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A GIS-BASED FRAMEWORK FOR INDUSTRIAL FRESHWATER PRODUCTION AND SUSTAINABLE WATER RESOURCE MANAGEMENT USING SOLAR ENERGY TECHNOLOGIES

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Annotatsiya. Iqlim o‘zgarishi, aholi sonining ortishi va sanoat ehtiyojlarining ko‘payishi natijasida chuchuk suv tanqisligi dolzarb muammoga aylanmoqda. Ushbu tadqiqotda quyosh energiyasi texnologiyalaridan foydalangan holda sanoat miqyosida chuchuk suv ishlab chiqarish va suv resurslarini barqaror boshqarishni baholash uchun GIS asosidagi yondashuv taklif etilgan. Metodika hududiy tahlil, quyosh resurslarini baholash va barqarorlik ko‘rsatkichlarini o‘z ichiga oladi. Tadqiqot natijalari GIS va qayta tiklanuvchi energiya texnologiyalarini integratsiyalash suv xavfsizligini ta’minlashga xizmat qilishini ko‘rsatadi.

Kalit so‘zlar: quyosh energiyasi, chuchuk suv ishlab chiqarish, GIS, suv chuchuklashtirish, suv resurslarini boshqarish, barqarorlik.

Аннотация. Дефицит пресной воды становится одной из наиболее актуальных глобальных проблем вследствие изменения климата, роста населения и увеличения промышленного потребления воды. В работе предложен ГИС-ориентированный подход к оценке промышленного производства пресной воды и устойчивого управления водными ресурсами с использованием солнечных энергетических технологий. Методика включает пространственный анализ, оценку солнечного потенциала и показатели устойчивого развития. Результаты исследования подтверждают эффективность интеграции ГИС-технологий и возобновляемых источников энергии для повышения водной безопасности и устойчивого развития.

Ключевые слова: солнечная энергия, производство пресной воды, ГИС, опреснение воды, управление водными ресурсами, устойчивое развитие.

Abstract. Water scarcity has become a major global challenge due to climate change, population growth, and increasing industrial demand. This study proposes a GIS-based framework for industrial freshwater production and sustainable water resource management using solar energy technologies. The approach integrates spatial analysis, solar resource assessment, and sustainability indicators to identify suitable locations for solar-powered water desalination systems. The results demonstrate the potential of combining GIS and renewable energy technologies to improve water security and support sustainable development.

Keywords: Solar energy, freshwater production, GIS, desalination, water management, sustainability.

INTRODUCTION.

Freshwater scarcity has become one of the most critical global challenges due to climate change, population growth, and increasing industrial water demand. At the same time, the transition toward renewable energy technologies has accelerated worldwide as countries seek sustainable solutions to environmental and resource management problems. Solar energy technologies offer significant opportunities for producing freshwater while reducing dependence on conventional energy sources.

Despite the growing deployment of solar-powered desalination and water treatment systems, challenges remain in identifying suitable locations, optimizing resource utilization, and ensuring sustainable water management. Effective planning requires the integration of spatial information, solar resource availability, water demand characteristics, and environmental considerations.

Geographic Information Systems (GIS) provide powerful tools for spatial analysis and decision support in water resource management. By combining GIS-based assessment with solar energy technologies, it becomes possible to identify optimal sites for freshwater production and improve the efficiency of desalination systems.

Therefore, this study proposes a GIS-based framework for industrial freshwater production and sustainable water resource management using solar energy technologies. The proposed approach integrates spatial analysis, solar resource assessment, and sustainability indicators to support decision-making and enhance water security in water-stressed regions.

LITERATURE REVIEW.

The rapid expansion of renewable energy systems has generated a growing body of academic research focusing on governance mechanisms, digital transparency, and infrastructure monitoring technologies. Previous studies have explored various aspects of renewable energy transitions, including policy frameworks, institutional governance structures, digital transparency tools, and spatial monitoring systems. Understanding these research contributions is essential for identifying existing knowledge gaps and developing new analytical frameworks for renewable energy governance.

This section reviews the existing literature related to renewable energy governance, digital transparency in the energy sector, and GIS-based monitoring technologies for energy infrastructure. First, the literature on renewable energy governance and institutional frameworks is examined. Second, studies addressing digital transparency and open data systems in energy governance are reviewed. Finally, research focusing on GIS-based monitoring systems and spatial analysis for renewable energy infrastructure planning is discussed.

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2.1 Renewable Energy Governance

The transition toward renewable energy systems has become one of the central strategies for addressing global climate change and achieving sustainable development goals. Renewable energy technologies such as solar, wind, and hydropower play an essential role in reducing greenhouse gas emissions and improving environmental sustainability. Empirical studies show that increasing renewable energy adoption significantly contributes to lowering carbon emissions and promoting sustainable economic development (Hasan, 2023). However, the expansion of renewable energy infrastructure requires not only technological innovations but also effective governance frameworks to ensure successful implementation.

