Harnessing the Earth's Hidden Power: Illuminating the Human Geography Nexus of Geothermal Power in the Western Pacific Countries

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ABSTRACT

Geothermal energy, being a renewable energy source with the potential to reduce greenhouse gas emissions, has garnered significant international attention. In contrast to previous research primarily focused on the geological and natural scientific aspects of geothermal resources, this study adopts a perspective from the humanities and social sciences. The study delves into examining the correlation between geothermal development and human geography in Western Pacific countries: Japan, Indonesia, the Philippines, and Taiwan. These countries, located in geothermally active zones, offer compelling case studies for unraveling this relationship. Four representative factors, namely population density, Gross Domestic Product (GDP), land prices, and transportation, have been selected for analysis. By utilizing geographic information systems (GIS), correlation coefficient formula, and questionnaire surveys (in the case of Taiwan), the research investigates the spatial distribution and conducts quantitative analysis of the correlation. The primary objective of this research is to enhance the understanding of the present condition and trends in geothermal development within Western Pacific countries. It underscores the significance of incorporating local human geographical considerations during the formulation and execution of geothermal energy plans.

Introduction

With global climate change, the United Nations Climate Change Conference of the Parties (COP26) held in 2021 witnessed the signing of the Glasgow Climate Pact by many countries. This agreement calls for comprehensive and sustained reduction of global greenhouse gas emissions, gradual phase-down of coal-fired power generation, and phasing out subsidies for fossil fuels. The ultimate goal is to achieve net-zero emissions around 2050 (Pact, 2021). In light of these efforts, the adjustment of energy structures becomes an inevitable challenge, and the utilization of renewable energy is a crucial factor in the energy transition process. Renewable energy, which includes solar energy, wind energy, geothermal energy, and biomass energy, plays a significant role in this transition. Among them, "geothermal energy" is capable of providing stable base-load power (Tester et al., 2006) and has lower impacts on human health and ecological environment (Hertwich et al., 2016). As a result, this power from the earth's core has gained significant attention in recent years from various countries.

Geothermal resource development requires initial exploration to confirm factors such as depth, temperature, and geological structure for estimating its reserves, thus establishing a strong correlation with geology (Wang et al., 2019). However, when considering the entire lifecycle of geothermal development, it is not solely dependent on natural geological factors. From the early stages of resource exploration to the later phases of power plant construction and operation, there are connections with human geographical factors (Wang et al., 2019). After all, geothermal development is a long-term and high-cost investment, and the suitability of human and geographical aspects will directly or indirectly impact development outcomes. Nevertheless, the existing literature on the relationship between geothermal development and human geographical factors remains scarce, with the limited studies mostly focused on policy and technical aspects. Hence, this study examines four human geographical factors: population density, GDP, land price, and transportation, with Japan, Indonesia, the Philippines, and Taiwan (the author's background) as the target research regions.

Japan, Indonesia, and the Philippines all have well-established operational geothermal power plants. Taiwan possesses nine areas with higher geothermal potential and three operational geothermal power plants. The research methodology involved using QGIS software to overlay the geothermal power plant locations with human geographical attribute data (population density, GDP, land price, and transportation) to visualize their spatial distribution and analyze their correlation coefficients. The research results showed that in Japan, the local geothermal development exhibited a negative correlation trend with the aforementioned human geographical factors. Conversely, in Indonesia and the Philippines, the local geothermal development showed a positive correlation trend with population density, GDP, and land price. Additionally, the results from the questionnaire survey on Taiwan's geothermal development demonstrated that transportation was the most positively correlated factor among the four factors. This is because convenient transportation contributes to the progress of geothermal exploration, construction, and maintenance activities. The analysis results of this research aim to compare neighboring countries in the Western Pacific, illustrating the impact of human geographical aspects on geothermal development. It provides valuable reference data for industry investments in geothermal projects, government initiatives in promoting geothermal development, and public concerns regarding geothermal issues.

Literature Review

Geothermal power generation possesses advantages such as stability, high efficiency, and low pollution, making it one of the most forward-looking energy sources, especially with the increasing demand for renewable energy (Li et al., 2015). Countries located in the Western Pacific Ring of Fire have abundant geothermal resources due to volcanic activities and tectonic compression, as shown in Table 1.

Table 1. Estimated geothermal resource

Country	Potential Geothermal Resource Amount (MW)	Global Ranking
Indonesia	27,790	2
Japan	23,470	3
Philippines	6,000	5
Taiwan	989	-

Data source: Agency for Natural Resources and Energy (2016); Liu et al. (2012)

This article first reviews the geothermal development in Japan, Indonesia, the Philippines, and Taiwan, which are situated in the Western Pacific Ring of Fire. Japan reemphasized geothermal power generation after the Fukushima nuclear power plant incident (Taghizadeh-Hesary et al., 2020). However, it still faces challenges related to natural park regulations, costs, development risks, and social acceptance (Yasukawa, 2019). In Indonesia, geothermal development has been hindered by underdeveloped infrastructure and price competitiveness, but it has received support from international development agencies in recent years (Chelminski, 2022; Yudha et al., 2022). In the Philippines, larger-sized and higher-quality geothermal resources have already been discovered and developed. The current focus is on the development of secondary resources (Yasukawa & Anbumozhi, 2018). In Taiwan, geothermal development has experienced fluctuations but has been gradually recovering in recent years, with site selection, technology, and regulatory support being key factors (Chung, 2020).

