



ARTICLE

The Development of Very Low Frequency Electromagnetic (VLF-EM) in Determining Soil Zones for Renewable Energy Infrastructure Optimization

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Received: 13 February 2026; Accepted: 27 May 2026; Published: 12 July 2026

ABSTRACT: The global energy transition toward net-zero emissions requires the massive development of renewable energy infrastructure. However, the efficiency and safety of installations such as wind turbines, solar panels, and energy storage systems are highly dependent on subsurface physical characteristics. Neglecting geological structures such as active faults or corrosive zones, risks structural failure and electrical system malfunctions. This research proposes the use of the Very Low Frequency Electromagnetic (VLF-EM) method as a fast and non-destructive geophysical screening tool. This method utilizes low-frequency signals to map variations in subsurface electrical conductivity. Furthermore, the data were processed using the Karous-Hjelt filter to identify fault structures and apparent current densities. Next, 2D inversion modeling was performed to visualize depth cross-sections and determine soil layer stability. The mapping results were classified into three risk zones that correlate directly with future energy needs. The yellow zone (stable) is a priority for heavy structure development (turbines/panels). The orange zone (transition) is an area for transmission lines and electric mobility. Meanwhile, the blue zone (conductive) represents areas to be avoided for heavy loads, but can be optimized as grounding points to protect the smart grid from lightning strikes. The targets and impacts of this research are cost efficiency, infrastructure safety, and sustainability. Based on the Karous-Hjelt filtering and 2D inversion images, area 4 is highly conductive, as indicated by the predominance of blue tones in this zone. Meanwhile, area 3 is the most resistive, marked by a predominance of yellow and orange. In terms of cost efficiency, this approach reduces initial geotechnical survey costs through electromagnetic screening methods. For infrastructure safety, it minimizes the risk of damage to sensitive electronic devices in electric vehicles and energy storage systems through grounding system optimization. Regarding sustainability, this provides a roadmap for energy developers to select the most geophysically stable and safe locations in Indonesia. This research demonstrates that the synergy between electromagnetic waves and energy technology is the key to creating an energy ecosystem that is not only clean but also safe for subsurface structures.

KEYWORDS: Very low frequency electromagnetic; soil zones; resistivity; energy

1 Introduction

The relationship between electromagnetic waves and energy technology in this project can be summarized into three critical stages. First, electromagnetic waves for the earth emits or reflects physical signals such as magnetic anomalies, thermal radiation, and electrical resistivity [1]. Second, energy technology for the use of sensors to capture these analog signals, convert them into digital data, then present them in the form of images such as tomography or spectrogram images [2]. Third, image processing for using algorithms to clean up noise, sharpen contrast, and perform automatic segmentation on images from electromagnetic wave surveys [3].

The Very Low Frequency Electromagnetic (VLF-EM) method is an electromagnetic technique that utilizes low-frequency radio signals (15–30 kHz) from global submarine navigation military communications [4]. In the context of renewable energy, the efficiency of infrastructure development heavily depends on subsurface conditions [5]. VLF-EM offers a quick and non-destructive solution for mapping conductive zones such as groundwater or fault zones that are crucial for the stability of wind turbine foundations [6], underground cable placement for solar panels [7], and even early identification of shallow geothermal manifestations [8].

Basically, VLF-EM utilizes a primary electric current that is introduced into the ground and generates a secondary current commonly known as the Eddy Current [9]. The VLF-EM method can be used to penetrate below the ground surface. The VLF-EM waves in the atmosphere can propagate through the earth-ionosphere waveguide [10]. But, in practice, the propagation of this signal often encounters interference [11]. Noise that is also detected in the data recording must be eliminated to obtain optimal results [12]. Research on hydrogeological has been practiced for identification of groundwater potential in Nigeria. However, it is still not clearly visible which zones are resistive and which zones are conductive [13]. In addition, research on VLF-EM has also been conducted as a tool for fault investigation in Türkiye [14]. But, it has not yet been able to fully map the basis of the argument screening to avoid the risk of tectonic disaster. The mapping areas based on resistivity values can help identify which areas are at high risk of landslides and which areas are safe. This serves as preliminary information for construction, agriculture, and projects utilizing renewable energy.

Amidst the growing challenges of climate change and rapid urbanization [15], the integration of advanced technology is key to building a sustainable future [16,17]. This research explores a broad spectrum of innovations, ranging from disaster risk management at the macro level to the development of smart materials at the micro level [18]. The main focus is on the use of geospatial approaches, energy system optimization, and renewable energy harvesting [5,19,20].