Renewable energy governance involves the institutional arrangements, regulatory policies, and stakeholder interactions that guide the development and management of energy systems. According to Geels (2020), energy transitions should be understood as socio-technical transformations that require coordinated interactions between technological innovations, policy frameworks, and social actors. In this context, governance mechanisms play a crucial role in shaping energy transitions by influencing investment decisions, regulatory structures, and policy coordination.

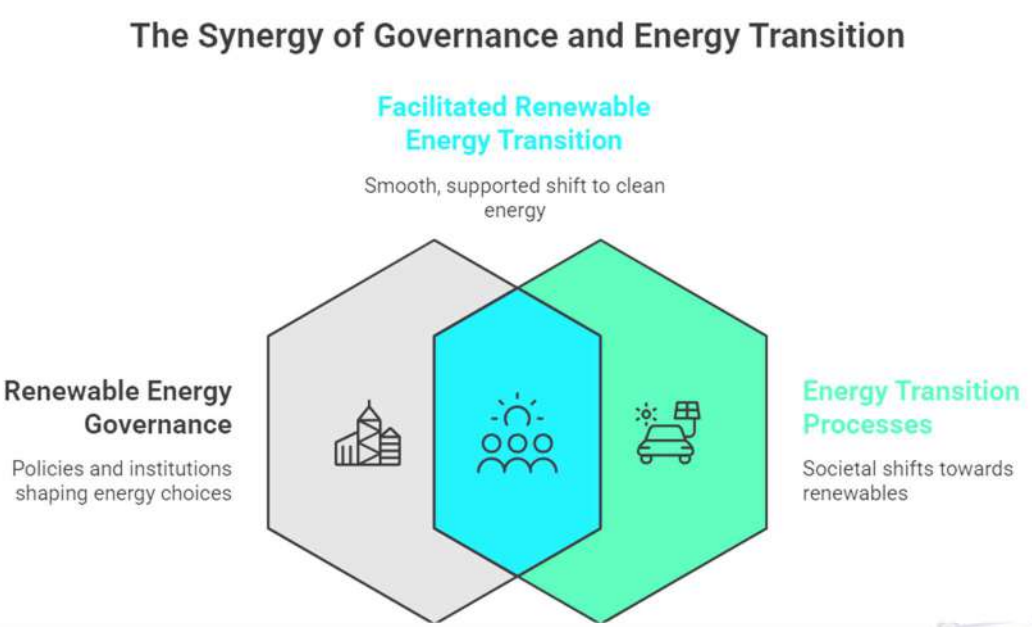


Figure 1. Conceptual framework of renewable energy governance and energy transition processes.

Source: Adapted from Geels (2020).

Several studies emphasize that institutional quality and policy effectiveness significantly influence the development of renewable energy systems. For example, Mahalik and Mallick (2021) demonstrate that strong institutional frameworks and governance quality positively affect renewable energy

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consumption and environmental sustainability. Similarly, Zhao et al. (2022) highlight that institutional quality and governance effectiveness are critical factors in supporting renewable energy development and achieving sustainable environmental outcomes. These findings indicate that governance structures play an essential role in enabling the successful implementation of renewable energy policies.

In addition, the governance of renewable energy systems often involves multiple stakeholders, including governments, private investors, local communities, and regulatory agencies. Effective governance mechanisms must therefore facilitate coordination among these actors to ensure efficient policy implementation and infrastructure development. Busch and McCormick (2022) emphasize that sustainability governance and local energy transitions require strong institutional collaboration and policy coordination to achieve long-term sustainability objectives. Similarly, Neij and Johansson (2021) argue that energy system transitions and climate-neutral development strategies depend heavily on effective governance frameworks and integrated policy approaches.

Recent studies also highlight the importance of governance principles in large-scale renewable energy projects. Söylemez (2024) notes that governance transparency, public participation, and accountability mechanisms are essential for increasing public acceptance of renewable energy megaprojects. Without transparent governance frameworks, renewable energy projects may face resistance from local communities and stakeholders. Furthermore, Dujany et al. (2024) argue that governance frameworks for energy transitions must address institutional dynamics, policy coherence, and stakeholder engagement in order to ensure sustainable energy transitions.

Overall, the literature suggests that renewable energy governance plays a crucial role in supporting energy transitions and sustainable development. Effective governance mechanisms can enhance policy coordination, improve institutional capacity, and increase stakeholder participation in renewable energy infrastructure development.

2.2 Digital Transparency in the Energy Sector

In recent years, digital technologies have emerged as important tools for improving governance transparency and accountability in the energy sector. Digital platforms, open data systems, and information technologies enable stakeholders to access information about energy infrastructure projects, monitor project development, and evaluate policy implementation more effectively. The increasing availability of digital technologies has created new opportunities for enhancing transparency in energy governance systems.

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Open data initiatives and digital transparency mechanisms play a significant role in strengthening public oversight and improving accountability in infrastructure development. Janssen et al. (2020) highlight that open data systems can improve transparency and enable better collaboration between governments, policymakers, and citizens. By providing access to information about public infrastructure projects, open data platforms can enhance public trust and support evidence-based decision-making processes.