Furthermore, this article conducts a review of literature related to four human geographic factors, population density, GDP, land prices, and transportation:

1. Population Density: It is an indicator of how concentrated the population is in a region, which may influence the feasibility and social acceptance of geothermal energy development. Wang et al. (2021) in Taiwan consider population density as an important factor in geothermal site selection because of Taiwan's high population density and limited available land, which cannot be ignored in its impact on geothermal development. In a study conducted in Japan, Hymans and Uchikoshi (2022) examined site selection and argued that if Lesbirel (1998) is correct in stating that land availability is a critical factor driving energy project siting, then a decrease in population density in a region might also present opportunities for energy project construction.
2. GDP: It is a crucial indicator of economic development and reflects the region's financial and technological capabilities for geothermal energy development. Yudha et al. (2022) point out that technical, financial, and infrastructure issues in Indonesia may affect investors' willingness to invest in geothermal energy projects. In the case of the Philippines, there is an emphasis on the need for the development of new technologies, along with an increase in subsidies and funding, to support the development of secondary resources (Chelminski, 2022). Both of these studies show that geothermal development in economically higher regions in Indonesia and the Philippines has more advantages.
3. Land prices: Land prices are an important indicator of land value, which may affect the cost of geothermal energy development. Although there is no direct literature related to land prices, indirect studies suggest that the location of geothermal resources in countries like Japan and Indonesia, which have a high proportion of geothermal resources within national parks or nature reserves, might indirectly influence the relationship between land prices and geothermal development (Lu et al., 2021).
4. Transportation: Transportation accessibility is a crucial human geographic factor that may influence the geothermal energy development. In Taiwan, Weng et al. (2021) state that transportation accessibility is a necessary condition for geothermal development, as exploration and operation rely on transportation coordination, and a well-developed transportation network can facilitate the transportation of resources and equipment.

The results of these literature reviews indicate that there are relationships between geothermal development and human geographic factors. Understanding and analyzing these interactions will aid in formulating more effective strategies for geothermal energy development and promoting sustainable energy development.

Methodology

Data Collection

This study collected data on administrative divisions, population density, GDP, land prices, and geothermal power plants in the target regions from the sources indicated in Table 2. Since the Taiwanese government does not disclose the GDP of each administrative division, average disposable income per capita was used as an indicator of economic development. Additionally, land appraised values, as announced by the Taiwanese government, were used as an indicator of land prices.

Table 2. Data collection sources

Factor	Country	Website
administrative boundary	Japan	The Humanitarian Data Exchange
	Indonesia	
	The Philippines	
population density	Japan	Municipalities of 47 prefectures
	Indonesia	City Population
	The Philippines	
GDP	Japan	Statistical Table (Prefectural Residents' Economic Calculations)
	Indonesia	Gross Regional Domestic Product
	The Philippines	Philippine Statistics Authority Open STAT
land price	Japan	Land Prices in Japan
	Indonesia	Land Price per Meter in Jabodetabek
	The Philippines	Land for Sale in the Philippines
geothermal power plant locations and installed capacity	Japan	Think GeoEnergy
	Indonesia	
	The Philippines	
	Taiwan	Geothermal Data Platform
administrative boundary	Taiwan	Government Open Data Platform
population density		
average disposable income per capita		
land appraised value		

Spatial Distribution Analysis

In this study, the Quantum Geographic Information System (QGIS) was used to stratify the attribute data of population density, GDP, and land prices for the administrative divisions of each country. The results were visualized using a choropleth map, which applies color shading based on the strata (Ujaval Gandhi, 2023). The locations of geothermal power plants were then overlaid on the map to understand their spatial distribution within the research targets' human geography factors.

Regarding transportation, the study utilized the Travel Time plugin in QGIS to calculate the area that can be reached within a 30-minute drive from each geothermal power plant. This concept is known as isochrones, which represent the areas that can be reached within a specified travel time constraint. Isochrones provide an indication of the transportation convenience level in a given area, to a certain extent (Louisa Bainbridge, 2021).

Correlation Quantitative Analysis

The Pearson product-moment correlation coefficient, or correlation coefficient for short, is used to measure the degree of linear correlation between two variables. The formula for the correlation coefficient is the covariance of the two variables divided by the product of their standard deviations.

Equation 1: Correlation coefficient formula:

$$\rho_{X,Y} = \frac{cov(X,Y)}{\sigma_X \sigma_Y} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \bar{X})^2}\sqrt{\sum_{i=1}^{n}(Y_i - \bar{Y})^2}}$$

Where n is the sample size, X_i and Y_i represent individual samples indexed by i, and $\bar{X}$ and $\bar{Y}$ denote the mean of the samples.

In this study, we aim to investigate the association between the level of local geothermal development and variables such as population density, GDP, land prices, and transportation. The capacity of geothermal installations serves as a crucial indicator of the level of geothermal development. Generally, larger geothermal capacity implies a higher level of geothermal development. Therefore, in this study, we quantify the level of geothermal development using the total capacity of geothermal installations in the respective areas.

Questionnaire Survey

Due to Taiwan's current early stage of geothermal development and utilization, there are only three geothermal power plants in commercial operation. Using correlation coefficients alone cannot objectively demonstrate the correlation between the level of geothermal development and human geographical factors. Therefore, a questionnaire survey was conducted, targeting 26 participants including geothermal developers and relevant stakeholders involved in commercial geothermal operations in Taiwan. The survey aimed to gather their perspectives and evaluations regarding population density, economic development, land value, and transportation convenience as factors to consider.