The global transition towards sustainable energy systems has driven innovations that harness ambient energy from the surrounding environment to generate useful electrical power [21]. This is explore the crucial role of electromagnetic fields [22], electroactive polymers [23], and triboelectric energy harvesters [24] in addressing the challenges of energy efficiency and autonomous environmental monitoring. The use of electromagnetic fields in thermal processes, such as optimizing water freezing [25] and saving energy in industrial processes [26]. This innovation offers a new, more eco-friendly economic route [27] in the management of conventional energy resources [28]. On magnetic levitation-based energy harvesting, exploration of innovative mechanical architecture that utilizes the principle of levitation to minimize friction. This technology enables the conversion of environmental vibration energy into electricity with high efficiency, which has great potential to supply power to infrastructure monitoring sensors without relying on conventional batteries [29]. In Load Frequency Control (LFC) as the penetration of fluctuating renewable energy sources (such as wind and solar) into the power grid increases, maintaining the balance between supply and demand becomes more complex. This review maps the latest trends in LFC strategies to ensure the stability of modern power systems from frequency disturbances [30].

This study will discuss how effective the Very Low Frequency Electromagnetic (VLF-EM) method is in identifying fault structures or conductivity anomalies that can disrupt the stability of renewable energy infrastructure, as well as the relationship between subsurface conductivity values obtained from VLF-EM measurements and the optimization of grounding systems in renewable energy installations that are vulnerable to lightning strikes. In standard Very Low Frequency Electromagnetic (VLF-EM) methods, field data recordings are typically processed directly to determine the distribution of the area based on resistivity

values. In this study, noise in the raw data from the VLF-EM instrument was first removed using Karous-Hjelt filtering. Then, data processing was performed using inversion to determine the distribution of the area based on the resistivity values at the resulting scale and the depth of the material.

The focus of integration between electromagnetic methods and renewable energy are geothermal, wind and solar energy, as well as smart grids. In geothermal energy, this study identifies shallow hydrothermal alteration zones and controls reservoir boundaries through differences in rock resistivity values. In wind and solar energy, this study detects the presence of groundwater and weak geological structures before constructing heavy foundations such as turbines or panel racks. In smart grids, this study determines locations with low impedance for grounding systems to protect sensitive electronic devices from current surges.

The novelty of this research lies in the integration of traditional geophysical methods with the specific needs of modern renewable energy infrastructure. Specific Applications for Energy Infrastructure Optimization. Unlike general geophysical surveys, this study specifically adapts the VLF-EM (Very Low Frequency Electromagnetic) method to determine optimal locations for three types of renewable energy infrastructure such as wind turbines/solar panels (heavy loads), transmission lines, and grounding systems. Then, conductivity based risk zone classification introduces a zone classification system (Yellow, Orange, Blue) that directly links soil resistivity values to the structural stability and electrical safety of smart grid systems. Finally, efficiency of non-destructive methodology, the use of VLF-EM as a fast screening tool to detect active fault structures and soil corrosivity without damaging the surface, which is crucial for the early planning phase of clean energy projects.

2 Methods

This research was divided into four main processes:

2.1 Acquisition

The field data acquisition process used a VLF-EM instrument. Installation of very low frequency electromagnetic sensors. Data acquisition was performed at 1 m intervals along each line in the study area. Next, the raw signals were converted into a 2D image format.

2.2 Pre-Processing

Interference signals or noise recorded by the VLF-EM instrument were removed using Karous Hjelt filtering. The filtered result was a two dimensional image with color variations. The blue areas represented conductive zones. The yellow areas represented resistive zones.

2.3 Processing

The noise filtered signal was processed using inversion to determine both qualitative and quantitative characteristics. The qualitative characteristics were indicated by color differences, while the quantitative characteristics were indicated by the resistivity values shown on the scale.

2.4 Interpretation

The data interpretation was performed by analyzing the processed data. This provided an overview of areas that were more conductive or more resistive. In addition, the resistivity values and the depth of the material can be determined based on the scale shown in the inversion results.

2.5 Validation of Results

a. Use of Mathematical Standards for Internal Validation

Validation is performed internally through rigorous data processing procedures. The use of the Karous-Hjelt filter and 2D inversion are standard methods in geophysics that cross-validate each other (cross-checking between apparent current density and resistivity values). Additionally, skin depth calculations are used to mathematically validate that the mapped depths align with the physical parameters of the 19 kHz frequency at that location.

b. Validation Based on Soil Physical Parameters

The document includes references to soil electrical conductivity values (as in reference [26] in the file). The author correlates the VLF-EM mapping results with the physical characteristics of materials generally known in geotechnical literature:

- Conductive Zone (Blue): Identified as an area with the presence of groundwater or fractures, which is physically validated as an ideal location for grounding systems.
- Resistive Zone (Yellow): Identified as bedrock or hard soil, physically validated as a stable area for heavy infrastructure loads.

c. Scientific Validation through Data Processing

- Noise Filtering: Initial validation was performed by cleaning the raw data using the Karous-Hjelt filter to ensure that the analyzed signals were free from interference before interpretation.
- 2D Inversion Modeling: The data was further validated through two-dimensional inversion modeling to convert electromagnetic signals into visual representations of soil depth cross-sections. This allows for the determination of soil characteristics both qualitatively (through color differences) and quantitatively (based on resistivity values on the inversion output scale).
- Skin Depth Calculation: This study employs mathematical validation using the wave penetration formula $\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \approx 504 \sqrt{\frac{\rho}{f}}$ to ensure the measured material depth aligns with the natural frequency in the data acquisition area (19 kHz).

