GIS-based Suitability Analysis for PV Site Selection in Switzerland

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ABSTRACT

The transition to renewable energy is crucial for addressing climate change and ensuring energy security, with Switzerland positioned to lead in this shift. This study focuses on identifying optimal locations for photovoltaic (PV) farms through a comprehensive analysis combining Geographic Information Systems (GIS), economic modeling, and policy evaluation. Using data from government and private sources, I examined key factors such as solar irradiation, land suitability, economic viability, and policy influences. The GIS-based analysis revealed that the southern regions of Switzerland, particularly the Alps, offer high solar exposure, moderate temperatures, and strong infrastructure connections, making them ideal for PV development. An economic assessment of comparable projects indicated that PV farms in these regions have competitive installation costs, with a levelized cost of electricity (LCOE) as low as $14.03/MWh, contributing to a favorable payback period. The policy review highlighted supportive measures, such as feed-in tariffs of $0.20 per kWh, decreasing over time, and tax rebates covering up to 30% of installation costs, while also noting potential regulatory hurdles. My findings suggest that Switzerland's southern regions are highly suitable for PV development, contributing to the country's sustainability goals, while legislative and public concerns regarding Alpine developments highlight the need for balanced solutions. My study's integrated approach offers insights for renewable energy development in Switzerland and similar contexts.

KEYWORDS

renewable energy, photovoltaics, Geographic Information Science, economic modeling, policy review

INTRODUCTION

In the face of escalating global climate change challenges, the transition to renewable energy sources emerges as a pivotal strategy for mitigating environmental impact while ensuring energy security. Switzerland, with its commitment to sustainability and ambitious climate goals, potentially stands at the forefront of this transformation. The country's dedication to reducing carbon emissions and promoting renewable energy aligns with global efforts to combat climate change and transition towards more sustainable energy systems (Weiss et al. 2021). This pursuit is not merely an environmental or ethical imperative; instead, it's a pragmatic approach to safeguarding the nation's energy future in a world increasingly conscious of the finite nature of fossil fuels and the environmental degradation they cause (Weiss et al. 2021). Renewable energy projects, particularly photovoltaic (PV) farms, are integral to Switzerland's strategy for attaining the country's sustainability and climate objectives. The country's geographical diversity, characterized by its varied topography and solar exposure, presents unique opportunities and challenges for the deployment of solar energy infrastructure (Díaz et al. 2017). As such, identifying optimal locations for photovoltaic farms is crucial to maximizing both their efficiency and contribution to the national energy grid. This process, however, requires a nuanced understanding of a complex array of factors, including but not limited to, solar radiation levels, land suitability, and environmental constraints (Munkhbat and Choi 2021). Given the intricate interplay of these considerations, GIS technology has become an indispensable tool in the renewable energy sector. GIS enables the detailed analysis and visualization of geospatial data, facilitating informed decision-making in the selection of sites for renewable energy projects (Malczewski 2004). This technological approach enhances the efficiency and effectiveness of site selection processes while aligning with Switzerland's innovative and forward-thinking approach to development within the renewable energy sector.

GIS provides a dynamic platform for the analysis, visualization, and management of spatial data, offering invaluable insights into the geographical distribution of renewable energy resources. This capability is particularly relevant in the context of photovoltaic farm site selection, where factors such as land topography, solar radiation, and proximity to infrastructure must be meticulously evaluated to determine the most suitable locations for development (Panagiotidou et al. 2016). Recent studies have demonstrated the efficacy of GIS in identifying potential sites for renewable energy projects by leveraging spatial analysis to assess various geospatial factors. For instance, recent research highlights a GIS-based suitability analysis for siting solar power plants in Kuwait using distinct methodology (Hassan et al., 2021). Similarly, another study utilized GIS to analyze wind energy potential, highlighting the adaptability of GIS technologies to various types of renewable energy sources and their specific locational criteria (Merrouni et al,. 2018). Furthermore, applying GIS in renewable energy site selection extends beyond technical and environmental considerations, incorporating socio-economic factors such as land ownership, zoning regulations, and community acceptance (Pereira and Duckstein 1993). This holistic approach ensures that selected sites are not only technically feasible but also economically viable and socially sustainable. Moreover, GIS facilitates the integration of renewable energy projects into existing energy systems, allowing for a more seamless transition to sustainable energy sources (Clark & Lee, 2019). In Switzerland, the use of GIS for renewable energy development is of particular significance due to the country's complex geography and stringent environmental regulations. The Swiss approach exemplifies how GIS can be tailored to accommodate local conditions, ensuring that renewable energy projects contribute positively to the national energy mix while adhering to environmental conservation standards.

The economic feasibility and policy environment play crucial roles in the successful deployment of renewable energy projects. In Switzerland, a country known for its high environmental standards and commitment to sustainability, these factors are especially significant. The economic modeling of renewable energy projects involves assessing various indicators such as cost of installation, operational expenses, return on investment, and market incentives, which are critical for determining the viability of projects in different locations (Tudisca et al. 2013). Additionally, the consideration of externalities, such as environmental and social impacts, is essential for comprehending the full economic value of renewable energy projects (Zegardlo et al. 2024). Economic assessments are complemented by a comprehensive policy analysis that examines the regulatory framework governing renewable energy development. Switzerland’s energy policy landscape is characterized by a multi-level governance structure, with policies at the federal, cantonal, and municipal levels influencing the selection of locations for renewable energy projects (Díaz et al. 2017). Federal policies such as the Energy Strategy 2050 highlight Switzerland's ambition to increase the share of renewable energies, reduce energy consumption, and decrease dependency on fossil fuels. This strategy provides a clear policy direction, incentivizing the development of renewable energy projects through subsidies, tax incentives, and regulatory support (BFE 2022).

Despite the considerable advancements in renewable energy technologies and the extensive application of Geographic Information Systems in site selection, a significant research gap persists in the comprehensive integration of GIS technology, economic modeling, and policy analysis for renewable energy projects – especially within the Swiss context. While studies have individually explored the utility of GIS in identifying potential sites for renewable energy, the economic viability of these projects (Fischer & Prahl, 2020), and the influence of policy frameworks, there remains a lack of research that combines these aspects to optimize renewable energy deployment in Switzerland. Within this framework, this paper's central research question is how effectively can GIS technology, economic modeling, and policy analysis identify optimal locations for renewable energy projects in Switzerland to meet its sustainability, and energy security goals? Specifically I ask:

1. What are the key geospatial factors, such as solar radiation and land suitability, that influence the selection of optimal locations for renewable energy projects in Switzerland?
2. How can economic modeling be used to assess the financial feasibility of renewable energy projects in different locations in Switzerland, and what are the key economic indicators influencing project viability?
3. What existing energy policies in Switzerland influence the selection of renewable energy project locations?

METHODS

Study site

To define the geographic scope of the research, I selected the entire country of Switzerland as the study site. This decision was based on the entire country's commitment to enhancing its renewable energy infrastructure and the diversity of its topography and climatic conditions, significantly influencing solar energy potential (Kannan et al. 2022). The varied landscape, from flat plains to mountainous regions, provides a unique opportunity to evaluate the suitability of different terrains for PV farms. Switzerland's small size and the comprehensive, detailed geographic and environmental data also facilitated a nationwide analysis, ensuring an overarching assessment of potential locations for renewable energy projects.

Data collection

To assess the geospatial factors influencing the suitability of locations for photovoltaic farms in Switzerland, a comprehensive collection of geospatial data was conducted. This involved acquiring data from multiple government databases such as the Swiss Federal Office of Energy (SFOE) and private entities that provide detailed environmental and geographical information. The key variables collected included solar irradiation levels, slope, average temperature, and proximity to existing power lines and power stations (Table 1). Land use data was also obtained to understand the current utilization of potential sites.

Table 1. Summary of geospatial variables used in the study. Data was downloaded from various databases including ESRI, MeteoSwiss, and SFOE.

Variable	Data Type	Units of Measurement
Daily Normal Irradiation	Raster	kWh/m^2
Land Use	Raster	N/A
Slope	Raster	Degrees (0-90)
Power Lines	Point	N/A
Power Stations	Line	N/A
Yearly Average Temperature	Raster	Celcius (°C)

For the economic analysis, I gathered data regarding existing and planned PV farm projects. This included information on installation costs, operational expenses, and projected returns, sourced from industry reports and project proposals. These data points are essential for comparing the financial feasibility of projects in identified suitable regions.

Policy-related data was extracted from various online sources, including news portals and official government websites. This involved reviewing recent policy changes, legislative developments, and government incentives related to renewable energy. The objective was to understand the current policy landscape and its impact on the deployment of renewable energy projects in Switzerland.

Suitability analysis

To analyze the suitability of various locations across Switzerland for photovoltaic farms, a meticulous GIS-based multi-criteria analysis was employed, inspired by successful methodologies referenced in prior studies (Hassaan et al. 2021). This method integrated a combination of Boolean and favorable criteria to evaluate the potential of various sites effectively.

Identifying Criteria and Data Preparation

Initially, key siting criteria were identified based on their relevance to the performance and feasibility of PV farms. These included:

- <u>Solar Irradiation:</u> Recognizing the paramount importance of solar exposure for efficient PV operation, areas with high solar irradiation levels were prioritized. This data was sourced from national meteorological agencies and validated against satellite data to ensure accuracy and consistency.
- <u>Yearly Average Temperature:</u> Temperature significantly affects PV efficiency; thus, data on yearly average temperatures was integrated into the analysis. Locations with moderate temperatures, which optimize PV panel efficiency, were identified using climate databases.
- <u>Slope:</u> The topography of potential sites was analyzed using Digital Elevation Models (DEM) to assess the slope. Areas with minimal slope were considered ideal to minimize construction and maintenance costs and maximize the installation area.
- <u>Land Use:</u> Using updated land cover datasets, sites were evaluated to ensure they were neither agriculturally valuable nor environmentally protected. This ensured compliance with regulatory standards and social sustainability.
- <u>Proximity to Power Lines/Power Stations:</u> Proximity to existing infrastructure was assessed using the Euclidean Distance tool in GIS. Sites closer to power lines or power

stations were rated higher due to the lower costs and technical challenges associated with connecting to the grid.