Similarly, digital governance frameworks have become increasingly important in modern urban and energy systems. Meijer and Bolívar (2021) argue that digital governance and smart city technologies can significantly improve transparency, accountability, and citizen participation in public administration. These digital governance tools allow governments to share information about infrastructure development, environmental performance, and policy implementation with the public.

International organizations have also emphasized the importance of digital transparency in improving governance performance. According to the World Bank (2022), open data platforms and digital monitoring systems can significantly improve transparency in infrastructure projects by enabling real-time monitoring and public access to project information. These systems allow regulators and stakeholders to track project progress, identify potential risks, and evaluate the effectiveness of policy interventions.

Similarly, the United Nations Development Programme (UNDP, 2023) highlights that digital transparency mechanisms can enhance governance in the energy sector by increasing accountability and strengthening public participation. Digital monitoring systems allow policymakers and regulators to monitor infrastructure performance and ensure compliance with environmental and regulatory standards.

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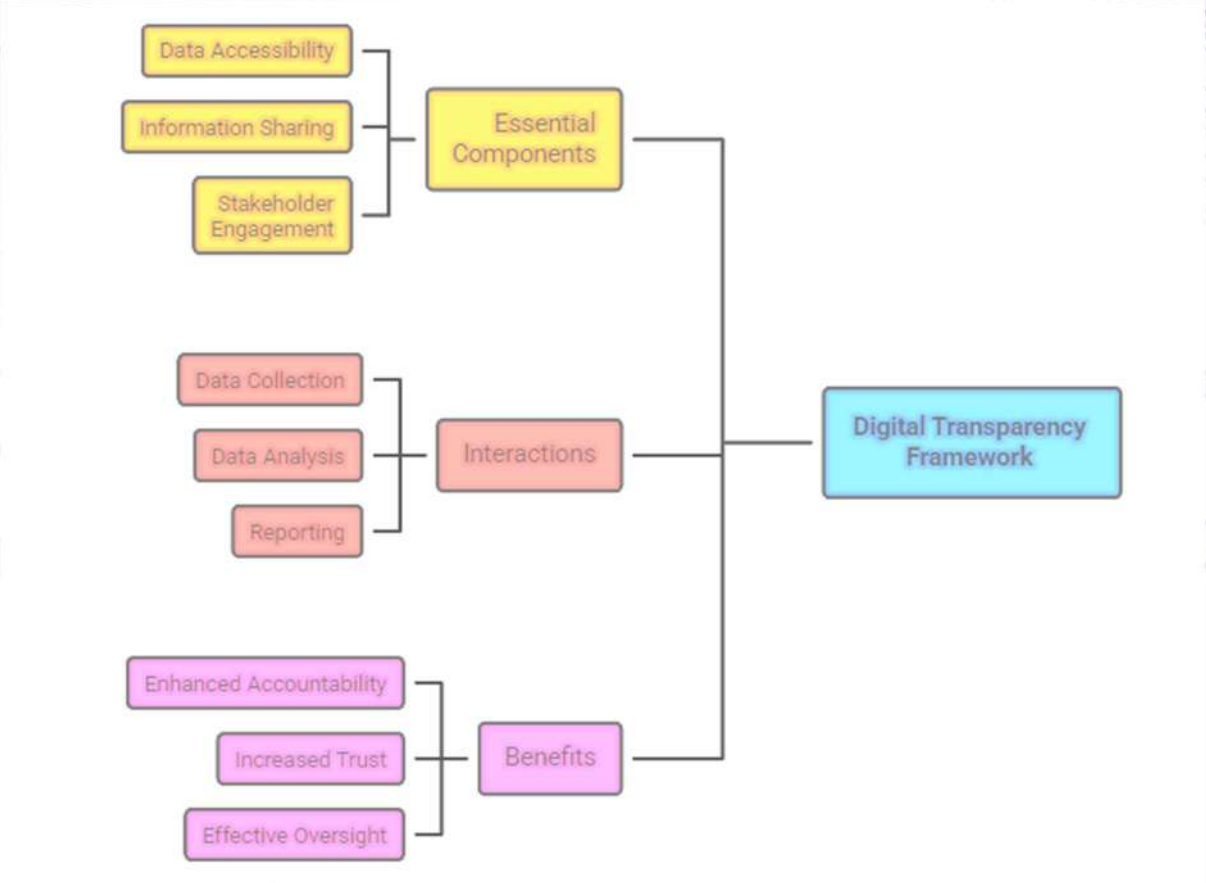


Figure 2. Digital transparency framework for energy infrastructure governance.

Source: Adapted from Janssen et al. (2020).

Overall, the literature indicates that digital transparency technologies play an important role in modern energy governance systems. By integrating digital platforms, open data systems, and monitoring technologies, governments can improve transparency and strengthen the management of renewable energy infrastructure.

2.3 GIS-Based Monitoring Systems for Renewable Energy Infrastructure

Geographic Information Systems (GIS) have become widely used tools for spatial analysis and monitoring of renewable energy infrastructure. GIS technologies enable researchers and policymakers to analyze spatial data related to energy resources, environmental conditions, and infrastructure networks. These technologies play an important role in energy planning, site selection, and infrastructure management.