d. Ground Truthing and Field Interpretation

- Identification of Geological Structures: The capability of the VLF-EM method was validated by identifying fault structures and apparent current density to determine the stability of soil layers.
- Resistivity Value Correlation: Mapping results are correlated with the physical parameters of rocks and soil in the field. For example, conductive zones (blue) are validated as areas with low impedance suitable for grounding systems, while resistive zones (yellow/orange) are validated as stable materials for heavy foundations.
- Risk Zone Classification: On-site verification is conducted by grouping areas into three risk zones (Yellow, Orange, Blue) directly related to future energy infrastructure needs.

3 Results

The signal capture still containing noise (Figs. 1–6). The red line is imaginer (quadrature). The blue line is real (inphase). The noise must be eliminated or minimized. This study supports several key claims regarding the use of the VLF-EM method for renewable energy infrastructure. Yellow zone (stable) is claimed to be a priority for the construction of heavy structures such as wind turbines and solar panels. Orange zone (transition) is claimed to be suitable for transmission lines and electric mobility. Blue zone (conductive) is should be avoided for heavy loads but optimized as grounding points to protect the smart grid from lightning strikes. This VLF-EM method serves as a screening tool that has the potential to improve the cost efficiency of

follow-up surveys and provide an additional layer of information for infrastructure safety risk management, rather than as standalone, definitive proof of effectiveness of initial geotechnical surveys and minimize the risk of damage to sensitive electronic devices through an optimized grounding system. Researchers have demonstrated that the synergy between electromagnetic waves and energy technology is key to creating a clean and safe energy ecosystem for subsurface structures. These mapping results are claimed to provide a roadmap for energy developers in selecting the most geophysically stable locations in Indonesia.

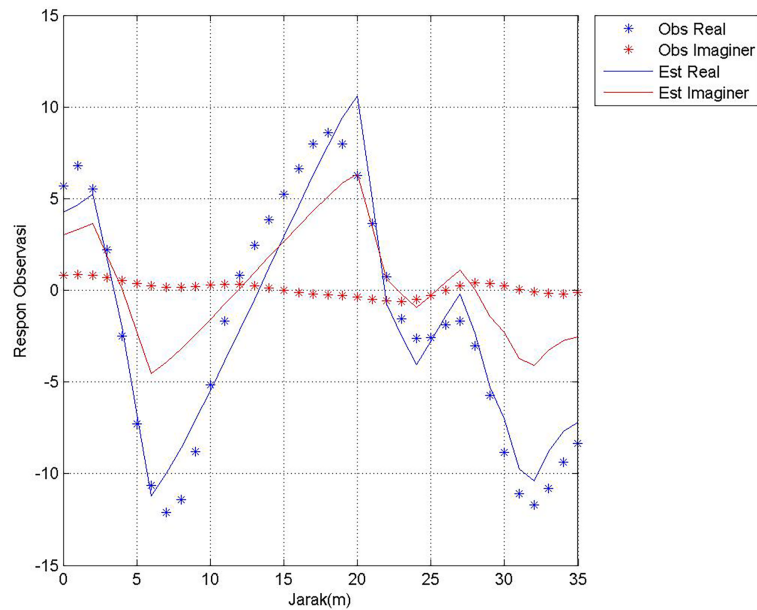


Figure 1: Signal capture graph still containing noise in area 1.

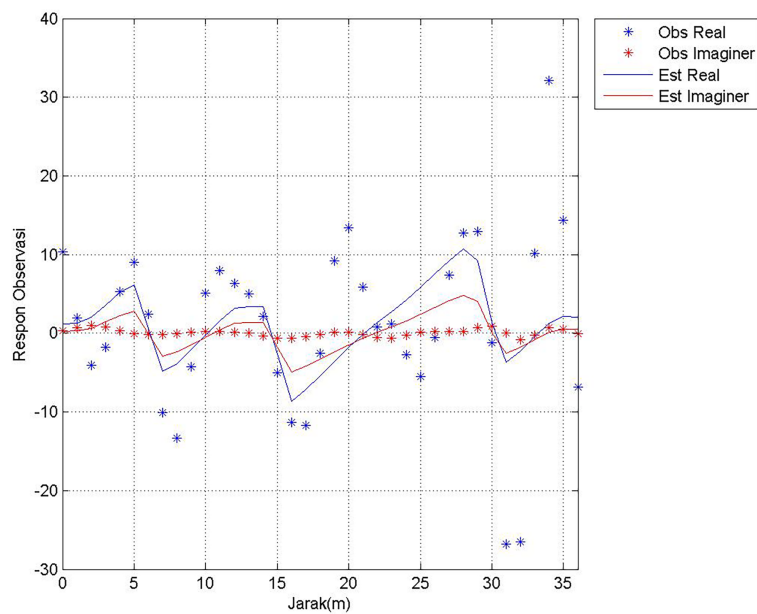


Figure 2: Signal capture graph still containing noise in area 2.