Developing a Composite Suitability Index

Each criterion was assigned a weight according to its impact on the site's overall suitability for hosting a PV farm. Weights were determined using the Analytic Hierarchy Process (AHP), facilitating a systematic evaluation of each criterion's relative importance based on literature review (Alami Merrouni et al. 2018). The normalization process adjusted the data such that higher values consistently denoted higher suitability (Table 2):

- For positively correlated criteria like solar irradiation, higher values were directly equated to higher suitability scores.
- For negatively correlated criteria like distance to power lines, inverse functions were applied so that closer distances scored higher.

Table 2. Criteria Weights and Normalization for PV Farm Site Suitability Analysis.

Criterion	Description	Correlation to Suitability	Normalization Approach
Solar Irradiation	Amount of solar energy received	Positive	Higher values → Higher suitability scores
Distance to Power Lines	Proximity to existing power infrastructure	Negative	Closer distances → Higher suitability scores (inverse function)
Land Slope	Steepness of the terrain	Negative	Lower values → Higher suitability scores
Average Temperature	Mean annual temperature	Positive	Higher values → Higher suitability scores
Land Use	Current usage of the land	Negative	Compatible uses → Higher suitability scores

Economic feasibility

To evaluate the economic feasibility of potential PV farm locations identified through the GIS-based land suitability analysis, I conducted an extensive economic assessment. The focus was on determining the project's viability within Switzerland's economic and energy landscapes, using key financial metrics to assess the potential for profitability and long-term sustainability. Data for these indicators were sourced from industry reports, financial statements of existing projects, and databases containing information on renewable energy economics.

Economic Indicators and Data Collection

Key economic indicators critical to the assessment included:

- Levelized Cost of Electricity (LCOE): The LCOE will be a central factor in evaluating the economic performance of potential PV farm locations. This metric accounts for the total lifecycle costs of the project, including capital, operational, and maintenance expenses, and compares them to the projected energy output over the system's lifetime.
- Interest Rates and Cost of Money: Interest rates and the cost of capital play a significant role in determining the project's financial viability. The study will consider current interest rates in Switzerland, as well as the potential impacts of financing arrangements on the overall project cost and payback period.
- Profit and Loss Analysis: To assess the long-term economic sustainability of the project, the analysis will include a detailed profit and loss projection. This will account for factors such as initial capital investment, operating costs, potential revenue from electricity sales, and expected profitability over time.
- Return on Investment (ROI): A crucial metric to determine the profitability of the investment, calculated by comparing the expected returns over the life of the project to the initial investment.

Comparative Economic Analysis

In the ideal scenario, each potential site identified in the GIS analysis would be assessed using a standardized economic model. However, due to data availability and access constraints it proved difficult to run a comprehensive economic analysis of each site identified within the suitability analysis. Henceforth, a more holistic approach was taken when looking into economic viability assessing other completed PV farm projects or those currently in the development pipeline. A selection of 3 projects were chosen based on parameters comparable to those developed from the suitability model:

- Al Kharsaah PV farm: Located 80 km west of Qatar's capital, Doha, the Al Kharsaah Solar PV Independent Power Producer (IPP) project is the country's first large-scale solar power plant (Total Energies 2022). The plant was built in two phases of 400 megawatts-peak (MWp) each, and therefore has a full capacity of 800 MW.
- Elazig Solar PV Park: The project was developed by Asunim U.K and Phoenix Solar. The project is currently owned by Akfen Holding. Asunim Elazig Solar PV Park is a ground-mounted solar project which is spread over an area of 156,500 square meters. The project generates 14,613.45 MWh of electricity thereby offsetting 16,000t of carbon dioxide emissions (CO2) a year (Power Technology 2023).
- Lac des Toules solar project: This is the world's first high-altitude floating solar farm. The installation consists of 2,240 square meters of solar panels, arranged in five rows of eight over all but one of the 36 floats (World Economic Forum 2022). The project has more or less 800-megawatt hour production per year, which represents 225 households' needs (World Economic Forum 2022).

Integration of Economic and GIS Data

The economic feasibility results were integrated with the GIS-based land suitability index to produce a comprehensive overview of each location's overall attractiveness for PV development. This integration allowed for a prioritized ranking of sites based on both their geospatial suitability and economic viability.

Policy review

Policy Impact Consideration

Additionally, my analysis considered the impact of current and potential future Swiss energy policies, such as subsidies for renewable energy, tariffs on solar power, and tax incentives, which could influence the economic outcomes of the PV projects. To understand how existing energy policies influence the selection of locations for PV farms in Switzerland, a thorough review of the current regulatory policy landscape was conducted (Table 3). During my data collection, I found select policies that constituted a majority of its climate and renewable energy goals, including:

Table 3. Swiss energy policy landscape. Various legislative policies regarding Switzerland's commitment to reduce carbon emissions and increase its renewable energy footprint. Data was obtained from the SFOE.

Policy	Key Characteristics
Energy Strategy 2050 (2017)	Reduce the country's dependency on fossil fuels by developing renewable energy supply
Climate and Innovation Act (2023)	1. Carbon neutral by 2050 2. 50% reduction in admissions by 2040
Swiss CO2 Act (2013)	Domestic greenhouse gas emissions must be reduced overall by 20 per cent as compared with 1990 levels, by 2020
Swiss Energy Act (2016)	Increases Renewable Capacity by 5400 GWh by 2030

Analysis of Policy Impact

The policy review concentrated on understanding various aspects crucial for the development of PV farms. It began with an examination of the financial incentives available, such as tax breaks, feed-in tariffs, and grants, assessing how these can enhance the economic feasibility of renewable energy projects. Additionally, the review identified potential regulatory barriers, including environmental impact assessments and zoning restrictions, which could delay or limit the development of PV farms. Lastly, it analyzed the strategic alignment of PV farm siting with national and regional goals for renewable energy production and carbon emission reduction.

RESULTS

Suitability Model

Solar Irradiation

The analysis of daily normal irradiation levels across Switzerland reveals significant regional variations, crucial for placing photovoltaic systems. The highest solar irradiation is observed in the southern regions, specifically in the Valais and Ticino cantons, with values reaching up to 1840 kWh/m². Conversely, the northern regions, near the Jura Mountains and parts of the Northeast – exhibit the lowest irradiation levels, with values as low as 82.9 kWh/m². These disparities in solar exposure are essential for prioritizing areas that could yield the highest solar energy output (Figure 1).

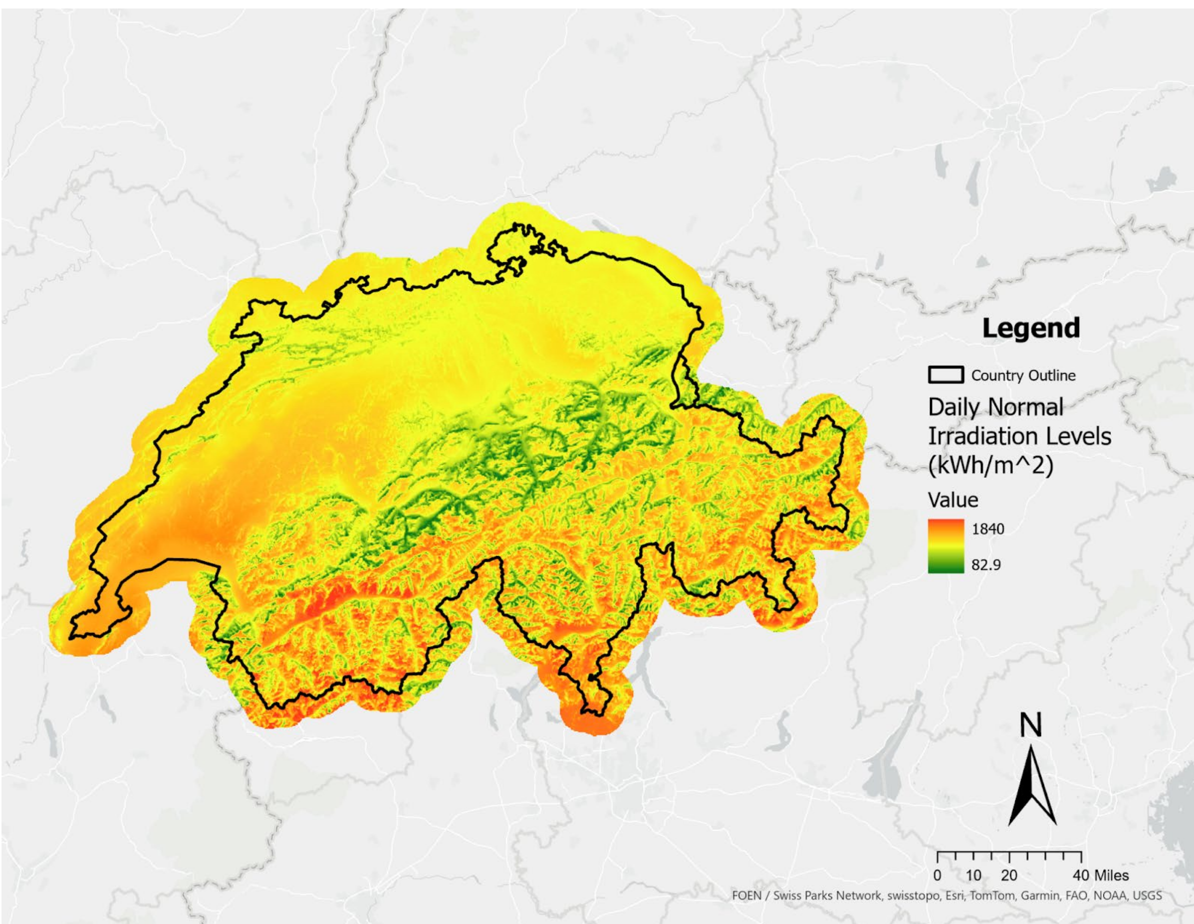

Figure 1. Daily normal solar irradiation levels for Switzerland.