Results and Discussion

Spatial Distribution Analysis of Japan, Indonesia, and the Philippines

Using the QGIS software, we visualized the spatial distribution by overlaying the geothermal power plants in Japan, Indonesia, and the Philippines with the human geographical factors discussed in this study. Additionally, we ranked the values of human geographical factors (population density, GDP, and land prices) within each country's administrative regions and calculated the average ranking percentage for the administrative regions where the geothermal power plants are situated. The ranking percentages are shown in Figure 1, and the visualized results are presented in Figures 2, 3, and 4.

In terms of population density, the average ranking of the administrative regions where geothermal power plants are located in Japan is at the 31st percentile. In contrast, the average ranking percentage in Indonesia and the Philippines is higher, at the 57th and 70th percentiles, respectively, indicating that these two countries' geothermal power plants are typically situated in areas with higher population density.

Regarding GDP, the average ranking of the administrative regions where geothermal power plants are located in Japan, Indonesia, and the Philippines falls at the 57th, 65th, and 58th percentiles of their respective countries. Indonesia's ranking is slightly higher than the other two. As for land prices, the average ranking of geothermal power plant locations in all three countries ranges from the 49th to the 54th percentiles. This implies that the plants are located in regions with relatively moderate land prices.

In terms of transportation, Figures 2d, 3d, and 4d show the 30-minute travel time isochrones for geothermal power plants in red. The average area of transportation isochrones for Japan, Indonesia, and the Philippines are 177 km², 154 km², and 318 km², respectively. The results show that the reachable area within a 30-minute drive from geothermal power plants is larger in the Philippines compared to the other two countries.

Through these data visualizations and ranking methods, we can gain a deeper understanding of the distribution of geothermal power plants in these countries, enabling comparative studies across different regions and discerning patterns in the locations of geothermal power plants.

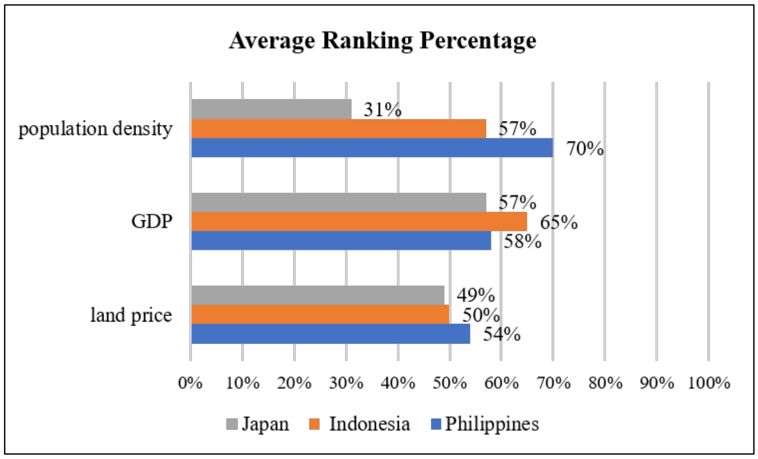

Figure 1. Average ranking percentages of human geographical factors in their respective countries