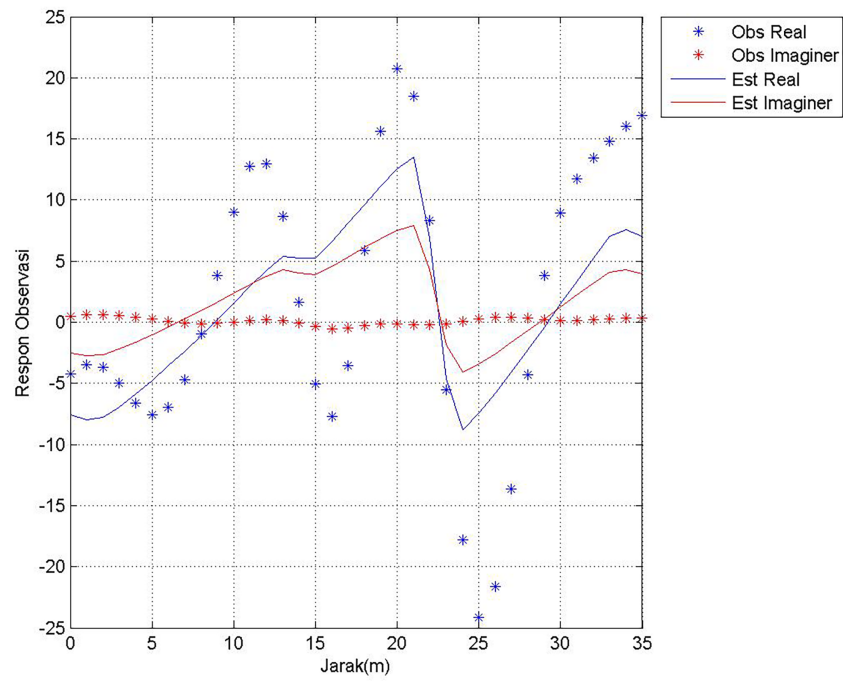


Figure 3: Signal capture graph still containing noise in area 3.

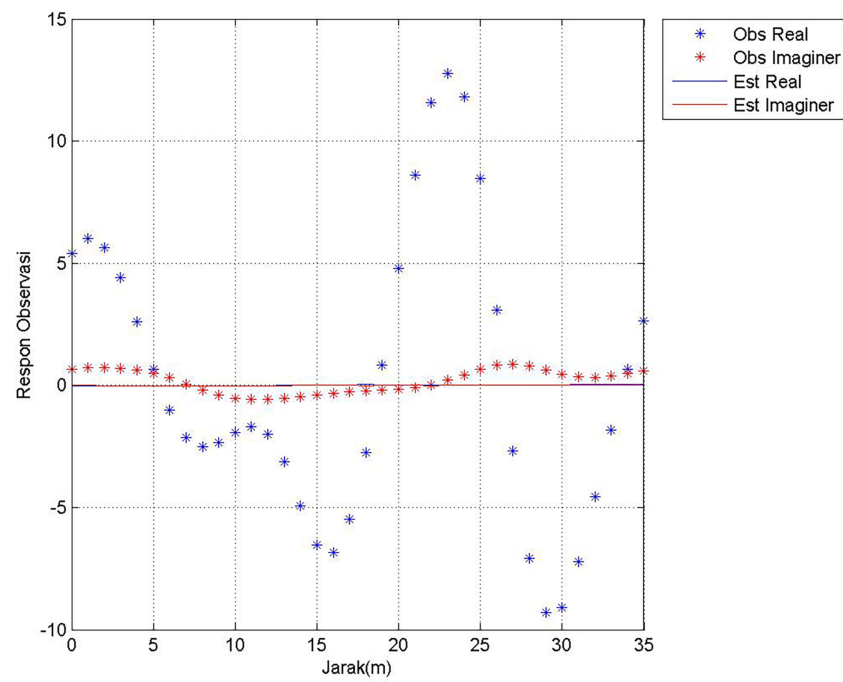


Figure 4: Signal capture graph still containing noise in area 4.