Electric Power Infrastructure

The distribution of electric power lines and power stations, as shown in the second map, indicates a well-established network across most of the country, with dense clusters around urban centers and prominent industrial areas such as Zurich, Basel, and Geneva. Notably, the central and southern regions show a robust grid infrastructure, which is advantageous for connecting future PV farms to the national grid. This extensive network has the potential to reduce costs and complexities associated with connecting PV farms to the energy grid, which would increase the feasibility of site placements even in remote areas (Figure 2).

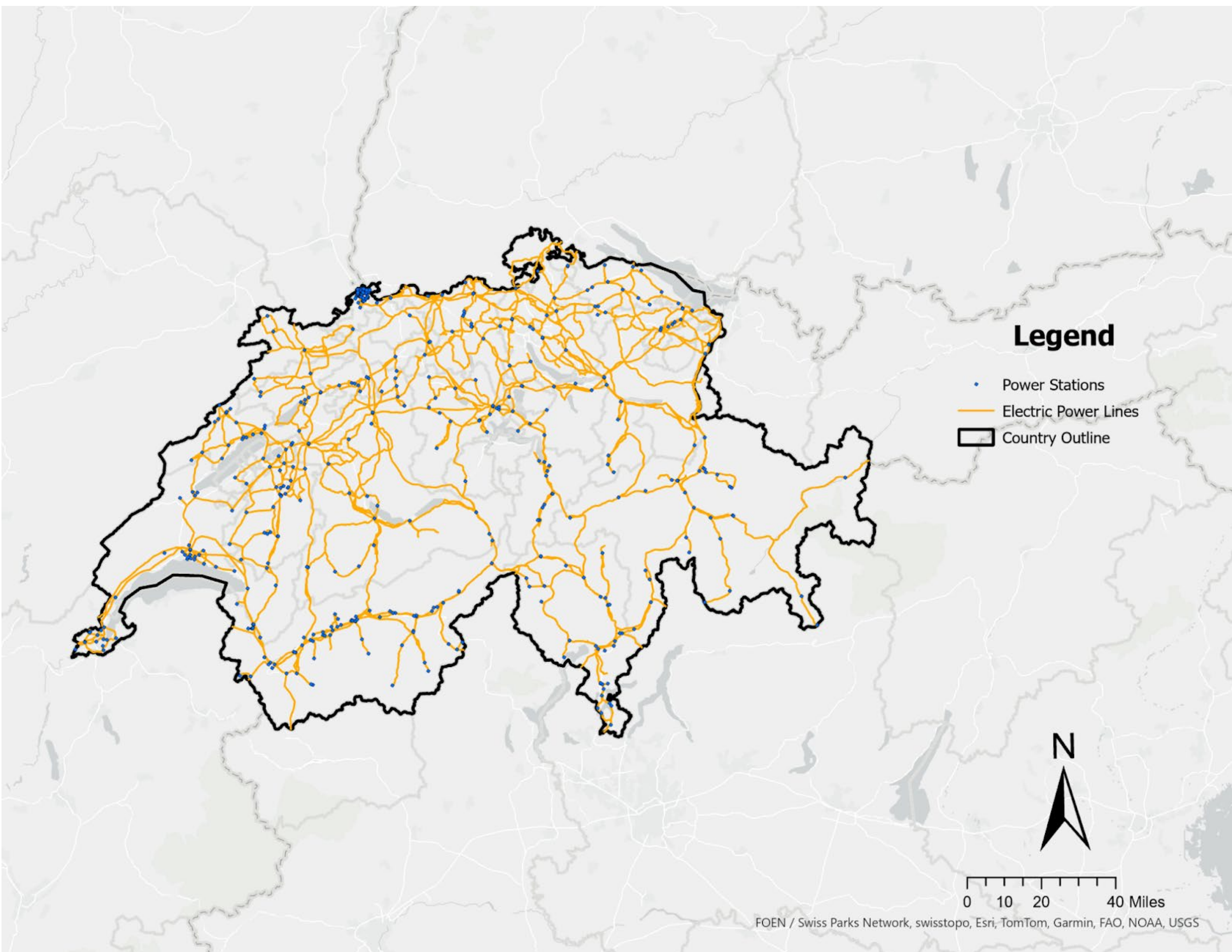

Figure 2. Weighted distance to Power Grid.

Topography

The analysis of slope aspects across Switzerland revealed predominately varied topography, due to the vast range of slope angles. Most of the Alpine region, characterized by steep slopes greater than 30.96°, poses challenges for PV installation due to potential barriers in construction and increased costs. However, the plateau regions, particularly in the Northwest and around the Central Plateau, show more favorable conditions with slopes less than 11.04°, making them more suitable for PV farm development (Figure 3).

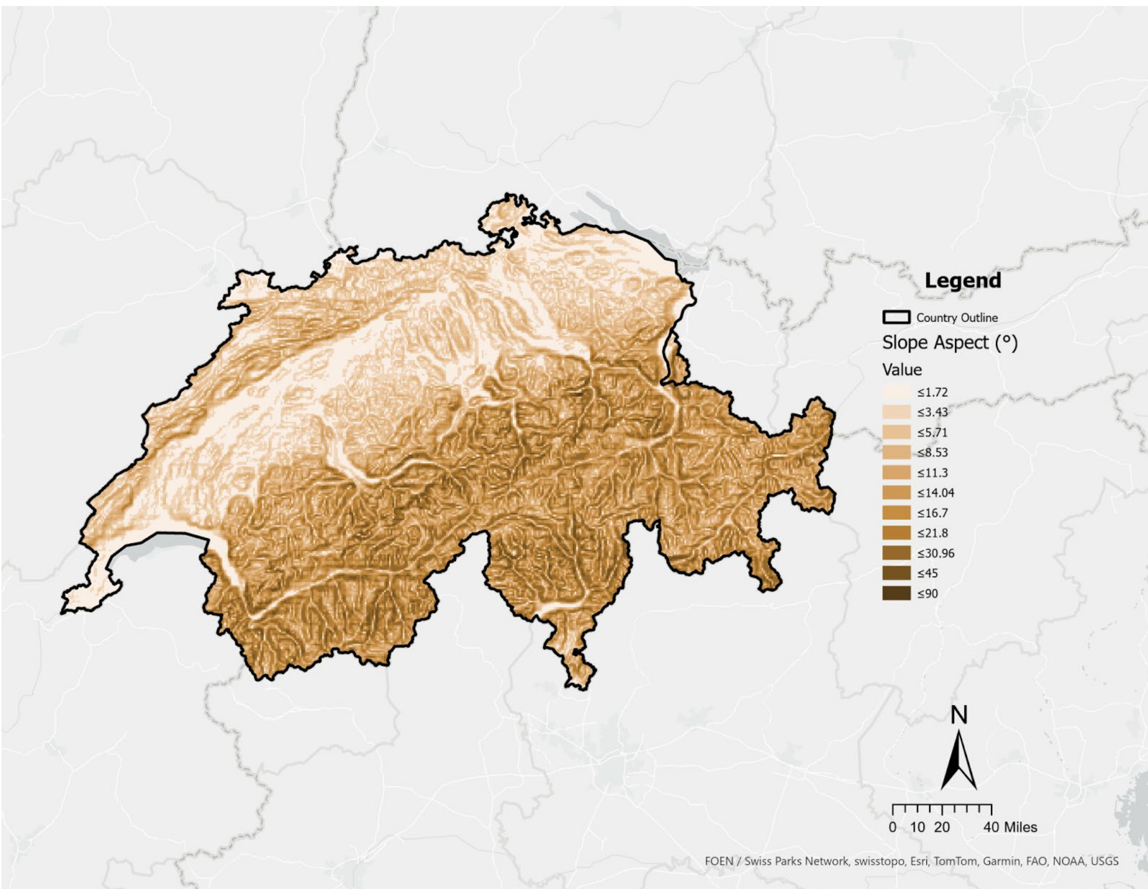

Figure 3. Weighted Slope Aspect. The map assists in understanding how terrain features affect sunlight exposure, which is key for photovoltaic farm placement.

Temperature

The yearly average temperature map highlights a gradient from colder Alpine regions to warmer lowland areas. The southern regions, particularly around Ticino, exhibit warmer temperatures, beneficial for PV efficiency, as extreme cold can reduce PV output efficiency.

Conversely, high-altitude areas with colder average temperatures might experience reduced efficiency but could still be viable with appropriate technology adjustments (Figure 4).

