites. While average wind speeds are modest at 2 $ms^{-1}$ to 3 $ms^{-1}$, coastal regions experience higher velocities during the Northeast Monsoon, reaching up to 10 $ms^{-1}$ (Lawan et al., 2020). Advancements in turbine technology now allow for effective energy capture even at these lower wind speeds. Additionally, with annual rainfall around 4,600 $mm$ (Huang et al., 2023) and plentiful rivers, hydroelectric power is a viable energy source for the region. generation.

Identifying optimal Green Energy Resources (GERs) requires evaluating various climatic, technical, accessibility, environmental, and social factors. This comprehensive approach ensures thorough assessment of potential sites. Multi-Criteria Decision-Making (MCDM) methods are instrumental in this process, offering a structured framework to balance conflicting criteria and determine the relative importance of each factor (Shao et al., 2020). These methods, which have evolved since the 1700s, are now integral across disciplines like mathematics, engineering, and economics. Common MCDM techniques include the Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for

Enrichment Evaluation (PROMETHEE), etc. Expert input is crucial in these evaluations to accurately weigh the significance of each criterion (Elkadeem et al., 2021).

Integrating identified green energy sites offers numerous benefits. Currently, power grid combines in Sarawak GERs with fossil fuel-based plants (Durin et al., 2022). Transitioning to a system solely powered by green energy is vital for sustainable development and achieving a zero-carbon footprint. This shift would reduce maintenance associated with combustion processes and eliminate risks tied to flammable materials. Moreover, utilizing inexhaustible resources like solar, wind, and hydro can lower operating costs and minimize environmental and health impacts due to reduced harmful emissions. Given the dispersed nature of GERs in Sarawak, designing optimal electrical power line routes is essential (Jong et al., 2022). This challenge parallels the Traveling Salesman Problem (TSP), which seeks the shortest path connecting multiple points (Pop et al., 2024). Both exact algorithms and approximate methods have been developed to address TSP, each with its own advantages and limitations (S. Wang et al., 2020). Comparing and validating these approaches is crucial when planning power line routes for GER integration.

Integrated Green Energy Systems (IGESs) require advanced monitoring, control, and automation to manage the variable nature of GERs and fluctuating energy demands (Deng & Lv, 2020). The Industrial Internet of Things (IIoT) facilitates real-time tracking of energy production and consumption, enabling optimized management strategies. Technologies like Supervisory Control and Data Acquisition (SCADA), combined with servers and cloud computing, enhance coordination between energy systems and demand, improving the reliability and resilience of IGESs (Albogamy et al., 2022). Developing simulation models that incorporate real-time data can provide insights into system behavior. Validating these