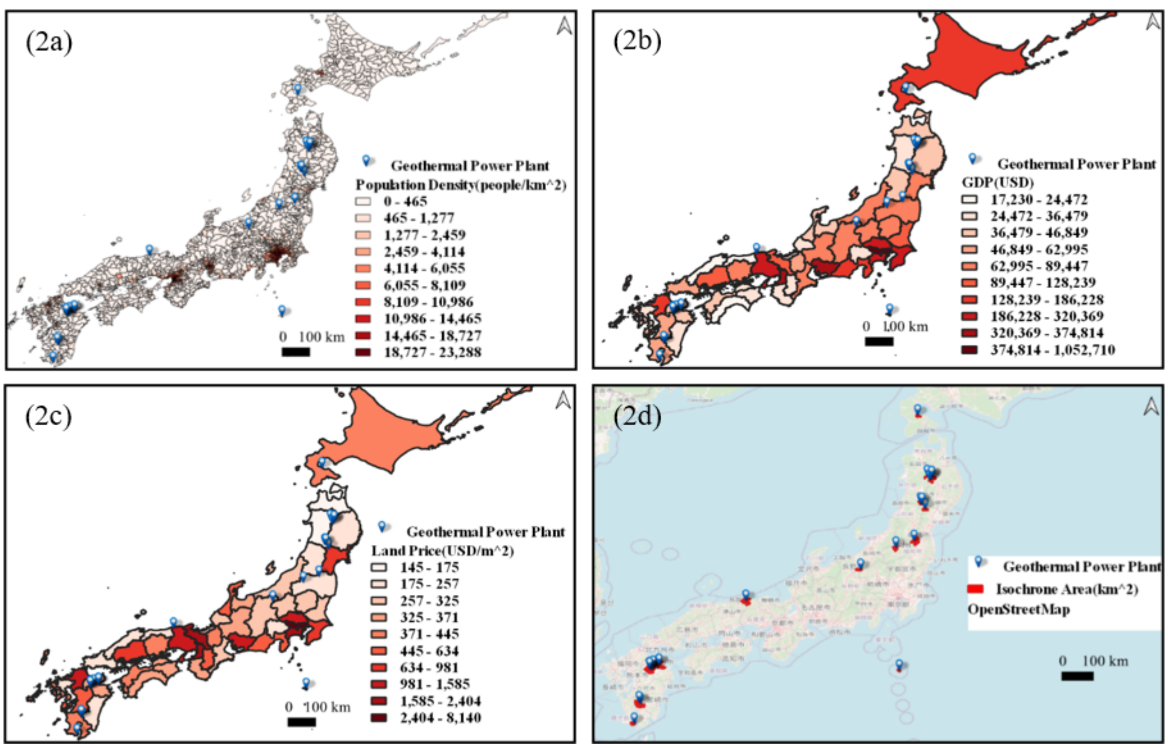

Figure 2. Spatial distribution of (2a) population density, (2b) GDP, (2c) land price, and (2d) isochrone area in relation to geothermal power plants in Japan

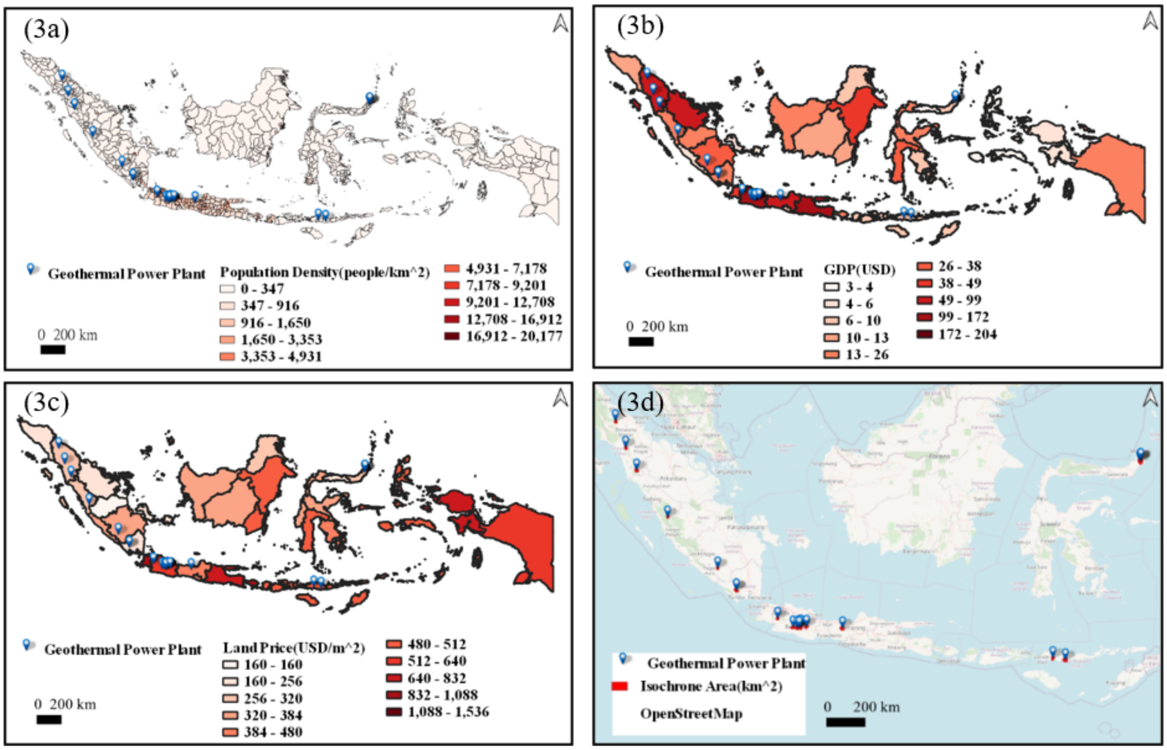

Figure 3. Spatial distribution of (3a) population density, (3b) GDP, (3c) land price, and (3d) isochrone area in relation to geothermal power plants in Indonesia