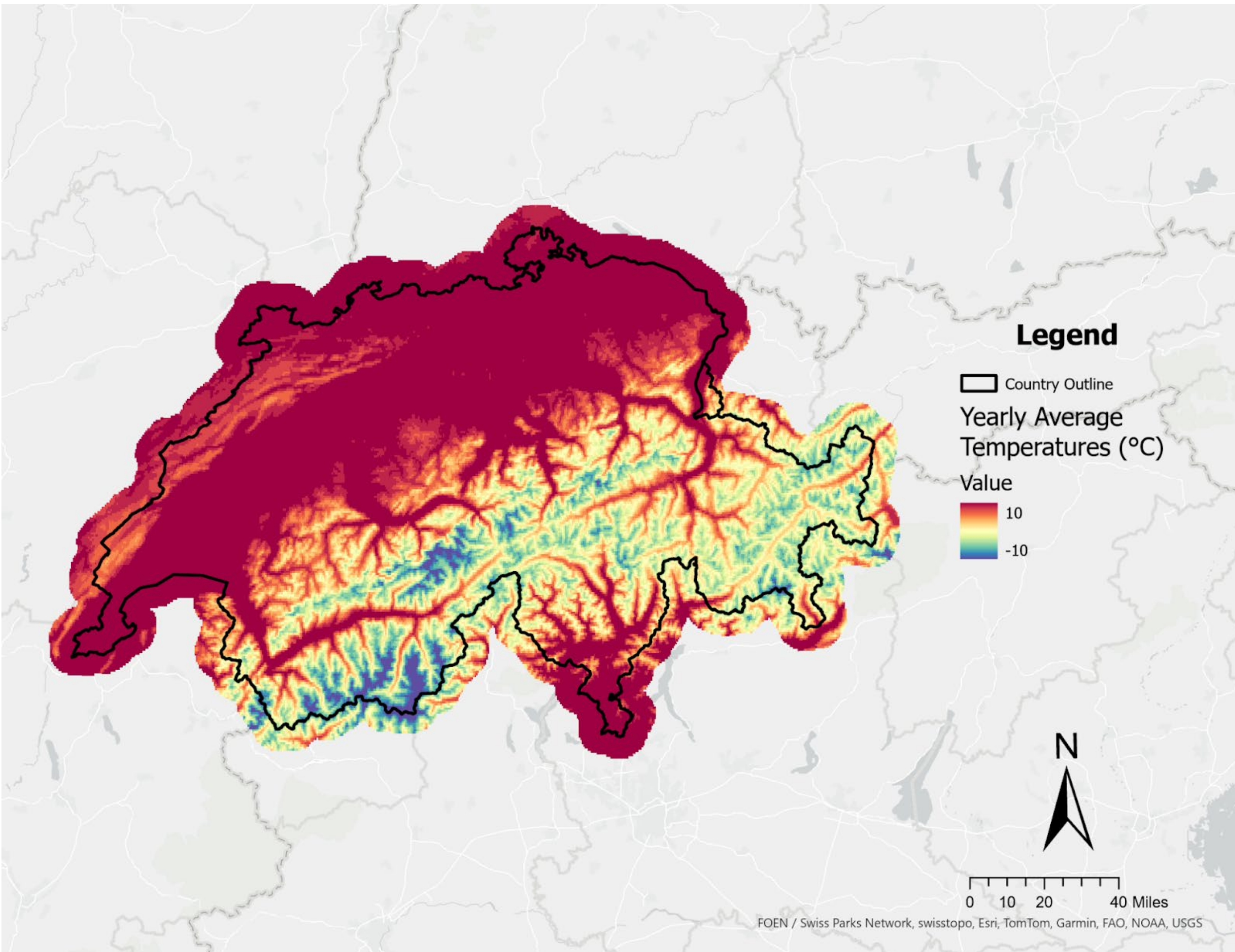

Figure 4. Yearly Average Temperatures. The map highlights cooler areas in blue and warmer regions in red, illustrating the diverse climate across the country

Full suitability model

The most suitable areas for PV farm development are primarily found in the southern parts of the country, where high solar irradiation, moderate temperatures, favorable topography, and good grid connectivity converge. These regions are delineated as highly suitable and are prioritized for potential development. Smaller, less contiguous areas in the eastern regions are categorized as marginally suitable due to lower irradiation levels or less favorable topography but may still be considered for development based on specific local conditions and technological solutions that mitigate geographical disadvantages (Figure 5).

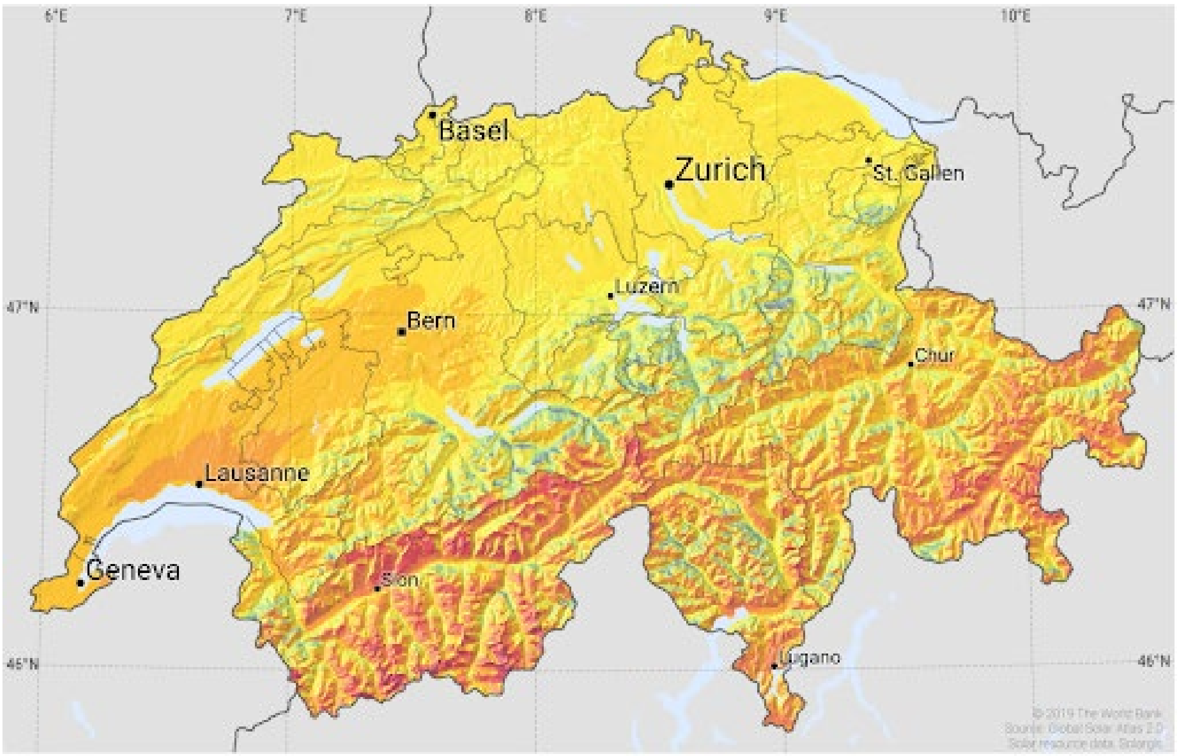

Figure 5. GIS-based suitability analysis for Switzerland.

<u>High Suitability Zones</u>: These zones are prominently visible in the southern region of the Alps, including the main southern valley that runs through Sion, and the northern parts of Ticino. These areas benefit from a combination of high solar irradiation, moderate slope gradients, optimal temperature conditions, and good proximity to existing power infrastructure – these regions are prime candidates for future PV farm developments.

<u>Moderate Suitability Zones</u>: Encroaching the high suitability areas, these zones exhibit moderately favorable conditions for PV site deployment. Such areas include the outskirts of Bern, Lausanne, and some parts near Geneva. While these areas may require more specific considerations (such as slightly lower irradiation levels), they still hold significant potential for PV farm development.

<u>Lower Suitability Zones</u>: Typically found in the Glarus Alpine regions, these areas have the lowest PV potential, largely due to challenging topographical features and cooler temperatures

which reduce PV efficiency. While not ideal, with technological advancements and strategic planning, small-scale or specialized PV installations could still be considered.

Economic Assessment

This section examines the economic viability of potential PV farm projects in Switzerland, integrating data from both the suitability analysis and economic feasibility factors discussed in the previous sections. The analysis focuses on the factors influencing the financial success of PV farms, such as installation costs, Levelized Cost of Electricity (LCOE), and long-term profitability.

Installation Costs

To estimate the economic feasibility of PV farms in Switzerland, the installation costs of a typical 1 MW solar power plant were assessed based on comparable projects. The costs for essential components, such as PV modules, inverters, and transformers, were taken from the benchmark data provided in Table 4. The overall cost for a 1 MW PV power plant in Switzerland, including construction, equipment, and other associated expenses, totals approximately $974,062.

Table 4. Cost of a 1 MW Solar Farm in USD (Zegardlo et al. 2024).

Factor	Cost
PV modules (270 W)	US$ 594,000
Inverter	US$ 98,600
Construction	US$ 78,078
Transformer kiosk	US$ 12,253
Distributing center	US$ 7840
DC cable	US$ 9744
AC cable	US$ 19,302
SCADA	US$ 9500

Transformer	US$ 12,000
Earthing	US$ 14,575
Board packages	US$ 24,464
Wire fence	US$ 5413
Camera and digital video recorder	US$ 7287
External lightning protection earth	US$ 6038
Panel mounting	US$ 11,556
Construction mounting	US$ 16,553
Area excavation	US$ 3123
Transport	US$ 7079
Financing cost	US$ 16,657
Unexpected expenses and others	US$ 20,000
TOTAL (without Value-added tax (%18))	US$ 974,062

Levelized Cost of Electricity (LCOE)

The economic feasibility of PV farms in Switzerland was evaluated through a comparison of LCOE to other generation technologies. The Alkarsaah PV farm had an LCOE of $14.03/MWh, substantially lower than conventional gas turbines. In Switzerland, where energy prices and production costs vary, achieving a competitive LCOE is crucial for economic viability.

Profitability and Payback Period

The economic analysis of PV farms should consider the long-term profitability and payback period. The economic feasibility study conducted in Turkey indicated a payback period of around 13 years for a 1 MW solar plant, while the Alkarsaah PV farm in Qatar demonstrated a lower LCOE, resulting in a shorter payback period. In Switzerland, the profitability of PV farms will depend on factors such as energy prices, government incentives, and the overall cost structure.

Projected Profit and Loss

The profit and loss projections for Swiss PV farms depend on installation costs, operating expenses, and revenue from electricity sales. Given the benchmark costs provided, and the suitability analysis identifying optimal locations, Swiss PV farms can achieve profitability if they secure favorable energy prices and government incentives.

Energy policy landscape

In assessing the policy landscape for photovoltaic (PV) system development in Switzerland, several key factors were examined, highlighting the country's robust framework used to promote renewable energy; simultaneously combining regulatory hurdles and ambitious national targets (Table 5).

Table 5. Synopsis of Current Swiss Energy Policy Landscape.