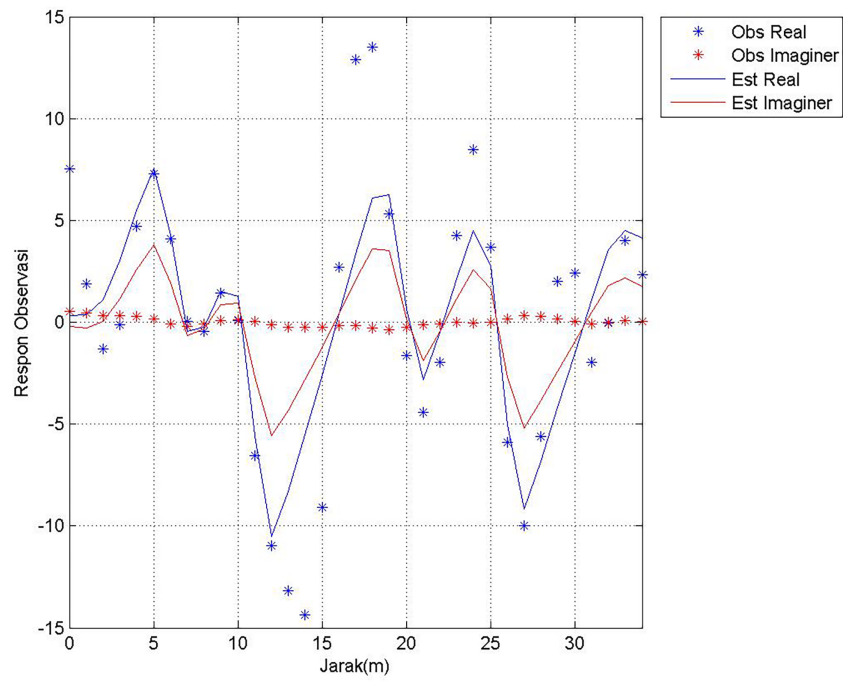


Figure 5: Signal capture graph still containing noise in area 5.

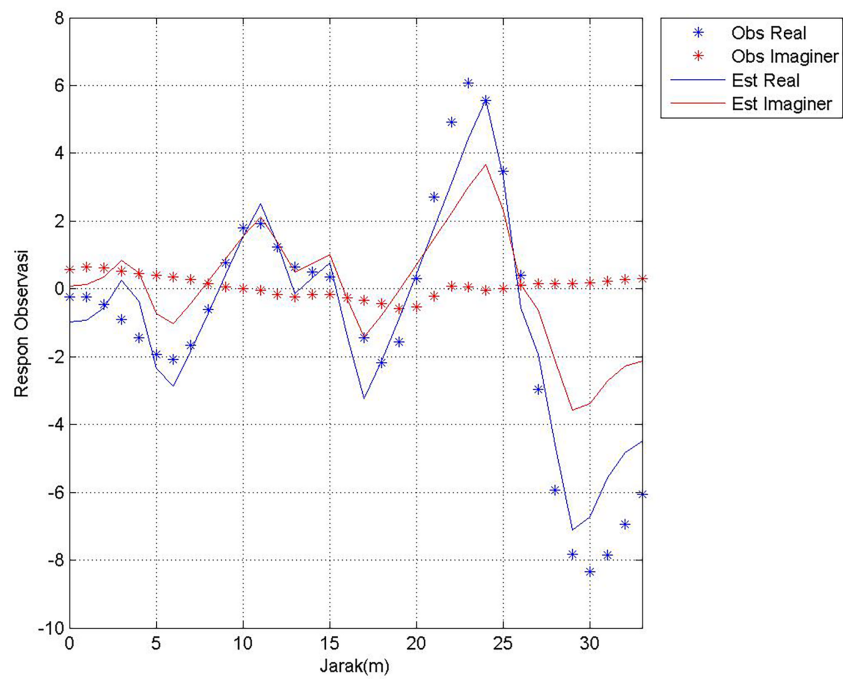


Figure 6: Signal capture graph still containing noise in area 6.

4 Discussion

The Karous Hjelt Filtering can be used to eliminate noise. This filter contains blue, yellow, and orange colors. Blue indicates that the area is conductive at a certain depth. Yellow indicates that the area is resistive. Orange indicates the resistivity value based on the scale.

The 2D inversion image can be used to determine of physical parameters of rocks and soil. As a Karous Hjelt Filtering, there are blue, yellow, orange, and the other color based on the scale to determine the resistivity value (Figs. 7–18).

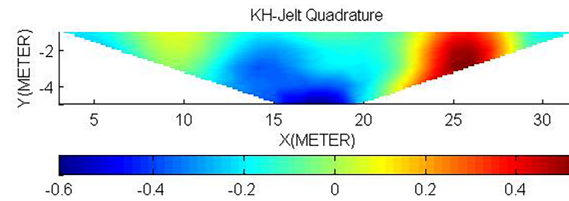


Figure 7: Karous Hjelt filtering for field noise reduction in area 1.

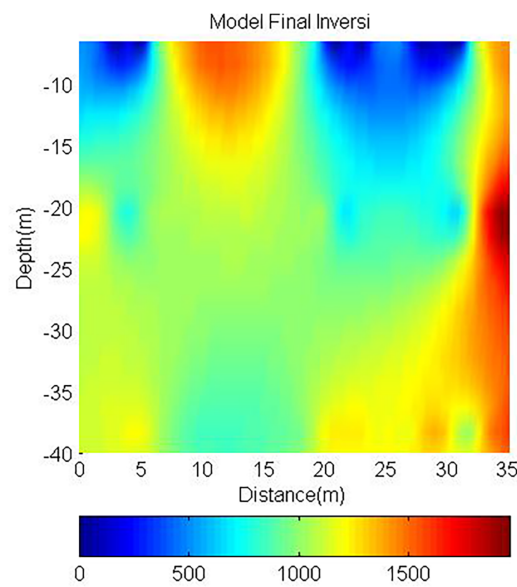


Figure 8: 2D Image to determine soil zones in area 1.

