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Quantifying Geothermal Potential: Embracing Uncertainty for Robust National Renewable Estimates

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ABSTRACT

Geothermal energy, a stable and baseload renewable resource, holds significant promise for decarbonizing global energy systems. However, to precisely quantify its potential remains a challenge due to inherent geological uncertainties. Traditional one-value estimates often fail to capture the full spectrum of possibilities, leading to potentially misleading national renewable energy projections. The present article explores the importance of incorporating uncertainty modelling into geothermal resource assessment and proposes a methodology for expressing national potential as a range, especially based on Neutrosophic Probability theory introduced by one of us (FS).

KEYWORDS Geothermal Energy, Renewable Energy Sources, Neutrosophic Probability, Geological Uncertainties

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INTRODUCTION

Geothermal energy, a stable and baseload renewable resource, holds significant promise for decarbonizing global energy systems, especially for countries seeking stable base load for energy supply without having to recourse to fission reactor. However, to precisely quantify its potential remains a challenge due to inherent geological uncertainties. Traditional single-value estimates often fail to capture the full spectrum of possibilities, leading to potentially misleading national renewable energy projections [2]. This article explores the importance of incorporating uncertainty modelling into geothermal resource assessment and proposes a methodology for expressing national potential as a range, from a lower to an upper band.

In a recent article by Trainor-Guitton *et al*. one expression is to relate standard deviation with We, which can be considered as a measure of temperature [1]. Then we shall consider how to improve the expression with Neutrosophic Probability theory introduced by one of us (FS).

THE INHERENT UNCERTAINTIES OF GEOTHERMAL RESOURCE ASSESSMENT

Geothermal reservoirs are complex geological systems characterized by significant heterogeneity in temperature, permeability, fluid composition, and reservoir volume [2]. These parameters are typically inferred from limited subsurface data obtained through geophysical surveys, well logging, and reservoir testing. Consequently, significant uncertainties are associated with:

- **Resource Size and Grade:** Estimating the total heat in place and the recoverable heat fraction is subject to substantial variability due to the limited spatial coverage of exploration data.
- **Reservoir Productivity:** Predicting well flow rates and long-term production capacity is challenging due to the complex interplay of permeability, fracture networks, and fluid properties.
- **Technological and Economic Factors:** The economic viability of geothermal projects depends on factors such as drilling costs, power plant efficiency, and electricity prices, which can fluctuate significantly over time.
- **Environmental Factors:** The environmental impact of geothermal development, including induced seismicity and greenhouse gas emissions, needs to be considered and quantified.

MOVING BEYOND SINGLE-VALUE ESTIMATES: UNCERTAINTY MODELLING

To address these uncertainties, it is crucial to adopt a probabilistic approach that incorporates uncertainty modelling into geothermal resource assessment. Common techniques include:

- Monte Carlo Simulation: This method involves generating numerous random samples from probability distributions representing uncertain parameters, allowing for the estimation of the probability distribution of potential outcomes.
- Geostatistical Modelling: This technique utilizes spatial statistics to interpolate and extrapolate subsurface data, providing a more realistic representation of reservoir heterogeneity.
- Scenario Analysis: This approach involves developing multiple scenarios based on different assumptions about key parameters, allowing for the assessment of potential outcomes under various conditions.
- Fuzzy Logic: This method uses degrees of truth rather than absolute true or false to account for the vague nature of some geological information.

EXPRESSING NATIONAL GEOTHERMAL POTENTIAL AS A RANGE

For national renewable energy estimates, it is essential to move beyond single-value projections and express geothermal potential as a range, reflecting the inherent uncertainties. This can be achieved by:

1. Conducting comprehensive resource assessments: Employing probabilistic methods to quantify the uncertainty in key reservoir parameters.
2. Developing multiple scenarios: Considering different technological, economic, and environmental scenarios to capture the full range of potential outcomes.
3. Defining a lower and upper band: Based on the results of the uncertainty analysis and scenario analysis, establish a lower band representing a conservative estimate of potential and an upper band representing a more optimistic estimate.
4. Communicating the range effectively**:** Clearly articulate the assumptions and uncertainties associated with the lower and upper bands, enabling policymakers and stakeholders to make informed decisions.

Example of Range Expression:
Instead of stating a single value like "National geothermal potential is 5 GW," express it as "National geothermal potential is estimated to be between 3 GW (lower band) and 8 GW (upper band), reflecting uncertainties in reservoir parameters and technological advancements."
Moreover, in a recent article by Trainor-Guitton et al. one expression is to relate standard deviation with We, which can be considered as a measure of temperature. Then we shall consider how to improve the expression with Neutrosophic Probability.