Policy Aspect	Policy Effect
Government Incentives	
Feed-In Tariff (FIT)	$0.20 per kWh, decreasing over time
Tax Rebate	Federal: 30% of installation costs; Cantonal: 10-20%
Subsidies	Up to 60% of installation costs
Regulatory Hurdles	
Zoning Laws	Special permits for agricultural land in some cantons
Building Permits	Average approval time: 6 months
Environmental Assessments	Mandatory EIAs for large PV farms
Renewable Energy Goals	
National Target	50% renewable electricity by 2030
Solar Quota	Utility quotas for solar energy sourcing

The Swiss government has established incentives aimed at bolstering a systematic implementation of PV's. A notable initiative is the Feed-In Tariff (FIT) program, which guarantees a payment of $0.20 per kWh for solar energy, with the rate decreasing over time to encourage early adoption and innovation (Concolato et al. 2020). Additionally, substantial tax rebates are offered, with federal incentives covering 30% of installation costs, and additional rebates at the cantonal level ranging from 10% to 20% (Concolato et al. 2020). Subsidies further enhance the feasibility of PV development, covering up to 60% of installation costs. These incentives substantially lower the financial barriers to entry for PV projects, making them more viable for developers and investors.

While the Swiss government provides considerable financial support for PV projects, various policy hurdles present a mixed regulatory landscape. Zoning laws vary by canton, with special permits required for agricultural land use in certain areas (Panagiotidou et al. 2016). This can complicate the development process for PV farms situated on agricultural sites. The building permit process, which typically takes around six months, presents a moderate delay, but this timeline is generally manageable for most projects. However, Environmental Impact Assessments (EIAs) are mandatory for large PV farms, which adds another layer of regulatory oversight. While necessary for environmental protection, these assessments can delay project timelines and increase development costs (Malczewski 2004).

Switzerland's ambitious renewable energy goals are driving the policy landscape for PV system development. The country has set a national target of 50% renewable electricity by 2030, underscoring a strong commitment to clean energy transition. This goal aligns with a solar quota system that mandates utility companies to source a specific proportion of their energy from solar (Bazilian et al. 2013). These objectives create a favorable market environment for PV systems, as they foster demand and signal a clear long-term direction for renewable energy.

The policy landscape also encourages public-private partnerships, a vital component for PV system development. Government-industry collaborations have been instrumental in joint PV farm projects, facilitating shared expertise and risk. Additionally, the Swiss government supports community solar projects, which in turn, allows local communities to invest in and benefit from solar energy (Weiss et al. 2021). These partnerships enhance social acceptance and facilitate the growth of distributed renewable energy generation.

In conclusion, Switzerland's policy landscape for PV system development is marked by supportive incentives, manageable regulatory hurdles, ambitious renewable energy goals, and robust public-private partnerships. This favorable environment provides a solid foundation for expanding solar energy, contributing to the country's clean energy transition.

DISCUSSION

In recent years, Switzerland has recognized the strategic importance of transitioning to renewable energy sources to address the escalating challenges of global climate change. This paper focused on leveraging GIS technology, economic modeling, and policy analysis to identify optimal locations for PV farm development in Switzerland. The study's results underscored the potential of integrating GIS-based suitability analysis with economic and policy considerations to inform renewable energy development, aligning with Switzerland's sustainability and climate goals while promoting economic growth and energy security.

Geospatial Factors Influencing Optimal Locations for Renewable Energy Projects

This section addresses the first subquestion by examining the geospatial factors that influence the selection of locations for renewable energy projects. The GIS-based suitability analysis conducted for this study revealed critical insights into solar irradiation, temperature, topography, and proximity to electric power infrastructure as significant factors.

Solar irradiation levels across Switzerland were found to vary significantly. The high solar exposure in the southern regions makes them prime candidates for photovoltaic farms which helps illustrate why those regions were deemed so favorable in the analysis, contrary to traditional conjecture. Due to the nature of how the individual criteria were weighted based on the AHP method, solar irradiation was the most influential factor for siting solar farms (Alami Merrouni et al. 2018). While the other factors played an additive role in refining the site selection process, the analysis placed heavy emphasis on the potential power generated as a result of the solar irradiance. It was also interesting to note, that although the southern alpine regions had very distinct topography, there were significant areas with moderate slope that proved key in siting the most suitable locations in that region. When looking at the respective elevation and slope maps, there are numerous regions at mid-level elevations with favorable slope characteristics. The proximity to existing power lines and stations further enhances the feasibility of developing PV farms in certain areas, as it reduces the cost and technical challenges of grid connection. This finding underscores the importance of comprehensive GIS analyses in the initial stages of renewable energy planning and development, aligning with studies that highlight the pivotal role of spatial data in enhancing site selection processes (Smith et al., 2020).

Economic Viability of Renewable Energy Projects

The economic feasibility of PV farms in Switzerland has been assessed drawing upon case studies, geospatial analysis, and key economic indicators. The results indicate that developing PV projects in Switzerland is economically viable, particularly when considering the advantageous conditions offered by certain regions and the potential for innovation in high-altitude PV installations.

The LCOE is a critical metric for assessing economic performance, reflecting the total lifecycle costs of a project against its projected energy output. The study highlighted the importance of LCOE in determining the financial viability of potential PV farms in Switzerland, drawing on examples like the Al Kharsaah PV farm in Qatar, which achieved a competitive LCOE of $14.03/MWh (Total Energies 2022). Interest rates and the cost of money significantly impact project feasibility. In Switzerland, the current interest rates and financing arrangements influence the overall project cost and payback period, echoing findings from the Elazig Solar PV Park in Turkey, where high interest rates negatively affected investments in solar power plants (Gürtürk 2019). These findings align with literature highlighting the importance of economic modeling in renewable energy development. The economic analysis, combined with the GIS suitability index, supports the second subquestion by identifying economically viable locations for PV development in Switzerland.

The comparative analysis of three case studies—Al Kharsaah PV farm, Elazig Solar PV Park, and Lac des Toules solar project—highlights the diversity and potential profitability of PV projects under varying geographical and economic conditions. The Lac des Toules solar project, located at a high elevation, serves as a prime example of the feasibility of developing alpine PV farms in Switzerland. This case demonstrates that despite the challenges associated with high-altitude installations, such as higher upfront costs and technical complexities, PV farms can still thrive economically in these locations (World Economic Forum 2022).

The geospatial analysis conducted in this study supports the notion that alpine or high-elevation PV farms in Switzerland can be economically viable. Regions with high solar irradiation, favorable temperatures, and good grid connectivity offer promising opportunities for PV development. However, it is crucial to acknowledge that higher upfront costs, such as those associated with challenging terrains or specific technical requirements, may vary across different locations. These differences in economic factors underscore the importance of site-specific assessments to evaluate project feasibility accurately (Concolato et al. 2020).

Energy Policies Influencing Renewable Energy Project Locations

Switzerland's policy landscape is marked by supportive incentives, such as the FIT program, which offers $0.20 per kWh for solar energy, decreasing over time. This initiative, along with tax rebates and subsidies, substantially lowers the financial barriers for PV projects, aligning with findings from the Al Kharsaah PV farm, where government incentives played a crucial role in project development (Total Energies 2022). Regulatory hurdles, such as zoning laws and building permits, present challenges for PV projects. The requirement for special permits on agricultural land and mandatory environmental impact assessments for large PV farms can delay project timelines, as noted in the policy review. These regulatory aspects highlight the importance of policy alignment with renewable energy goals, such as Switzerland's target of 50% renewable electricity by 2030 (Weiss et al. 2021).

Switzerland's policy landscape concerning renewable energy development and climate strategy has been evolving in a positive direction, positioning the country as a potential leader in the renewable energy sector. The favorable policy environment creates an encouraging atmosphere for renewable energy projects, particularly PV installations. The country's strategic focus on sustainability aligns well with global climate goals and reflects a progressive approach to renewable energy. However, despite these promising policy trends, renewable energy projects, particularly alpine-based PV farms, face significant challenges due to governmental and public hesitance. These challenges have led to major delays in proposed developments and, in some cases, have halted projects already in the pipeline (Young 2021). The hesitance stems partly from concerns about preserving the natural beauty of the Alps, which are a national treasure and a significant tourist attraction. The pushback against solar farms in alpine areas highlights the tension between renewable energy development and environmental conservation. The reluctance to establish solar farms in these scenic regions reflects a desire to maintain Switzerland’s aesthetic appeal, which is a critical component of its cultural identity and economic tourism sector. Balancing the need for renewable energy with the preservation of Switzerland’s natural beauty remains a complex challenge that requires thoughtful policy solutions to reconcile these competing interests.

Photovoltaic Site Development in Switzerland

In addressing the central research question, this study integrated GIS technology, economic modeling, and policy analysis to identify optimal locations for renewable energy projects in Switzerland. It found that regions in the southern parts of the country, particularly the Alpine regions, are highly suitable for photovoltaic (PV) development due to their favorable solar exposure, temperature, topography, and infrastructure. The economic modeling demonstrated the financial viability of Swiss PV farms, especially when supported by government incentives. Policy analysis highlighted both supportive measures, such as feed-in tariffs, and regulatory challenges, like zoning and environmental assessments. Despite the promising suitability of Alpine regions for PV development, public and legislative tensions exist, reflecting concerns about environmental impact and land use, which must be navigated carefully to achieve Switzerland's sustainability and climate goals while balancing economic growth and energy security.

Limitations and Further Direction

Throughout my research, I identified a couple potential errors and inconsistencies. One significant challenge encountered throughout the project was data privacy and accessibility due to paywalls and other entry barriers. There were countless examples of data being advertised as free or open source in the private sectors that ultimately required monetary contributions to gain access to in a meaningful manner. Oftentimes their advertised data turned out to be samples which only included a small subset of the actual data set. Additionally, the economic feasibility analysis faced challenges in obtaining consistent financial data from various PV projects, which was addressed by focusing on benchmark costs and utilizing industry reports for reference.