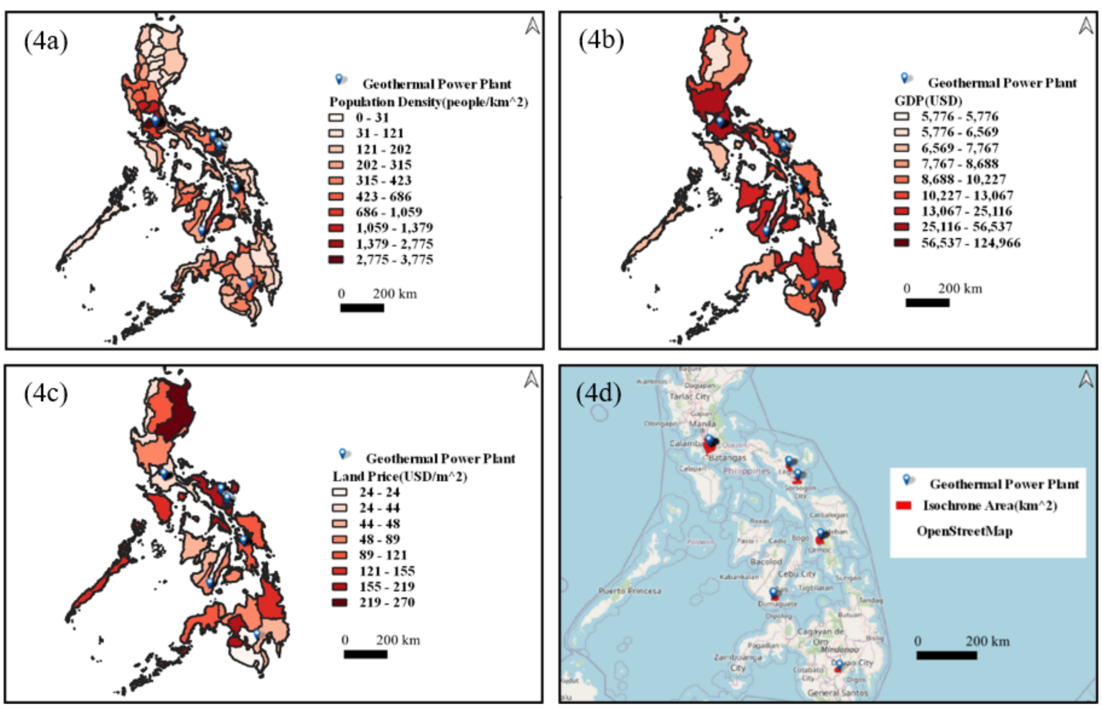

Figure 4. Spatial distribution of (4a) population density, (4b) GDP, (4c) land price, and (4d) isochrone area in relation to geothermal power plants in the Philippines

Correlation Coefficient Analysis of Japan, Indonesia, and the Philippines

In the administrative regions of Japan with geothermal power plants, there are negative correlations between the total installed capacity and population density, GDP, and land prices, with correlation coefficients of -0.39, -0.48, and -0.39, respectively (Figure 5). Additionally, a negative correlation is observed between geothermal power plant capacity and transportation isochrones for various locations in Japan, with a correlation coefficient of -0.44 (Figure 5d).

In Indonesia, geothermal power plants in administrative regions show a positive correlation between the total installed capacity and population density, GDP, and land prices, with correlation coefficients of 0.68, 0.67, and 0.54, respectively, indicating a relatively higher level of correlation (Figure 6). The transportation isochrones also exhibit a negative correlation with geothermal capacity, with a correlation coefficient of -0.33 (Figure 6d).

Similarly, in the Philippines, geothermal power plants in administrative regions show a positive correlation between the total installed capacity and population density, GDP, and land prices, with correlation coefficients of 0.25, 0.17, and 0.38, respectively, indicating a relatively lower level of correlation (Figure 7). The transportation isochrones also demonstrate a negative correlation with geothermal capacity, with a correlation coefficient of -0.31 (Figure 7d).

These findings shed light on the varying geospatial relationships between geothermal development and human geographical factors in the three countries. Japan's geothermal plants display negative correlations, indicating that they are more likely to be situated in remote areas. On the other hand, in Indonesia, geothermal power plants exhibit positive correlations, indicating a preference for locations with higher economic development. In the Philippines, the correlations are positive as well, though relatively weaker compared to Indonesia. All three countries show a negative correlation between geothermal development and transportation accessibility.

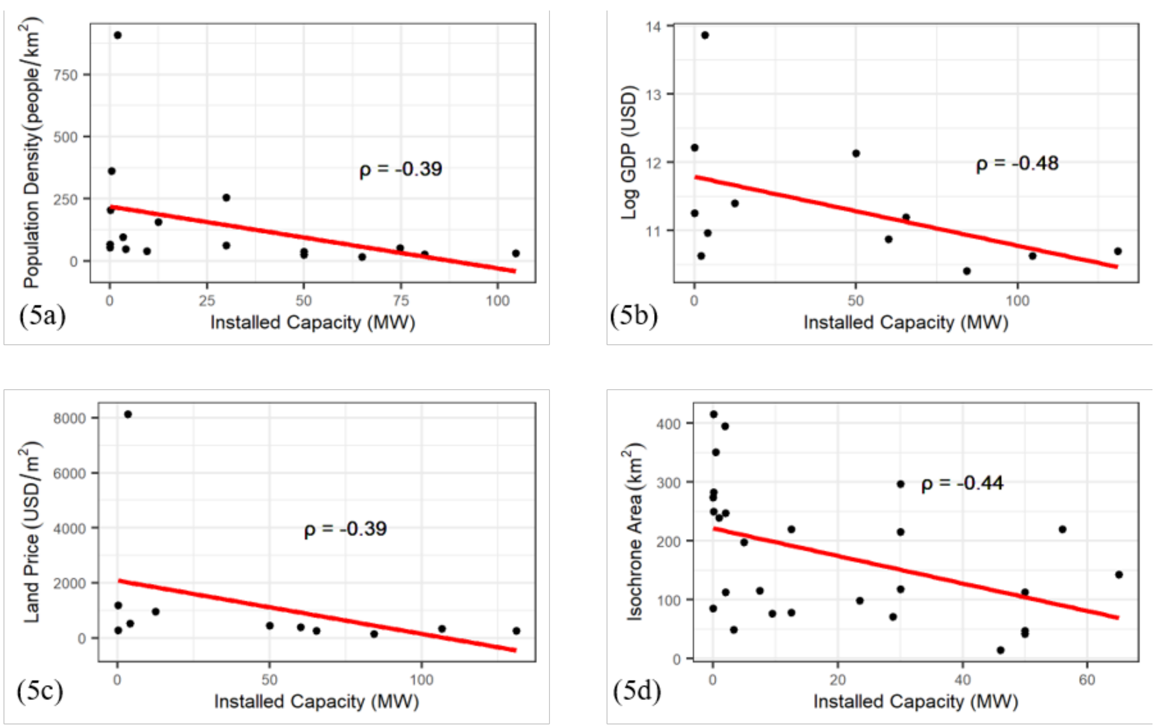

Figure 5. Correlation coefficient between (5a) population density, (5b) GDP, (5c) land price, and (5d) isochrone area and installed capacity of geothermal energy in Japan