GIS-based analysis has been widely applied in renewable energy resource assessment and infrastructure planning. For example, Wang et al. (2020) developed a GIS-based framework for assessing renewable energy resources and supporting spatial planning of energy systems. Their study demonstrates that GIS technologies can improve decision-making processes by enabling spatial analysis of renewable energy potential and infrastructure development.

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Similarly, Bódis et al. (2019) conducted a GIS-based assessment of solar photovoltaic energy potential, demonstrating that spatial analysis tools can help identify optimal locations for solar energy infrastructure. These technologies allow policymakers to evaluate renewable energy potential and plan infrastructure development more effectively.

Recent studies have also applied GIS technologies for monitoring renewable energy infrastructure and evaluating sustainability outcomes. Gwenzi et al. (2022) highlight that GIS-based modelling can support renewable energy infrastructure planning by integrating spatial data on environmental conditions, resource availability, and infrastructure networks. Such systems enable policymakers to monitor renewable energy infrastructure and assess environmental impacts more effectively.

GIS technologies are also widely used in solar energy system planning and infrastructure management. Charabi and Gastli (2021) demonstrate that GIS-based spatial analysis can improve solar energy planning by identifying suitable locations for solar power installations and evaluating environmental constraints.

Furthermore, recent research highlights the growing role of GIS technologies in renewable energy community planning and sustainable infrastructure development. Martinez-López et al. (2024) emphasize that GIS-driven planning models can support renewable energy communities by integrating spatial analysis with energy system modelling. These approaches enable policymakers and planners to design renewable energy infrastructure more efficiently and sustainably.

Despite the increasing use of GIS technologies in renewable energy infrastructure planning, existing research rarely integrates GIS monitoring systems with digital transparency frameworks. Most studies focus on spatial analysis and energy planning, while relatively few studies address transparency and governance aspects of renewable energy infrastructure monitoring.

Therefore, there is a need for integrated frameworks that combine GIS-based monitoring technologies with digital transparency mechanisms in order to improve governance transparency in renewable energy infrastructure systems.

LITERATURE GAP.

Although previous studies have examined renewable energy governance, digital transparency systems, and GIS-based monitoring technologies, limited research has integrated these approaches into a comprehensive analytical framework. In particular, there is a lack of quantitative models for evaluating transparency performance in renewable energy infrastructure projects. Therefore, this study proposes a digital transparency framework and introduces a

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Transparency Index model to evaluate governance transparency in renewable energy infrastructure systems

METHODOLOGY.

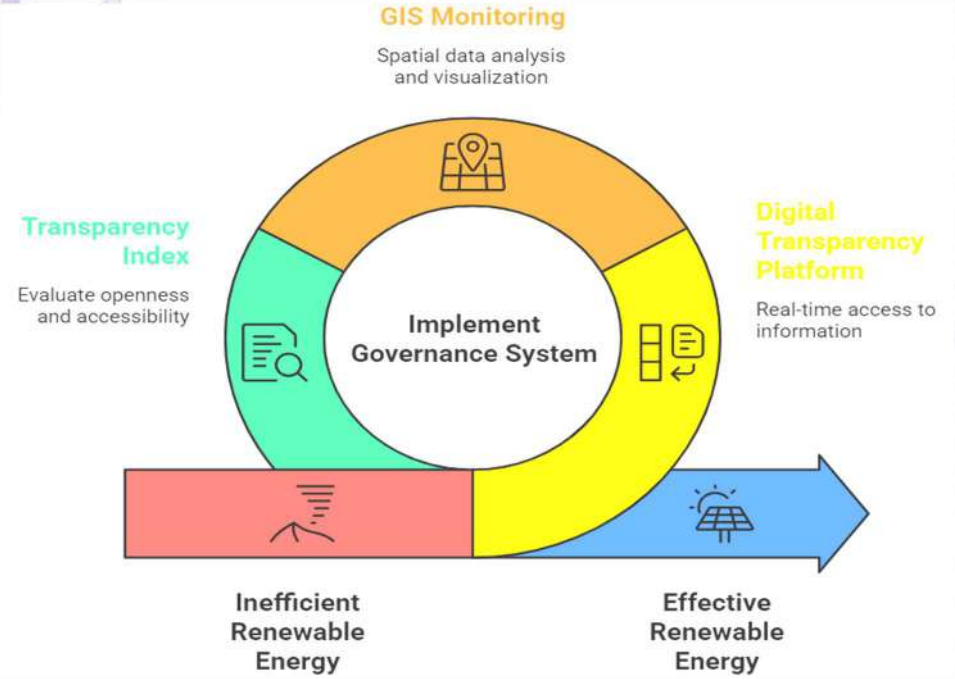


Figure 3. Conceptual framework of the digital transparency governance system for renewable energy infrastructure monitoring.

Source: Developed by the authors.