In this study, several limitations were acknowledged. The GIS model relied heavily on available geospatial data, which might not fully capture all relevant factors influencing PV suitability. Future research could benefit from more localized data collection and modeling to enhance precision. Additionally, given the public and legislative tensions around PV development in Alpine regions, future studies should focus on stakeholder engagement and explore alternative locations or designs that balance environmental concerns with energy needs.

The broader implications of this research align with themes from the introduction, particularly the transition to renewable energy and the need for strategic site selection for PV farms. The findings underscore Switzerland's potential as a leader in renewable energy, particularly in leveraging its unique geographical and economic landscape. By integrating GIS analysis, economic modeling, and policy review, the study provides a robust framework for sustainable energy development. This approach aligns with Switzerland's sustainability goals and also offers a model for other countries seeking to balance environmental stewardship with economic growth and energy security

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APPENDIX A: Raw GIS Data and Data Wrangling

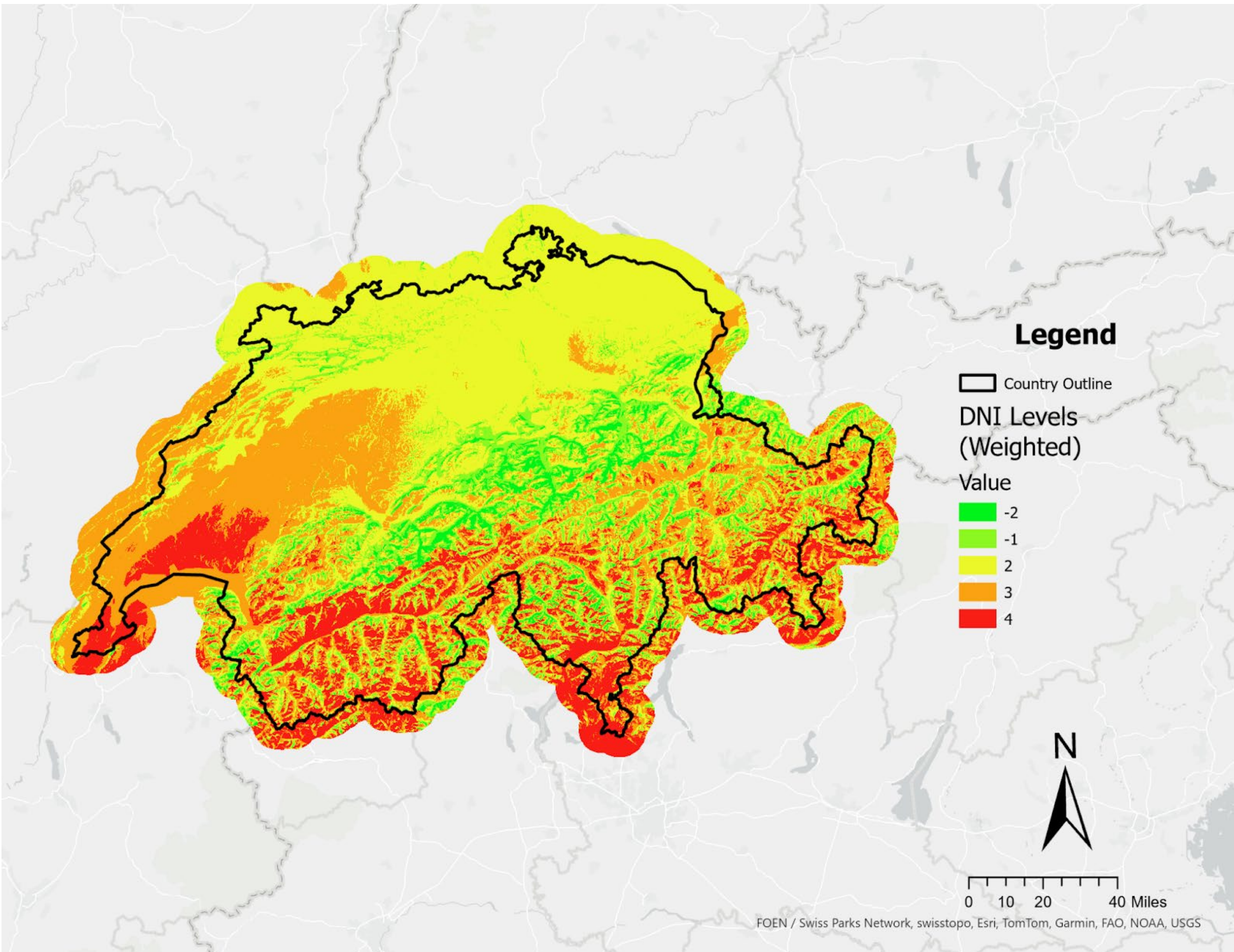

Figure A1. Weighted map of Switzerland displaying direct normal irradiation (DNI) levels. The weighted values highlight areas with the greatest potential for photovoltaic farm development, aiding in strategic site selection. The map is a result of using the reclassify tool in ArcGIS Pro to obtain 5 classes using the Jenks natural breaks optimization with the weighted values being assigned from AHP calculations. The weights range from -2 to 4 with regions receiving a 4 as a result of receiving the highest levels of solar irradiance.

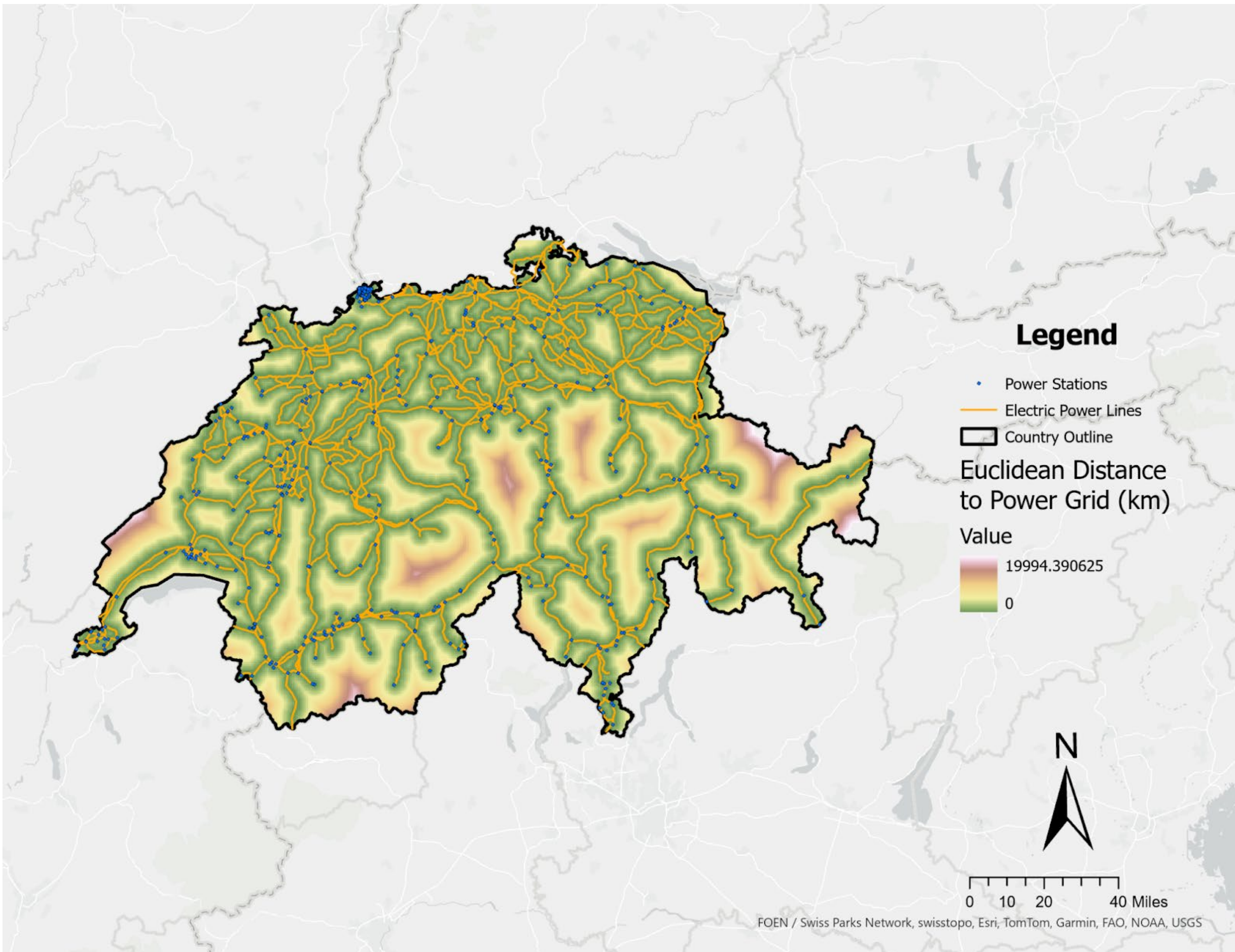

Figure A2. Map of Switzerland displaying the Euclidean distance to the power grid in kilometers. The map highlights the proximity of different areas to existing power stations and electric power lines. It was obtained by using the Euclidean Distance function within ArcGIS Pro to calculate the maximum deemed-acceptable distance from all power lines and stations. The function was set to calculate distance of 20 km from the sources, which is the pinkish-red color observed within the map.