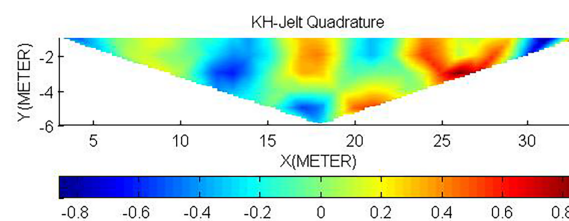


Figure 9: Karous Hjelt filtering for field noise reduction in area 2.

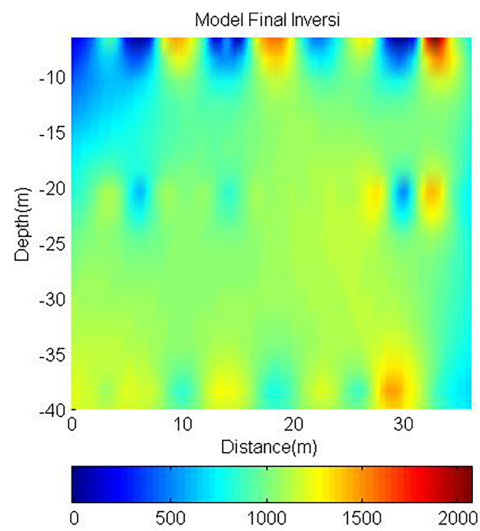


Figure 10: 2D Image to determine soil zones in area 2.

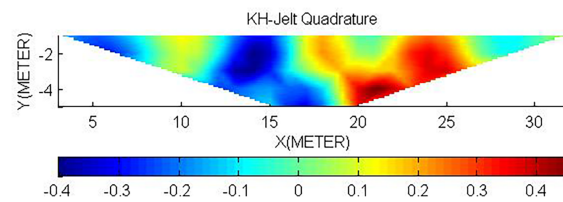


Figure 11: Karous Hjelt filtering for field noise reduction in area 3.

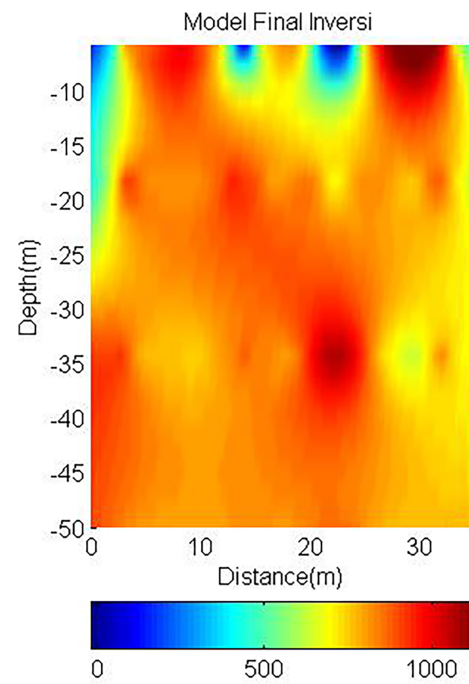


Figure 12: 2D Image to determine soil zones in area 3.

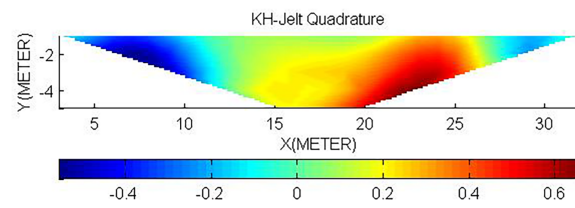


Figure 13: Karous Hjelt filtering for field noise reduction in area 4.

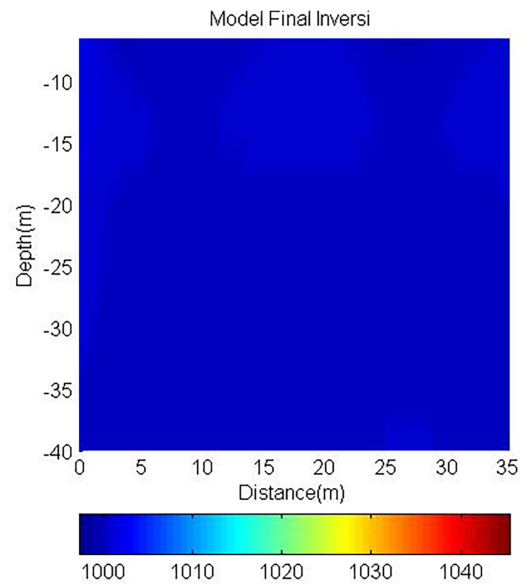


Figure 14: 2D Image to determine soil zones in area 4.