3.1 Research Framework

Figure 3 presents the proposed framework for enhancing governance transparency in renewable energy infrastructure systems. The framework consists of three interconnected components: GIS-based monitoring, digital transparency platforms, and the Transparency Index (TI). GIS technologies support spatial monitoring and infrastructure planning, while digital platforms improve information accessibility, accountability, and stakeholder engagement. The Transparency Index evaluates governance transparency through indicators related to information openness, monitoring accessibility, stakeholder participation, and institutional accountability. By integrating these components, the framework promotes more transparent, efficient, and accountable renewable energy governance systems.

3.2 Digital Transparency Platform Architecture

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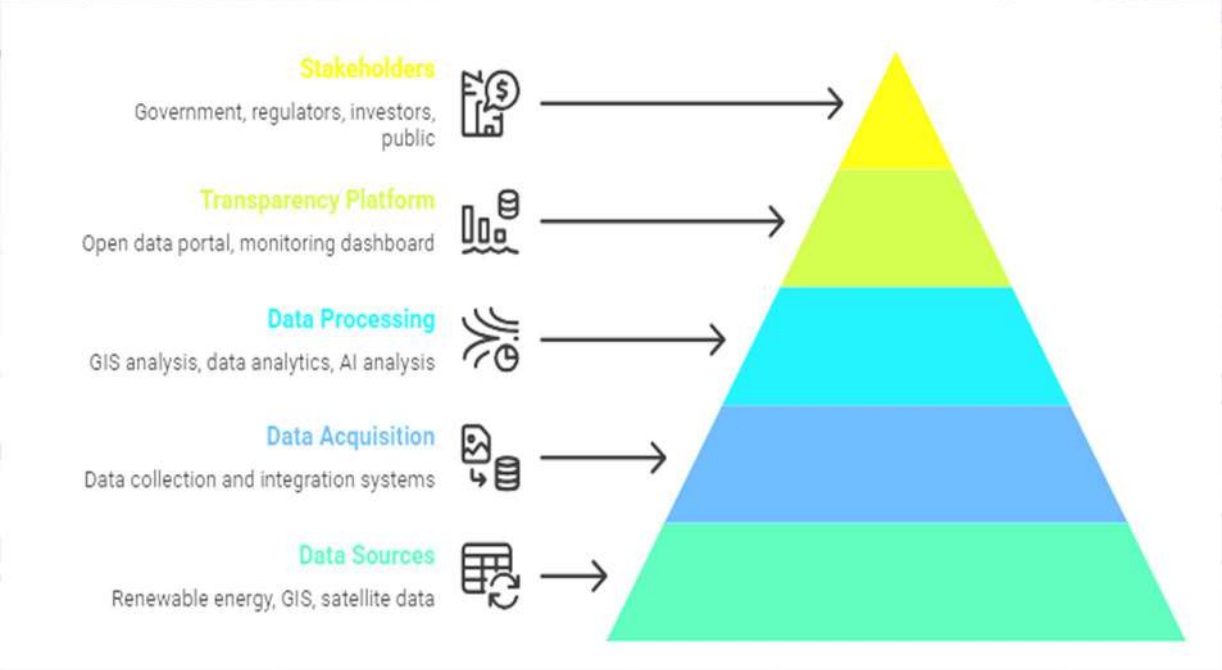


Figure 4. Architecture of the digital transparency platform for monitoring renewable energy infrastructure systems.

Source: Developed by the authors.

The proposed digital transparency platform is designed to improve transparency and accountability in renewable energy infrastructure governance. The platform integrates open data systems, monitoring tools, and digital technologies to provide real-time access to project information.

The platform consists of three main layers: **data acquisition**, **data processing and analysis**, and **transparency interface**. The data acquisition layer collects information from energy databases, GIS data, environmental monitoring systems, and institutional reports. The processing layer applies GIS and analytical tools to transform raw data into meaningful transparency and governance indicators. The transparency interface provides accessible information through digital dashboards and open data portals for governments, investors, regulators, and the public.

By integrating these components, the platform enhances information accessibility, stakeholder engagement, and evidence-based decision-making, contributing to more transparent and accountable renewable energy governance.