The expression by Trainor-Guitton *et al.,* is as follows [1]:

$$\sigma We = We * 0.4 * depth \quad (1)$$

where We represents the P50 value from the resource assessments above.

ENHANCING GEOTHERMAL POTENTIAL ESTIMATES: INCORPORATING NEUTROSOPHIC PROBABILITY FOR UNCERTAINTY AND INDETERMINACY

Geothermal energy holds immense potential for the United States' renewable energy portfolio. However, accurately quantifying this potential is challenging due to inherent geological uncertainties. The standard deviation expression proposed by Trainor-Guitton et al. [1], which relates the standard deviation of electrical potential (σWe) to the P50 value (We) and reservoir depth, provides a valuable starting point. However, it doesn't explicitly account for the indeterminacy and ambiguity inherent in geothermal resource assessments. This article proposes an extension of this expression using Neutrosophic Probability to address these limitations.
Limitations of the Standard Deviation Expression
The Trainor-Guitton *et al.* [1] expression, given by:
σWe=We∗0.4∗depth
relies on a deterministic approach, assuming a fixed relationship between depth and standard deviation. While depth is a significant factor, it doesn't encompass the full spectrum of uncertainties. Factors such as:

- Geological heterogeneity
- Limited subsurface data
- Variations in technological feasibility
- Economic fluctuations introduce significant indeterminacy that cannot be adequately captured by a single standard deviation value.

Introducing Neutrosophic Probability

Neutrosophic probability extends classical probability theory by explicitly addressing indeterminacy. It represents an event's probability as a triplet (T, I, F), where:[3][4][5]

- T: Truth-membership degree
- I: Indeterminacy-membership degree
- F: Falsity-membership degree

This framework considered herein allows us to model situations where information is incomplete, imprecise, or contradictory, which is common in geothermal resource assessments.

Neutrosophic probability emerges as a powerful generalization of classical probability, designed to handle situations where information is imprecise, ambiguous, or incomplete. Unlike traditional probability, which assigns a single numerical value to an event's likelihood, neutrosophic probability utilizes a triplet (T,I,F) to represent the truth, indeterminacy, and falsity degrees, respectively. Here, T indicates the degree to which an event is true, F represents the degree to which it is false, and I quantifies the degree of indeterminacy or uncertainty surrounding the event. This framework is particularly useful in scenarios where data is subjective, conflicting, or inherently vague, allowing for a more nuanced and realistic representation of uncertainty.

Extending the concept of standard deviation to neutrosophic probability involves adapting traditional statistical measures to accommodate the triplet structure. In essence, instead of a single value representing the spread of data, we obtain a neutrosophic interval or set. To achieve this, one can calculate the standard deviation for each component of the neutrosophic probability. For instance, if we have a set of neutrosophic data points, we can compute the standard deviation of their truth-membership degrees, indeterminacy-membership degrees, and falsity-membership degrees separately. This approach provides a more comprehensive understanding of the data's variability, accounting for the inherent uncertainty present in the neutrosophic framework.

Furthermore, alternative methods involve defining neutrosophic arithmetic operations and applying them to the calculation of standard deviation. This may include defining neutrosophic mean and variance, which would then be used to calculate a neutrosophic standard deviation. The precise definition of these operations can vary depending on the specific application and the desired properties of the neutrosophic statistical measures. Researchers have explored various approaches to define neutrosophic statistical measures, aiming to provide tools that are both theoretically sound and practically applicable in diverse fields.

In practical applications, extending standard deviation estimation to neutrosophic probability enables more robust decision-making in environments characterized by uncertainty. For example, in risk assessment, financial forecasting, or medical diagnosis, neutrosophic standard deviation can provide a more accurate representation of the variability of outcomes, accounting for the inherent ambiguities and uncertainties in the data. This approach enhances the reliability of statistical analysis and allows for more informed and cautious decision-making when dealing with complex and uncertain systems.

NEUTROSOPHIC EXTENSION OF THE STANDARD DEVIATION EXPRESSION

To incorporate Neutrosophic Probability, we can modify the Trainor-Guitton et al. [1] expression by introducing neutrosophic components. Let's express the standard deviation (σWe) as a neutrosophic number:

$$\sigma We = We * (0.4 + \varepsilon_1 . i_1) * (depth + \varepsilon_2 . i_2) \quad (2)$$

Where:

- ε1 and ε2 are small positive numbers representing the degree of indeterminacy.
- i1 and i2 are indeterminate components, representing the range of uncertainty.

This neutrosophic expression allows us to represent the standard deviation as a range rather than a single value. The indeterminate components i1 and i2 can be further defined based on expert judgment, historical data, or other relevant information.