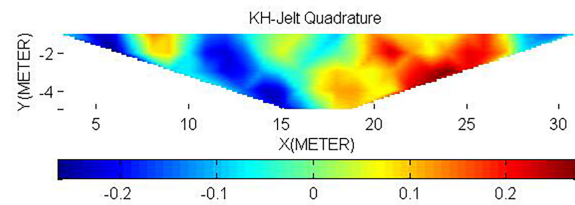


Figure 15: Karous Hjelt filtering for field noise reduction in area 5.

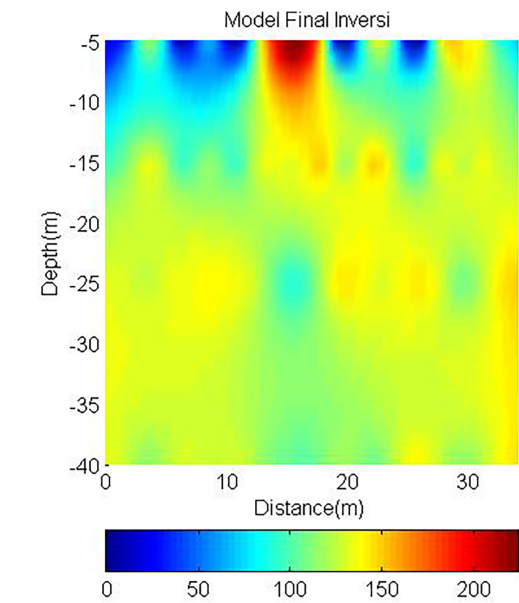


Figure 16: 2D Image to determine soil zones in area 5.

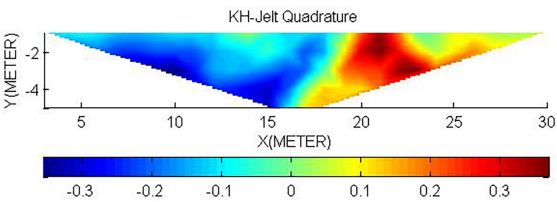


Figure 17: Karous Hjelt filtering for field noise reduction in area 6.

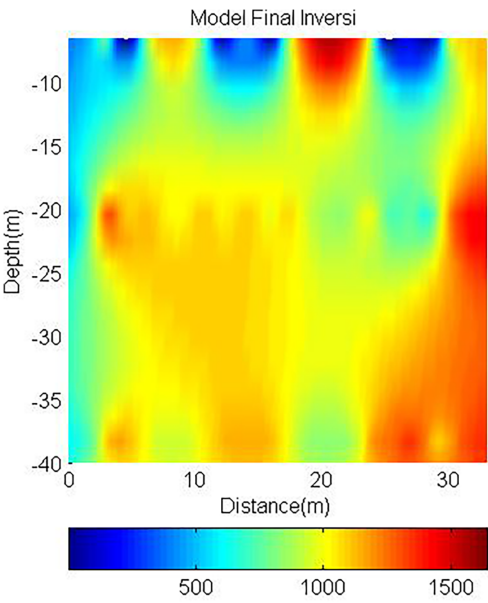


Figure 18: 2D Image to determine soil zones in area 6.

When there is a conductive medium beneath the surface, the magnetic field component of the primary electromagnetic wave induces a current in the medium (Eddy current). This current creates a new electromagnetic field known as the secondary electromagnetic field. This magnetic field consists of a component that is in phase with the primary magnetic field (inphase) and a component that is out of phase (quadrature). The magnitude of the secondary electromagnetic field actually depends on the type of conductivity of the object beneath the surface. Meanwhile, the depth of the material that can be measured using this VLF-EM device is influenced by the natural frequency in the data recording area. In this study, the environmental frequency was 19 kHz. The wave penetration depth in the electromagnetic method is formulated as $\delta = \sqrt{\frac{2}{\omega\mu\sigma}} \approx 504\sqrt{\frac{\rho}{f}}$. The implementation of this equation is shown in [Table 1](#).

Table 1: The variation of skin depth with wave frequency in a homogeneous medium.

f (Hz)	Skin Depth (m)			
	Resistivity (Ωm)			
	0.01	1	10^2	10^4
0.01	500	5000	5×10^4	5×10^5
10	16	160	1600	16,000
10^3	1.6	16	160	1600
10^4	0.5	5	50	500
10^5	0.16	1.6	16	160

4.1 Area 1

In area 1, the depth is 40 m ([Fig. 8](#)). A blue color indicates conductive material at depths of up to 15 m. Meanwhile, resistive material, shown in orange, is also visible at depths of up to 15 m. Additionally, there is resistive material with higher resistivity at a distance of 30–35 m and depths of up to 40 m.

4.2 Area 2

In area 2, there are several points of conductive material (blue zones) at depths of up to 10 m. In addition, resistive material is also present at several points at depths of less than 10 m. There are resistive zones at depths of 20 and 40 m ([Fig. 10](#)).