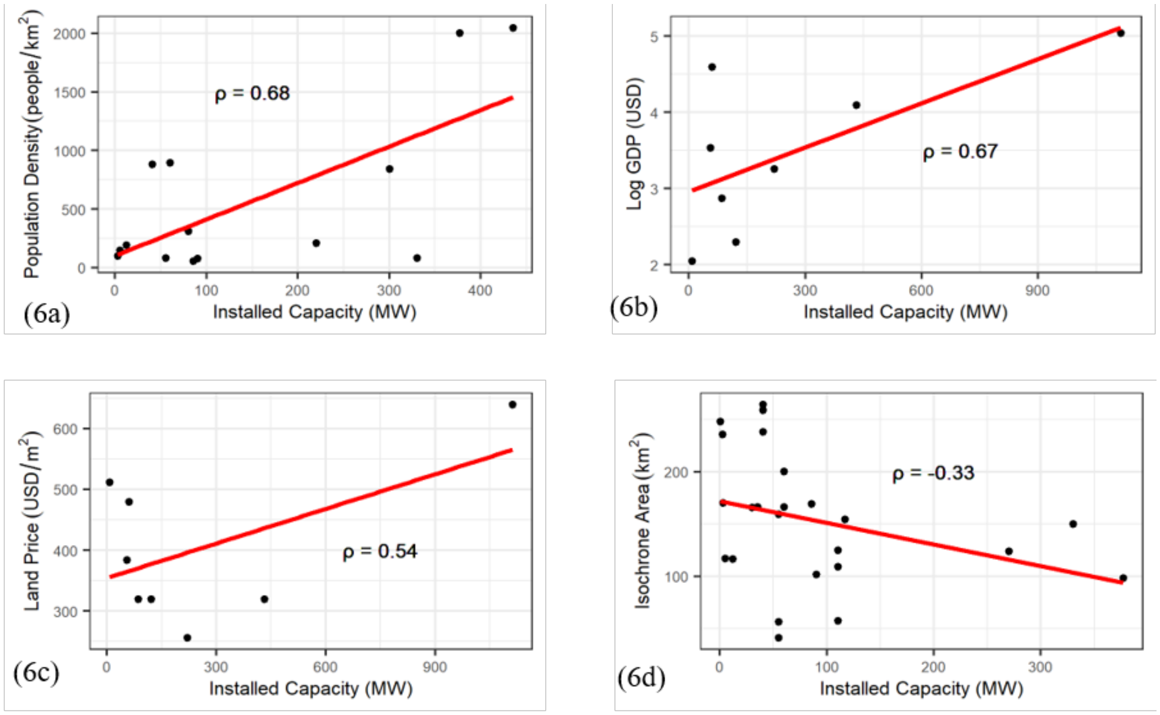

Figure 6. Correlation coefficient between (6a) population density, (6b) GDP, (6c) land price, and (6d) isochrone area and installed capacity of geothermal energy in Indonesia