Interpretation and Application

The neutrosophic standard deviation (σWe) can be interpreted as follows:

- The truth component (0.4 * depth) represents the deterministic part of the standard deviation, as in the original expression.
- The indeterminacy components (ε1i1 and ε2i2) represent the uncertainty and ambiguity associated with the depth and other factors.
- The overall neutrosophic value provides a range of possible standard deviation values, reflecting the inherent uncertainties in geothermal resource assessment.

Steps for Application:

1. Estimate the P50 value (We) and reservoir depth: Use existing resource assessments and geological data to estimate these values.
2. Determine the indeterminacy components (i1 and i2): Consult with experts and analyze historical data to estimate the range of uncertainty associated with depth and other relevant factors.
3. Define the indeterminacy degrees (ε1 and ε2): Assign values to ε1 and ε2 based on the level of uncertainty.
4. Calculate the neutrosophic standard deviation (σWe): Use the modified expression to calculate the range of possible standard deviation values.
5. Interpret and communicate the results: Clearly communicate the range of standard deviation values and the associated uncertainties to policymakers and stakeholders.

Benefits of Neutrosophic Extension:

- Improved uncertainty modeling: Explicitly accounts for indeterminacy and ambiguity in geothermal resource assessments.
- Enhanced risk assessment: Provides a more realistic assessment of the risks associated with geothermal development.
- More robust decision-making: Facilitates the development of more robust renewable energy policies and investment strategies.
- Increased transparency: Clearly communicates the uncertainties associated with geothermal potential estimates.

PLAUSIBLE FURTHER EXTENSION OF STANDARD DEVIATION NOTION WITH BAYESIAN NEUTROSOPHIC PROBABILITY

To extend the above neutrosophic standard deviation expression (2) into a Bayesian Neutrosophic Probability framework, we must incorporate prior knowledge and update it with observed data. This involves treating the indeterminate components, i_1 and i_2, as random variables with associated probability distributions, and then refining these distributions using Bayesian inference [6]. We can begin by assigning prior probability distributions to i_1 and i_2, reflecting our initial beliefs about their possible values. These priors might be derived from expert opinions, historical data, or theoretical models. For instance, if we believe the indeterminacy is centred around a specific value with a certain spread, we could use a Gaussian or triangular distribution.

Subsequently, we introduce Bayesian updating to refine the prior distributions based on observed geothermal energy data. This process involves defining a likelihood function that describes the probability of observing the data given specific values of i_1 and i_2. Using Bayes' theorem, we combine the prior distributions with the likelihood function to obtain posterior distributions for i_1 and i_2.

These posterior distributions represent our updated beliefs about the indeterminate components, incorporating both prior knowledge and observed evidence. The updated distributions of i_1 and i_2 can then be used to calculate a refined neutrosophic standard deviation, reflecting the increased certainty gained from the data.

By integrating Bayesian principles into the neutrosophic standard deviation framework, we can achieve a more robust and adaptive representation of uncertainty in geothermal energy potential. This Bayesian Neutrosophic Probability expression of standard deviation allows us to dynamically adjust our estimates as new data becomes available, leading to more accurate and reliable predictions. The resulting expression would not only capture the inherent indeterminacy of the variables, but also incorporate the refinement of knowledge through observed data, therefore combining the advantages of both Bayesian statistics and Neutrosophic theory. This alternative approach is particularly valuable in geothermal energy assessment, where data is often sparse and uncertain, and informed decision-making is crucial.

Advantages of Range-Based Estimates:

- Improved risk assessment: Enables more realistic assessment of the risks associated with geothermal development.
- Enhanced policy planning: Facilitates the development of robust renewable energy policies that account for potential variations in resource availability.
- Increased investor confidence: Provides investors with a more comprehensive understanding of the potential returns and risks associated with geothermal projects.
- More accurate national renewable energy projections: Improves the accuracy of national renewable energy targets and strategies.

CONCLUDING REMARK

Quantifying geothermal potential requires a paradigm shift from single-value estimates to range-based projections that explicitly address uncertainties. By adopting probabilistic methods and scenario analysis, we can develop more robust and reliable assessments of geothermal resources, leading to more informed policy decisions and greater investor confidence. Expressing national geothermal potential as a range, from a lower to an upper band, is essential for accurate national renewable energy estimates and the successful integration of geothermal energy into the global energy transition.

By extending the standard deviation expression with Neutrosophic Probability, we can develop more comprehensive and realistic estimates of geothermal energy national potential reserve in the USA, and other countries as well. The aforementioned approach allows us to move beyond deterministic models and embrace the inherent uncertainties and indeterminacies associated with geothermal resource assessments, leading to more informed and robust decision-making.

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VC, FS

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