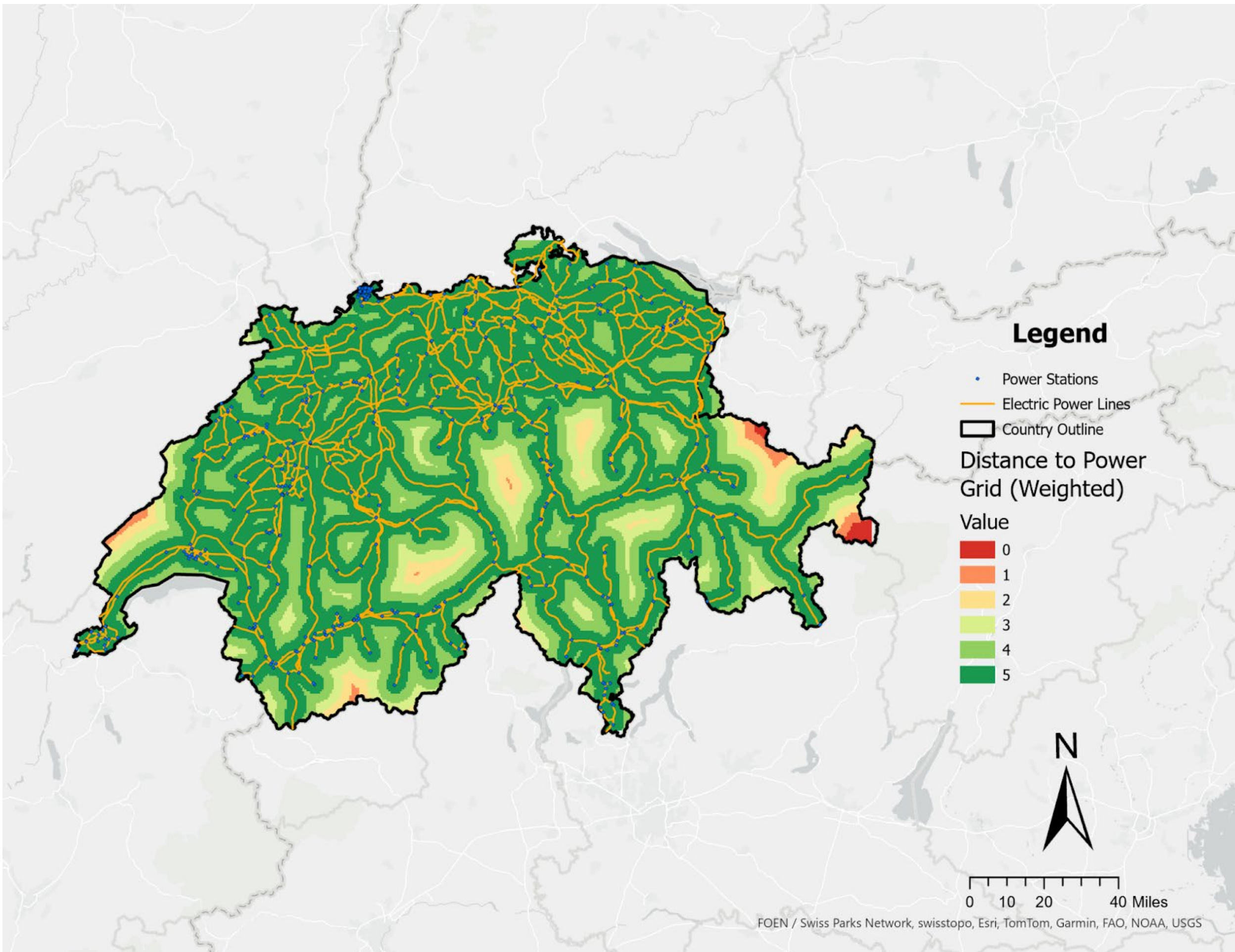

Figure A3. Weighted distance to power grid. The map illustrates the distribution of weights following the euclidean distance calculation of the original data. The map is weighted 0 to 5 with 5 being the most optimal as it would be within the closest proximity to the power grid. The map weighting was obtained by reclassifying the euclidean distance calculations into 6 classes using equal breaks.

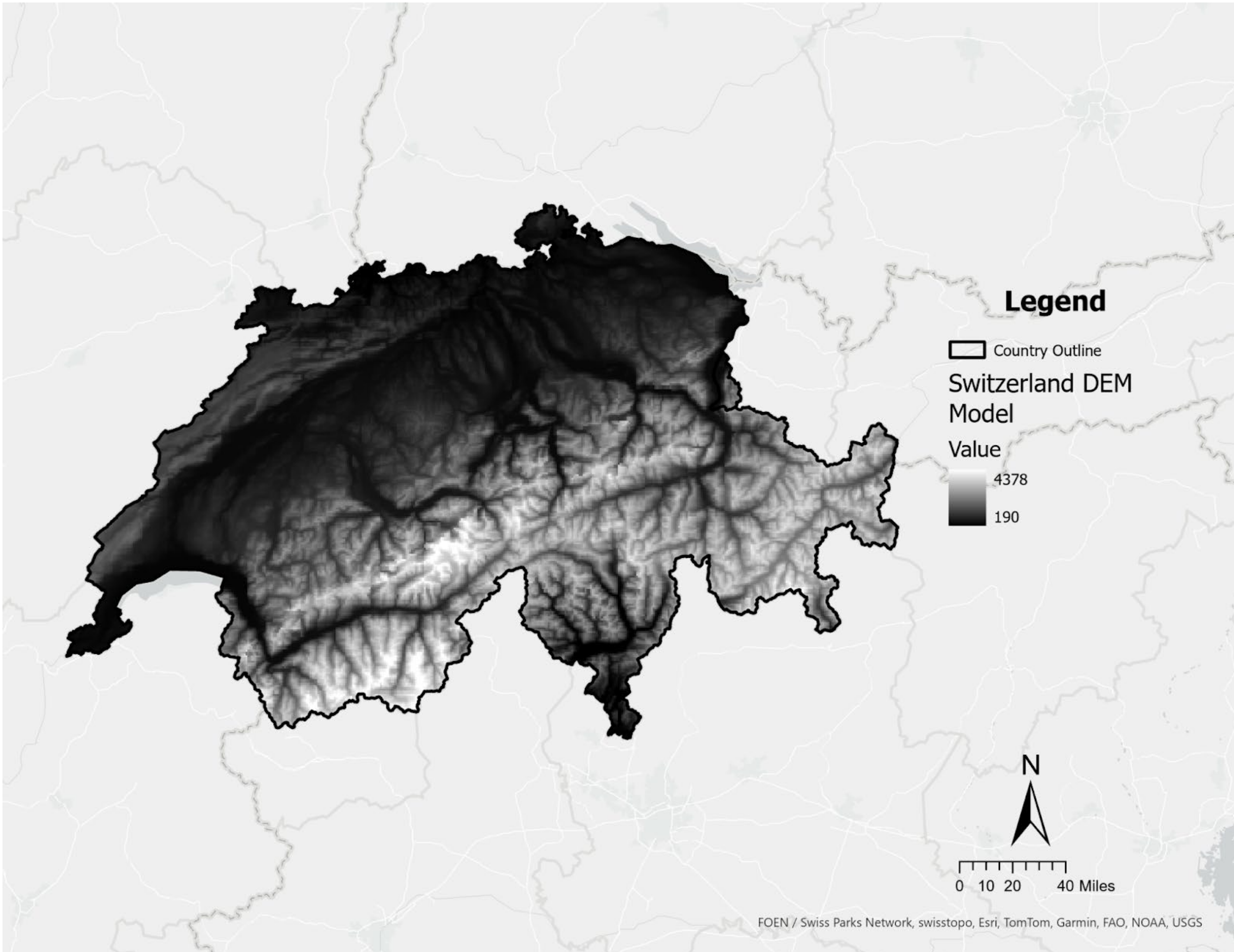

Figure A4. Digital elevation model (DEM) of Switzerland. The map highlights elevation changes across the region, with higher areas depicted in darker shades. This is the raw elevation data taken from the swissALTI3D dataset containing both the DEM and DSM datasets, updated annually by Swiss Topo (Swiss Topo 2023).