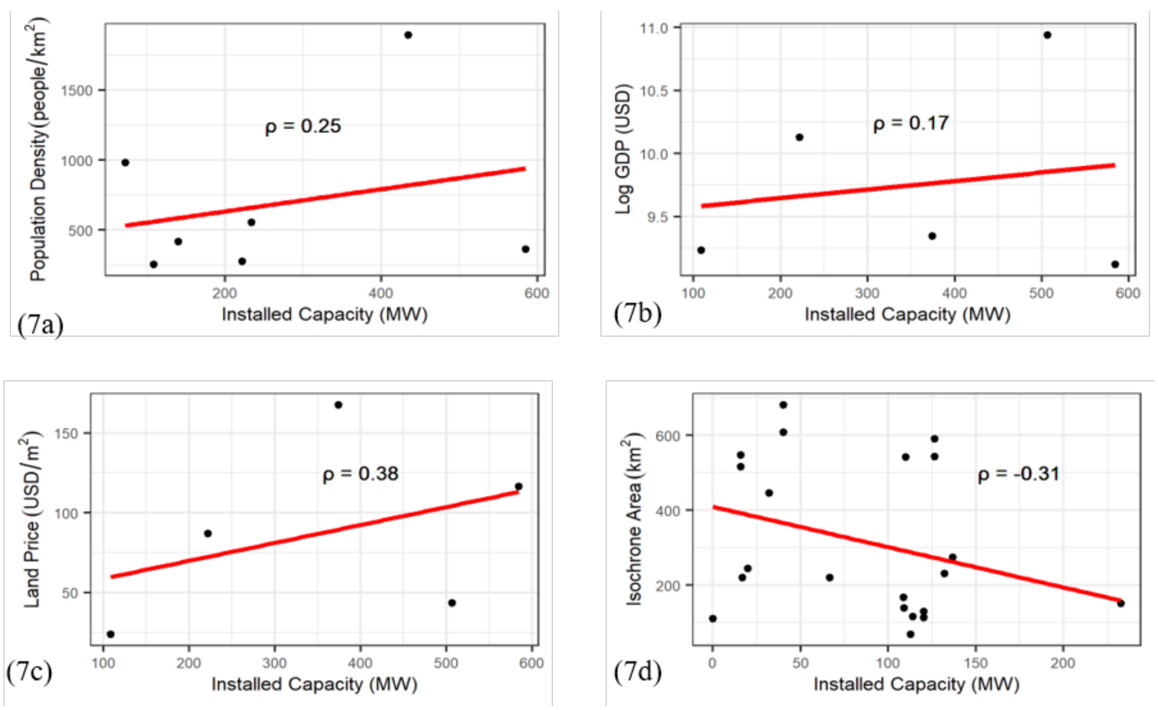

Figure 7. Correlation coefficient between (7a) population density, (7b) GDP, (7c) land price, and (7d) isochrone area and installed capacity of geothermal energy in the Philippines

Spatial Distribution Analysis of Taiwan

Taiwan currently has nine areas with high estimated geothermal potential and more comprehensive exploration data, as shown in Figure 8. The locations of exploration wells in the potential areas and the existing geothermal power plants, situated in Zhiben, Jinlun, and Chingshui, are marked in yellow and blue respectively, as depicted in Figures 8 and 9.

Regarding spatial distribution, QGIS software was utilized to visualize the data and analyze the population density, average annual disposable income per capita, and assessed present land value in the administrative regions where these geothermal potential areas are located. The results indicate that all these metrics are highest in the administrative region where the Datun Mountain geothermal potential area is situated. Although Datun Mountain is still some distance away from the prosperous areas of that administrative region, the spillover effects and impacts on surrounding towns still need to be considered for future development.

In terms of transportation, after evaluating the travel-time isochrones of each geothermal potential area, the range extends approximately from 44 square kilometers to 217 square kilometers. Among them, Datun Mountain, Zhihben, and Hongye show better transportation accessibility compared to the other geothermal potential areas.

Analysis of Questionnaire Survey Results of Taiwan

Taiwan's geothermal development is in its early stage of utilization. As the direction of investment can influence the trajectory of geothermal development in Taiwan, a questionnaire was employed to gather perspectives from geothermal industry participants and relevant stakeholders regarding human geographical factors. This indicator was used to assess the correlation with geothermal development.

The questionnaire asked respondents to rate each of the four factors, population density, economic development, land value, and transportation, using a scale from 1 (low) to 5 (high), allowing participants to evaluate the correlation of these factors. Then, the research calculated the weighted average of each factor's rating. The weights assigned to the scores corresponded to the scale, with 1 representing the lowest weight and 5 representing the highest weight. The results of the weighted average are presented in a radar chart, as shown in Figure 10.

Figure 10a demonstrates that survey respondents rated the transportation factor as having the highest positive correlation with geothermal development. Further survey reveals that they believe convenient transportation facilitates activities such as exploration, drilling, construction, and maintenance, while also reducing transportation costs. The second-highest score of positive correlation is associated with economic development. Further survey indicates that economic growth drives technological advancements, allows for the introduction or development of higher technologies, and benefits from a thriving commercial sector with high market demand, providing better prospects and business opportunities.

Figure 10b demonstrates that survey respondents rated the population density factor as having the highest negative correlation with geothermal development. They believe that higher population density can lead to public opposition and may impose more environmental restrictions. The second-highest score of negative correlation is associated with land value, as high land rents or prices increase construction and operating costs.