4.3 Area 3

In area 3 is dominated by resistive material. A resistive zone is visible at depths of up to 50 m ([Fig. 12](#)). The resistive material extends over a distance of more than 30 m.

4.4 Area 4

In area 4 is dominated by conductive material. This is in stark contrast to area 3. The conductive zone extends to a depth of 40 m and a distance of up to 35 m ([Fig. 14](#)).

4.5 Area 5

In area 5, conductive material is present at several points to a depth of up to 10 m. There is one point with a resistive zone extending to a depth of 15 m at a distance of 10–20 m. Additionally, this area is dominated by resistive material at depths ranging from 15 to 40 m ([Fig. 16](#)).

4.6 Area 6

In area 6, there are three points in a conductive zone at depths of up to 10 m. There are also two points in a resistive zone at the same depth. In addition, this area is dominated by resistive material at depths of 20 to 40 m over a distance of up to 30 m (Fig. 18).

The interpretation of the results and the main findings of this study are data processing using the Karous-Hjelt filter and 2D inversion classified the study area into several characteristics:

- Area 4 (Highly Conductive): This area is dominated by conductive material, indicated by blue color in the inversion image. This conductive zone extends to a depth of 40 m.
- Area 3 (Most Resistive): This area is the opposite of Area 4, where resistive materials dominate, indicated by yellow and orange colors. This resistive zone is visible down to a depth of 50 m.
- Other Areas (Mixed):
 - Area 1: Contains both conductive and resistive materials down to a depth of 15 m, with high resistivity material at a depth of 40 m at certain intervals.
 - Areas 2, 5, and 6: Show variations of conductive and resistive points at shallow depths (around 10 m), but are often dominated by resistive material at greater depths (20–40 m).

Although these values are estimates based on 2D inversion results at the study site, the criteria are now explained as follows:

- Yellow Zone (Resistive): Categorized based on relatively high resistivity values (estimated $>1000 \Omega\text{m}$) or low current density. Physically, this indicates more massive and stable rock material, which we recommend as a foundation for heavy infrastructure.
- Orange Zone (Transitional): A zone with medium resistivity values (estimated $500\text{--}1000 \Omega\text{m}$). This zone is identified as a mixed or transitional soil layer that still possesses sufficient stability for supporting installations such as transmission lines.
- Blue Zone (Conductive): Characterized by low resistivity values (estimated $< 500 \Omega\text{m}$) or high current density. Geophysically, this indicates the presence of groundwater saturation, clay material, or a fracture zone. This area is specifically recommended as a grounding point due to its ability to conduct electrical current with low resistance.

This study successfully demonstrated the great potential of the VLF-EM method as a practical and cost effective tool for the early detection and zoning of renewable energy sites (Table 2). Although the current interpretations are still based on single-resistivity modeling and should be treated as preliminary analyses requiring further field verification, this paper provides a strong conceptual foundation for the development of a more integrated geophysical roadmap to support the green energy transition.

Table 2: Resistivity zone classification.

Zona	Color in Model	Estimated Resistivity	Physical Characteristics	Infrastructure Recommendations
Resistive	Yellow	High	Massive/Dry Rock	Turbine/Solar Foundations
Transitional	Orange	Medium	Compacted Soil	Transmission Lines
Conductive	Blue	Low	Water Saturation/Faults	Grounding Systems

5 Conclusion

Based on the Karous-Hjelt filtering and 2D inversion images, area 4 is highly conductive, as indicated by the predominance of blue in this zone. Meanwhile, area 3 is the most resistive, as marked by the prominent yellow and orange colors. These results can serve as preliminary information for mapping the distribution of the subsurface structure.

Acknowledgement: Not applicable.

Funding Statement: The authors received no specific funding for this study.

Author Contributions: The authors confirm contribution to the paper as follows: Conceptualization, Miftakhul Maulidina, Erna Daniati; methodology, Miftakhul Maulidina; software, Miftakhul Maulidina; validation, Miftakhul Maulidina, Erna Daniati; formal analysis, Miftakhul Maulidina, Erna Daniati; investigation, Miftakhul Maulidina, Erna Daniati; resources, Miftakhul Maulidina, Erna Daniati; data curation, Miftakhul Maulidina, Erna Daniati; writing—original draft preparation, Miftakhul Maulidina; writing—review and editing, Miftakhul Maulidina, Erna Daniati; visualization, Miftakhul Maulidina; supervision, Miftakhul Maulidina, Erna Daniati; project administration, Miftakhul Maulidina; funding acquisition, Miftakhul Maulidina, Erna Daniati. All authors reviewed and approved the final version of the manuscript.

Availability of Data and Materials: Data available on request from the authors. The data that support the findings of this study are available from the corresponding author, [Miftakhul Maulidina], upon reasonable request.

Ethics Approval: Not applicable. This studies not involving humans or animals.

Conflicts of Interest: The authors declare no conflicts of interest.

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