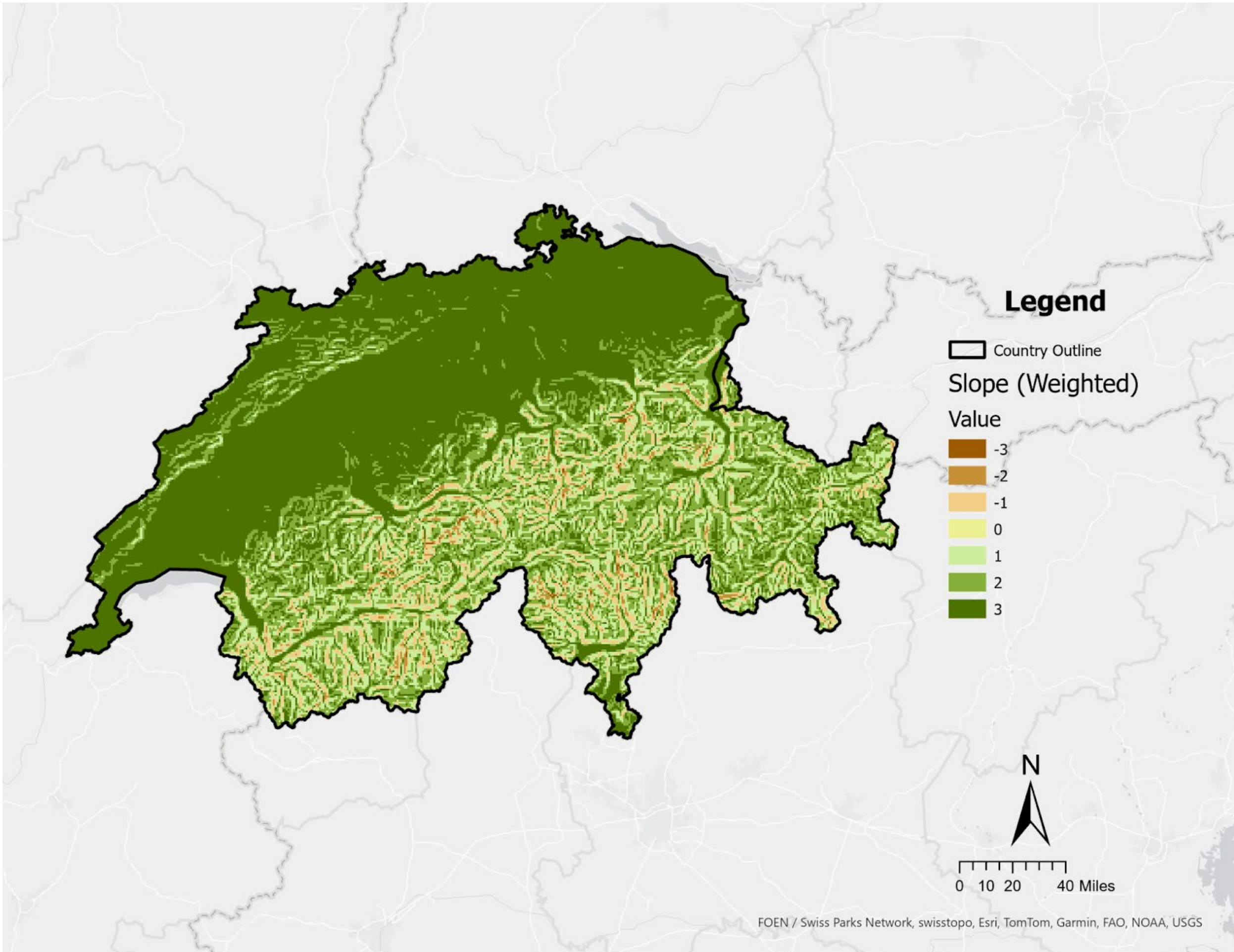

Figure A5. Weighted slope map of Switzerland. Different areas are classified based on their slope steepness and orientation. Following the slope calculator from the DEM, the data was reclassified into 7 classes using the Jenks natural breaks optimization with the weighted values being assigned from AHP calculations. The map is weighted from -3 to 3 with shallower, more favorable regions receiving a weight of 3. The map employs a color gradient to indicate slope values, aiding in the assessment of land suitability for photovoltaic farms.

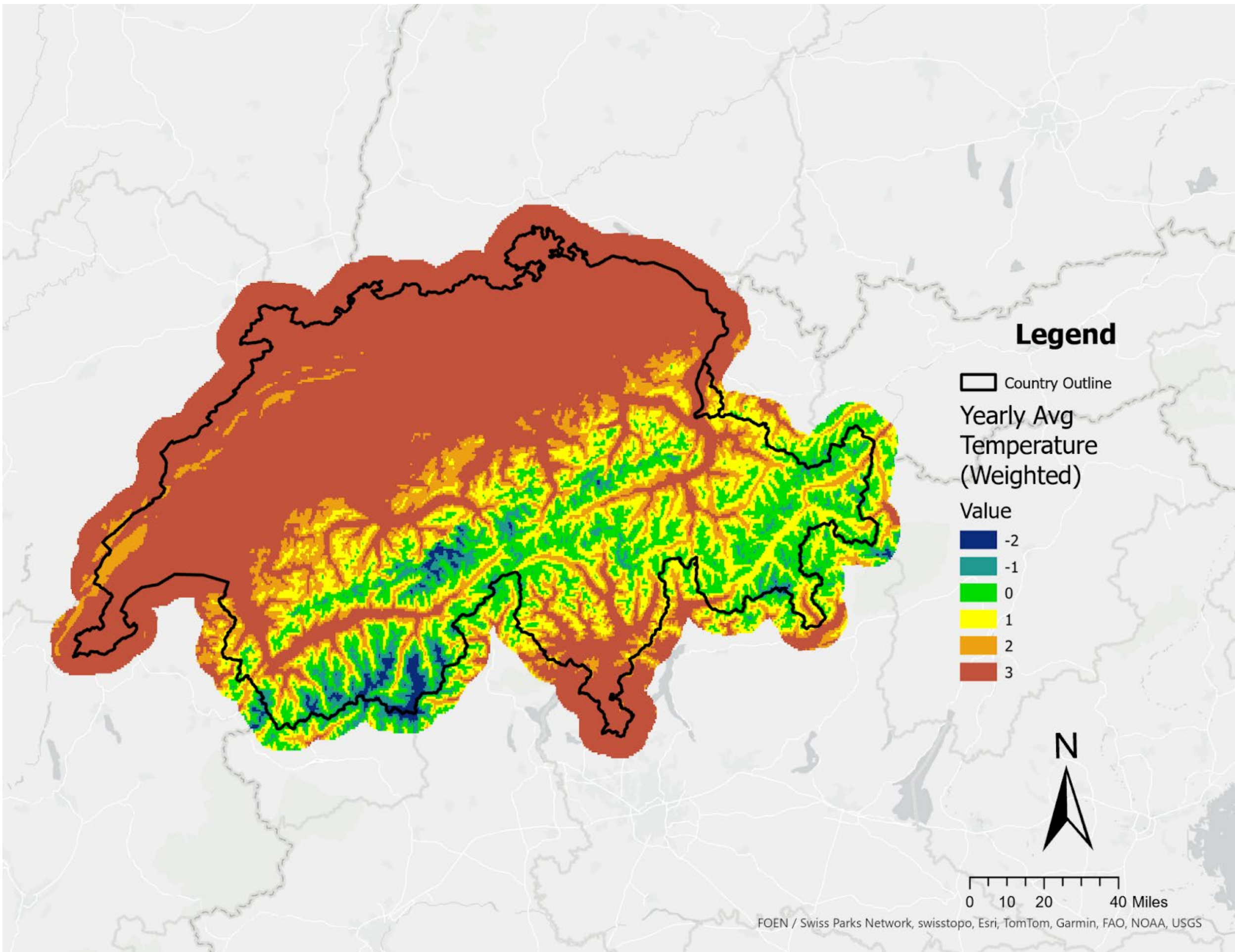

Figure A6. Weighted yearly average temperature map of Switzerland. Values adjusted to reflect the influence of altitude and topography on temperature distribution. The map is weighted from -2 to 3 with areas with a weight of 3 being the best suited for siting based on temperature. Obtained by using the reclassify tool in ArcGIS pro classifying the data into 6 equal classes. Weights were appropriately distributed based on AHP distributions.

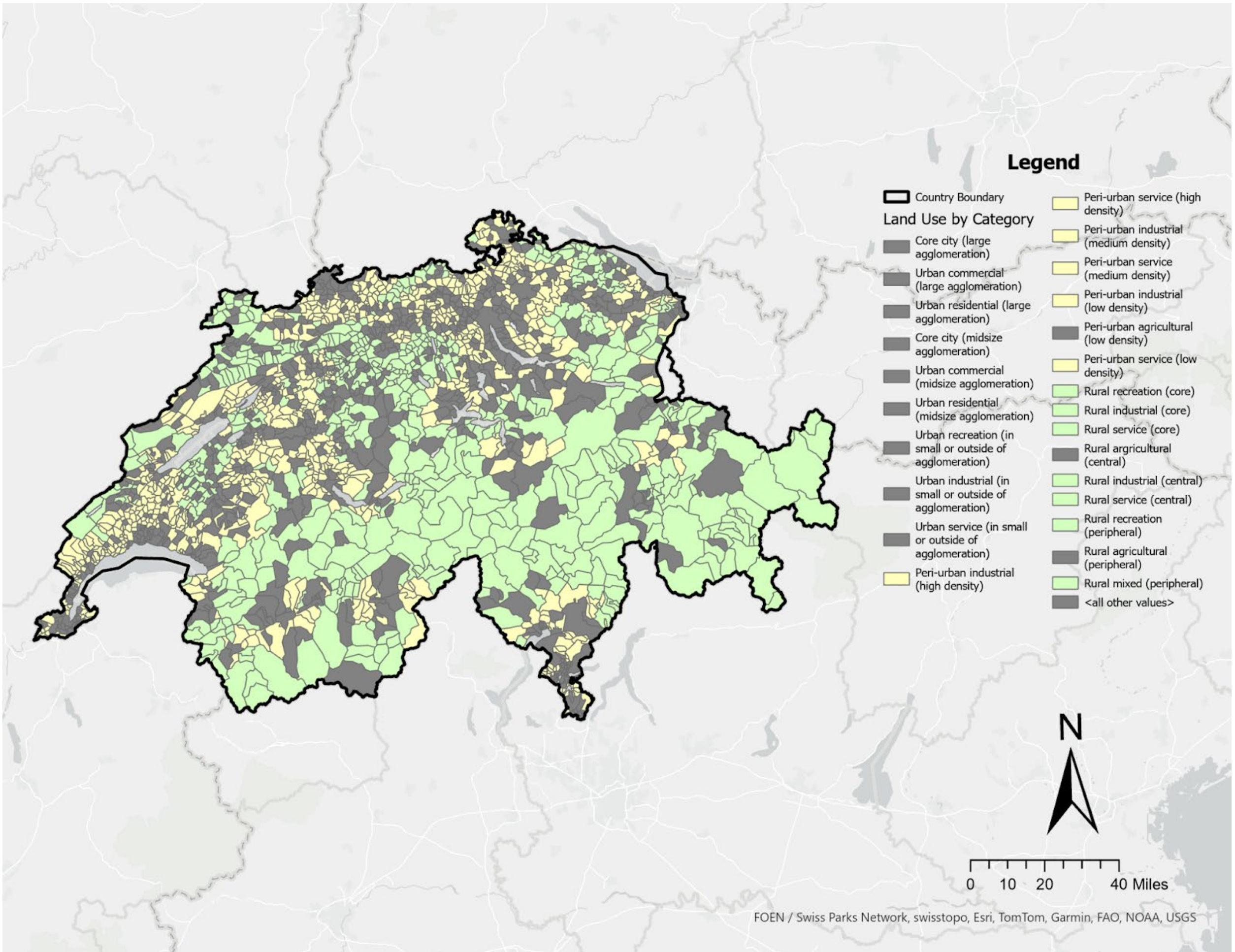

Figure A7. Land use categories in Switzerland, depicted with varying shades representing different types of land utilization. The map distinguishes between urban, peri-urban, and rural areas, each classified further based on density and type of use. While not directly involved in the final calculation of the suitability model, this categorization aids in understanding the suitability of various regions for photovoltaic farms and aligns with the focus on sustainable land use planning.