3.3 GIS-Based Monitoring System

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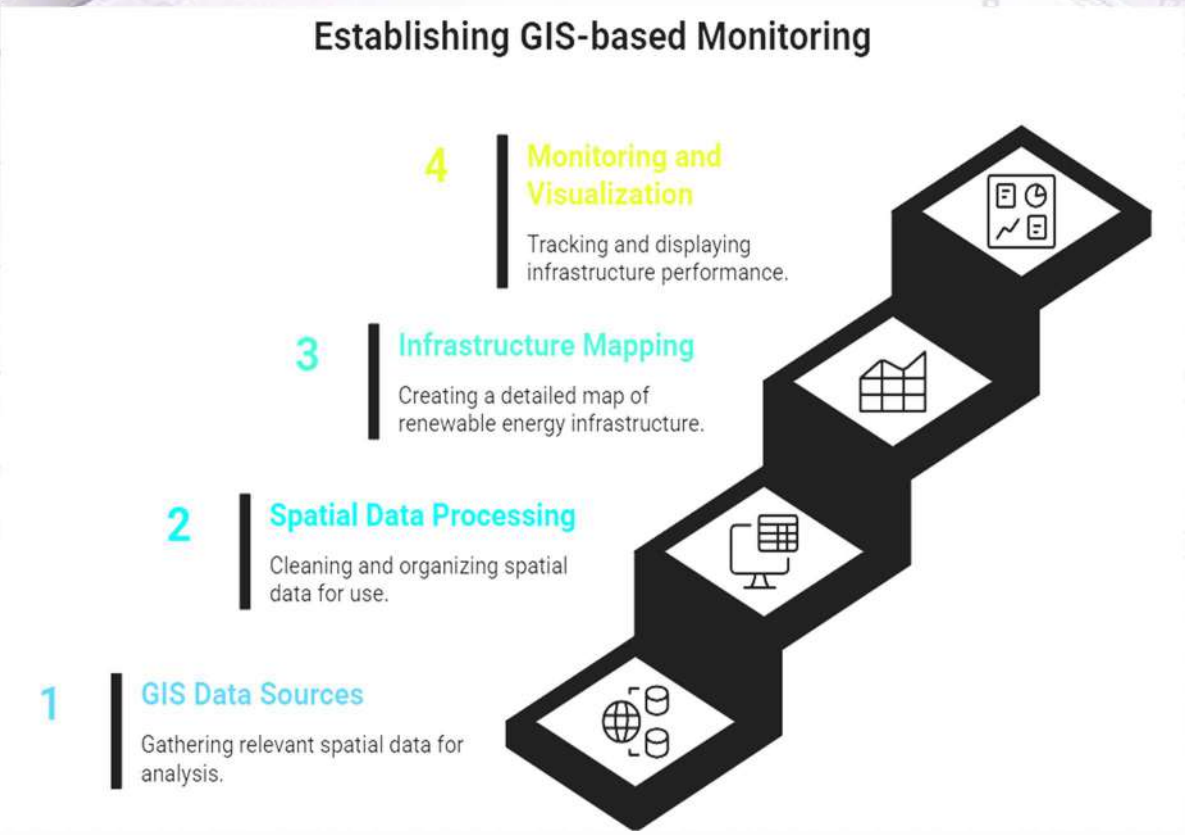


Figure 5. GIS-based monitoring framework for renewable energy infrastructure.

Figure 5 presents the workflow of the GIS-based monitoring system for renewable energy infrastructure management. The framework consists of four main stages: **GIS data sources, spatial data processing, infrastructure mapping, and monitoring and visualization**. Spatial data are collected from infrastructure databases, satellite imagery, GIS platforms, and environmental monitoring systems. The collected data are then processed and analyzed using GIS tools to ensure accuracy and consistency. Processed data are used to create spatial maps of renewable energy facilities, supporting infrastructure planning and assessment. Finally, GIS-based dashboards and visualization tools enable real-time monitoring, improve transparency, and support evidence-based decision-making in renewable energy management.

3.4 Data Sources and Data Collection

Reliable data sources are essential for monitoring renewable energy infrastructure and evaluating governance transparency. In this study, multiple data sources are integrated into the proposed digital transparency and GIS-based monitoring framework. These data sources provide spatial, environmental, and governance-related information required for infrastructure monitoring and transparency assessment.

The collected datasets include renewable energy infrastructure information, GIS spatial data, satellite imagery, and governance transparency indicators. These

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datasets enable spatial analysis, infrastructure mapping, and transparency evaluation within the proposed monitoring framework.

Table 1.

Renewable Energy Infrastructure Data

Data Type	Source	Description
Solar Power Plants	Energy databases	Location and capacity of solar installations
Wind Energy Facilities	Energy infrastructure reports	Information about wind farms
Renewable Energy Projects	Government datasets	Infrastructure development information

Table 2.

GIS and Spatial Data Sources

Data Type	Source	Description
Geographic Coordinates	GIS databases	Spatial location of infrastructure
Land Use Data	Environmental databases	Land classification and spatial planning
Satellite Imagery	Remote sensing systems	Environmental monitoring and spatial analysis

Table 3.

Transparency and Governance Indicators

Indicator	Description	Purpose
Data Accessibility	Availability of project data	Transparency evaluation
Monitoring Availability	Access to monitoring systems	Infrastructure tracking
Public Participation	Stakeholder engagement	Governance transparency
Institutional Accountability	Government reporting systems	Regulatory oversight

3.5 Transparency Index Model

To evaluate the level of governance transparency in renewable energy infrastructure systems, this study proposes a Transparency Index (TI) model. The proposed model integrates several indicators related to data accessibility, monitoring availability, public participation, and institutional accountability. These indicators reflect key aspects of transparency in renewable energy governance and enable quantitative evaluation of transparency performance.

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The transparency index combines multiple indicators into a single composite metric that represents the overall transparency level of renewable energy infrastructure systems. Each indicator contributes to the final transparency score according to its assigned weight, allowing a comprehensive evaluation of governance transparency.