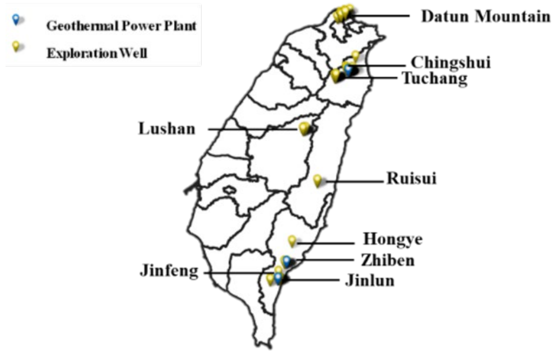

Figure 8. Relatively high-potential geothermal areas in Taiwan

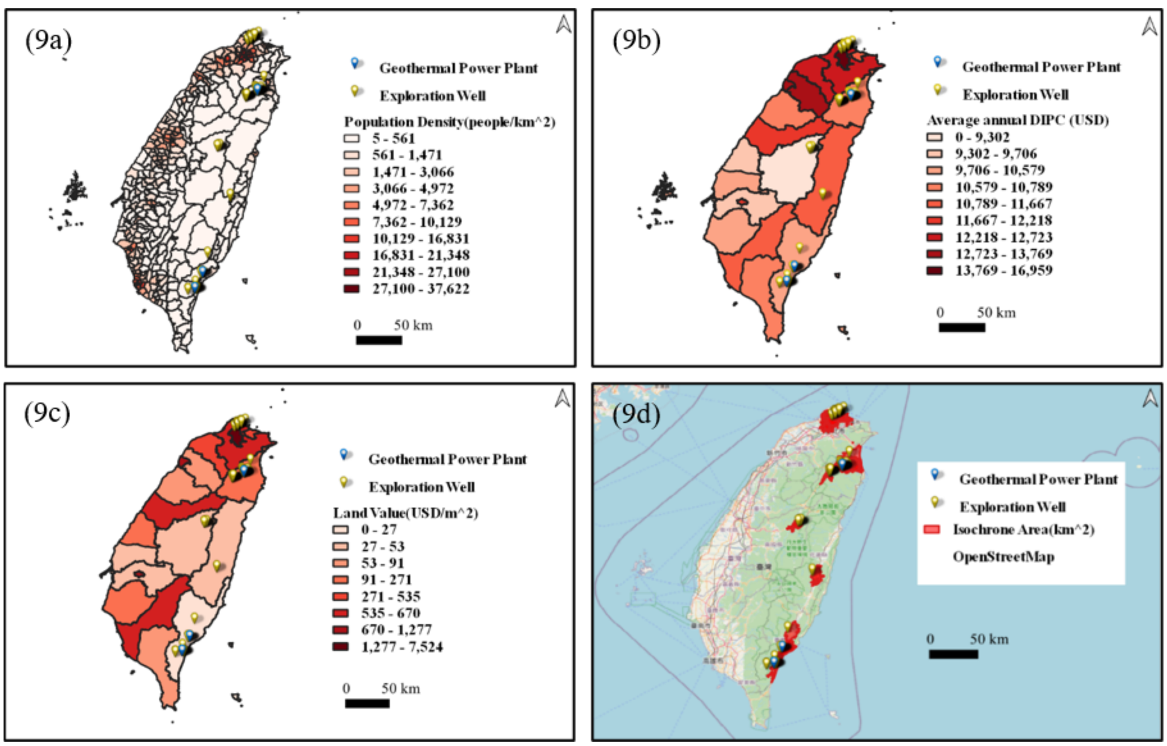

Figure 9. Spatial distribution of (9a) population density, (9b) average annual disposable income per capita, (9c) assessed present land value, and (9d) isochrone area in relation to geothermal power plants and exploration wells in Taiwan

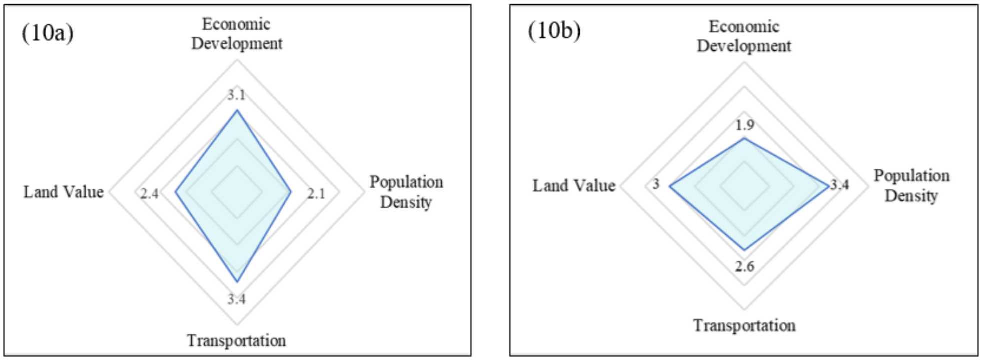

Figure 10. Radar chart of survey results in Taiwan: (10a) The weighted average of factors with a positive correlation, and (10b) the weighted average of factors with a negative correlation

Conclusion

This research provides valuable insights into the current status and trends of geothermal energy development in the countries of the Western Pacific region through the analysis of four human geographical factors: population density, GDP, land price, and transportation. By integrating spatial distribution, correlation analysis, and survey results from Taiwan, the following observations have been made:

1. Japan: Geothermal power plants are typically located in areas with lower population density, median values for GDP, and land prices. However, when the total installed capacity is higher, there is a tendency to develop geothermal projects in regions with lower GDP and land prices, indicating a preference for remote and underdeveloped areas.
2. Indonesia and the Philippines: Geothermal power plants are often built in areas with higher population density, higher GDP, and higher land prices, suggesting a preference for developed and economically active regions. The spatial distribution analysis for the Philippines also shows similar trends, with positive correlation in correlation analysis, though the correlation strength is relatively low.
3. Transportation: The time travel areas for Japan, Indonesia, and the Philippines are 177 km², 154 km², and 318 km², respectively. In these countries, there is a negative correlation between geothermal capacity and transportation factors, indicating that areas with higher total geothermal capacity tend to have relatively limited access to transportation.
4. Taiwan: The survey results indicate that respondents consider transportation to be the most positively correlated factor with geothermal development, while population density is viewed as a negatively correlated factor, highlighting the challenges and potential opposition in densely populated areas.

The results of this study underscore the importance of considering local human geographical factors when planning and implementing geothermal energy projects. The unique social, economic, and environmental backgrounds of each country play a crucial role in the success and acceptance of geothermal development plans. Policymakers, investors, and stakeholders should take these factors into account to ensure sustainable and effective utilization of geothermal energy. Taiwan, currently in the early stages of geothermal development, can learn from neighboring Western Pacific countries' experiences with the interplay of geothermal development and human geographical factors to explore suitable geothermal utilization models for the region's better development.

Overall, geothermal energy is a promising renewable energy source that can significantly contribute to greenhouse gas emissions reduction and the global transition towards a sustainable energy system. Through this research, it is evident that each country's specific conditions and challenges require tailored approaches and comprehensive planning to harness the potential of geothermal energy and promote its sustainable growth in the respective regions.

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