The transparency index is calculated using the following equation:

$$TI = \omega_1 D + \omega_2 M + \omega_3 P + \omega_4 A \quad (1)$$

TI – Transparency Index

D – Data openness and accessibility

M – Monitoring system availability

P – Public participation

A – Institutional accountability

w_1–w_4 – weighting coefficients for each indicator

The weights assigned to each indicator reflect their relative importance in evaluating transparency performance within renewable energy governance systems. The proposed model allows policymakers and regulators to quantitatively assess transparency levels and identify areas where governance improvements are required.

RESULTS AND DISCUSSION.

This section presents the results obtained from the application of the proposed digital transparency framework and transparency index model for renewable energy infrastructure management. The developed model was applied to selected renewable energy cases in order to evaluate the level of governance transparency, monitoring availability, and data accessibility. The results demonstrate how the integration of digital transparency platforms, GIS-based monitoring, and stakeholder participation mechanisms can improve decision-making efficiency and accountability in renewable energy projects.

The transparency index calculated in this study allows the comparison of different renewable energy systems based on key governance indicators. The obtained results are discussed in terms of transparency performance, effectiveness of digital monitoring tools, and the potential advantages of the proposed platform for sustainable energy management.

4.1 Application of the Transparency Model

In order to verify the applicability of the proposed transparency index model, the model was applied to selected renewable energy infrastructure cases. The purpose of this application is to demonstrate how the developed transparency framework can be used to evaluate the level of governance transparency in renewable energy projects. Three types of renewable energy infrastructure were selected for the case study, including a solar power plant, a wind energy facility,

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and a small hydropower station. These systems represent typical renewable energy projects that require transparent monitoring, reporting, and public accessibility of operational data.

The transparency level of each project was evaluated using the transparency index proposed in Section 3.5, which includes four key indicators: data accessibility (D), monitoring availability (M), public participation (P), and institutional accountability (A). These indicators reflect the main governance principles required for sustainable energy management and digital transparency in modern energy systems. Previous studies have shown that open data availability, digital monitoring technologies, and stakeholder participation significantly improve transparency and decision-making efficiency in renewable energy governance (Janssen et al., 2020; Neij & Johansson, 2021; Gwenzi et al., 2022).

The values of the transparency indicators were determined based on conceptual evaluation and analysis of previously published studies related to renewable energy governance, digital monitoring systems, and sustainability assessment. Since the purpose of this research is to demonstrate the functionality of the proposed model, the indicator values were assigned using a normalized scale from 0 to 1 according to the level of transparency reported in the literature for different renewable energy technologies. Similar conceptual and index-based evaluation approaches are widely used in sustainability and energy policy research (Geels, 2020; Mahalik & Mallick, 2021; Söylemez, 2024).

Equal weighting coefficients were used for all indicators to ensure balanced evaluation of transparency performance. The transparency index was calculated using Equation (1), and the results for the selected renewable energy cases are presented in Table 4.

Table 4.

Transparency index indicators for selected renewable energy projects

Project	Data Accessibility (D)	Monitoring Availability (M)	Public Participation (P)	Accountability (A)	Transparency Index (TI)
Solar Power Plant	0.80	0.90	0.70	0.80	0.80
Wind Energy Facility	0.60	0.70	0.50	0.60	0.60

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Small Hydropower Plant	0.70	0.60	0.60	0.70	0.65

The results show that the solar power plant demonstrates the highest transparency level due to the implementation of digital monitoring systems and higher accessibility of operational data. The wind energy facility shows a lower transparency level because of limited public participation and reduced availability of monitoring information. The hydropower plant demonstrates a moderate transparency level, reflecting partial implementation of digital reporting and monitoring technologies.

The obtained results confirm that the proposed transparency index model can be effectively used to evaluate governance transparency in renewable energy infrastructure. The integration of digital transparency platforms and GIS-based monitoring systems can significantly improve information accessibility, support public control, and increase accountability in renewable energy project management.

4.2 Evaluation of Renewable Energy Governance Transparency

The results obtained from the transparency index calculation allow a comparative evaluation of governance transparency in different renewable energy infrastructure systems. The calculated values show that the level of transparency is strongly influenced by the availability of digital monitoring technologies, accessibility of operational data, stakeholder participation, and institutional accountability mechanisms. These factors are essential for ensuring effective management, public control, and sustainable development of renewable energy projects.

The analysis of the transparency index values indicates that renewable energy systems equipped with digital monitoring platforms and open data access demonstrate higher transparency levels. In contrast, projects with limited monitoring capabilities and restricted public access to information show lower transparency performance. This confirms that the integration of digital transparency platforms and GIS-based monitoring tools plays an important role in improving governance quality and decision-making efficiency in renewable energy infrastructure.

To illustrate the difference in transparency levels between the selected renewable energy projects, the calculated transparency index values are presented graphically in Figure 6.

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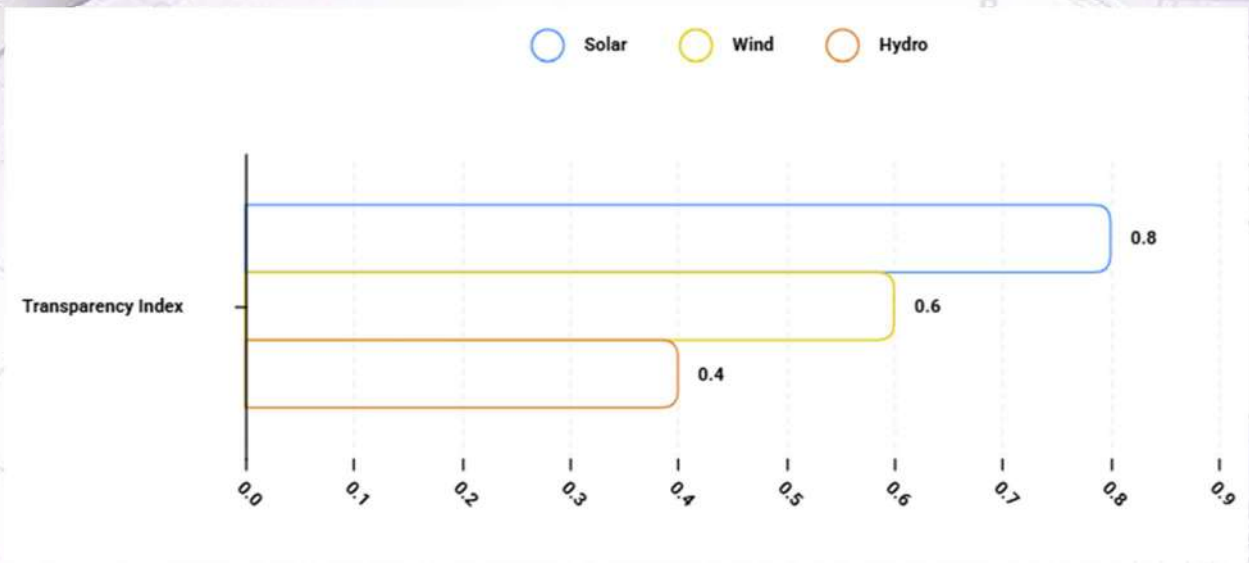


Figure 6: Transparency index comparison for selected renewable energy projects

Figure 6 shows the transparency performance of the selected renewable energy systems. The solar power plant achieved the highest Transparency Index value, followed by the hydropower plant, while the wind energy facility demonstrated the lowest transparency level. These results indicate that digital monitoring tools and open data platforms contribute significantly to improving governance transparency.

The analysis reveals that data accessibility and monitoring availability have the greatest impact on transparency performance. Projects equipped with real-time monitoring systems and digital reporting platforms provide better access to information, enhancing accountability and decision-making. Stakeholder participation and institutional accountability also play important roles in improving governance quality.

The obtained results are consistent with previous studies, which emphasize that digital transparency mechanisms, open data platforms, and GIS-based monitoring systems strengthen public trust, improve accountability, and support sustainable renewable energy management.

4.3 Advantages of the Proposed Transparency Framework

The proposed transparency framework provides a systematic approach for improving governance transparency in renewable energy infrastructure through the integration of digital monitoring technologies, GIS-based analysis, and transparency indicators. The framework enables continuous project monitoring, efficient information management, and evidence-based decision-making.

A key advantage of the framework is the Transparency Index, which combines multiple transparency indicators into a single metric, allowing quantitative evaluation and comparison of renewable energy projects. The use of

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GIS technologies and digital transparency platforms further supports real-time monitoring, data visualization, and improved planning and management processes.

In addition, the framework promotes stakeholder participation by providing open access to project information, thereby increasing accountability and public trust. Due to its flexibility, the framework can be applied to various renewable energy systems, including solar, wind, and hydropower projects, making it a useful tool for sustainable energy governance.

5. CONCLUSION.

This study proposed a digital transparency framework for improving governance and monitoring efficiency in renewable energy infrastructure. The developed approach integrates transparency indicators, GIS-based monitoring systems, and digital data platforms to provide a unified method for evaluating the openness and accountability of renewable energy projects. The proposed transparency index allows quantitative assessment of governance transparency based on data accessibility, monitoring availability, public participation, and institutional accountability.

The application of the model to selected renewable energy cases demonstrated that the use of digital monitoring technologies significantly increases transparency and improves decision-making efficiency. The results showed that renewable energy projects equipped with real-time monitoring systems and open data platforms have higher transparency levels compared to projects with limited access to operational information. The graphical and numerical analysis confirmed that the proposed index can be used as a practical tool for evaluating governance performance in different renewable energy systems.

The integration of GIS technologies and digital transparency platforms provides additional advantages for infrastructure management. Spatial monitoring allows better visualization of renewable energy projects and supports more effective planning and control processes. The proposed framework also improves stakeholder participation by providing open access to information, which increases public trust and supports sustainable development of the energy sector.

The results obtained in this research confirm that the implementation of digital transparency tools is an important factor for successful renewable energy governance. The proposed model can be applied to different types of renewable energy systems and can be adapted for use in various countries and regulatory conditions. Future research may focus on applying the transparency framework to real large-scale energy projects and integrating artificial intelligence methods for automated monitoring and decision support.

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