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Suitable Site Selection for Solar-Based Green Hydrogen in Southern Thailand Using GIS-MCDM Approach

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Abstract: Climate change mitigation efforts are in dire need of greener and more versatile fuel alternatives to fossil fuels. Green hydrogen being both renewable and flexible has the potential to offset fossil fuels as the primary fuel source. Countries around the world are planning to develop their green hydrogen industries and accurate potential assessment is vital. This study employed the consolidation of a geographic information system (GIS) and the analytical hierarchy process (AHP) technique of multicriteria decision making (MCDM) for the potential assessment of green hydrogen in southern Thailand, through the selection of suitable sites for solar-based green hydrogen production. Technical, economic, and environmental criteria with 10 sub-criteria were considered for the selection of suitable sites. With 0.243 (24.3%) weight, the distance from protected areas turned out to be the most important sub-criterion, whereas the criterion of elevation, with a 0.017 (1.7%) score, was considered the least important. Southern Thailand is a well-suited area for solar-based green hydrogen production, with a 4302 km^2 area of high suitability and a 3350 km^2 area of moderate suitability. These suitable areas can be utilized to develop the green hydrogen industry of Thailand, and the method developed can be employed for the assessment of green hydrogen potential in other parts of the country. Studies like these are vital for the development of green hydrogen road maps for Thailand to develop its hydrogen policy and promote investments in the sector.

Keywords: green hydrogen; solar energy; site selection; geographic information system; MCDM; analytical hierarchy process

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1. Introduction

Severe climatic disasters, such as floods, droughts, rising sea levels, wildfires, heatwaves, etc., are becoming a frequent occurrence throughout the world, causing widespread life and material losses. These severe climatic events are fueled by global warming, a result of extensive fossil fuel burning to meet our energy demands. About 81% of the world's energy demands were met by burning fossil fuels like oil, natural gas, and coal in 2018 [1]. The fossil-fuel-related CO_2 emissions have continued to rise and contributed a major portion of 30 $GtCO_2$ to global emissions in 2019 [2]. The mitigation of global warming has become the top priority of countries, as they all have pledged to make solid efforts to keep the global temperature rise well below 2 °C under the Paris agreement [3]. This ambitious target can only be achieved by limiting the use of fossil fuels and transitioning to renewables, not only in energy, but also in the industrial, transportation, and aviation sectors. A transition of this scale requires a truly universal fuel source that is not only renewable but flexible enough for application in multiple sectors. The current energy storage technologies, due to their limitations, fail to provide the versatility of applications in multiple sectors as they are designed to fulfill specific applications [4]. In addition, the intermittent nature of renewable energies like solar and wind will fail to provide the reliability of fossil fuels in the future zero-emission energy system without an efficient energy storage system [5]. The need for an efficient and flexible technology to utilize renewable energy sources for decarbonizing the energy industry is becoming more necessary than ever.

Green hydrogen, hydrogen produced from renewable energy sources like wind power, solar power, hydropower, etc., through electrolysis [6,7], is gradually emerging as a choice for countries to decarbonize their energy industry. Hydrogen is an energy carrier with a wide range of applications, such as electricity generation, heating, and fuel for vehicles, aircraft, and ships, as well as different industrial applications, such as steel productions, refineries, etc. [8]. Countries are planning to develop a green hydrogen industry, not only to decarbonize their energy industries, but also to develop it as an export commodity. Australia is developing its green hydrogen industry as a potential fuel source for reducing long-term emissions, creating jobs, and building a multi-billion dollar export industry [9]. The USA has also developed the Hydrogen Program Plan with a target to produce green hydrogen for $2/Kg and $2/Kg for its transportation along with other targets for hydrogen industry development to meet the increasing demand for hydrogen in the future [10]. The European Union is working on the development of green hydrogen across its member states to meet their climate neutrality targets and estimates that by 2050, green hydrogen will contribute 24% or 2250 TWh of their energy demand [11]. New Zealand's hydrogen opportunity report discusses the prospects of growing green hydrogen markets in Asia and the role it can play in exporting green hydrogen to those countries [12]. Similarly, 30 nations have published their green hydrogen road maps, which highlight the importance of developing a green hydrogen industry.

Thailand, an emerging economy in the ASEAN region, relies heavily on fossil fuels to meet its growing energy demands. A total of 36.1% of oil accounts for a majority share in meeting its energy demands, followed by natural gas and coal at 31.2% and 12.2%, respectively, and it is predicted to grow in the coming decades [13]. Due to very limited indigenous oil and coal reserves, Thailand imports the majority of these commodities, severely compromising its energy security. The generation of electricity in Thailand is also dominated by fossil fuels, with natural gas producing 63.2% of the electricity and coal generating 17.86% [14]. However, the country has planned some ambitious targets to diversify its energy mix and increase the share of renewable sources from 20% to 30% by 2036 [15]. This plan tends to increase the solar and wind power capacity of Thailand to 9000 MW, with solar power accounting for 6000 MW and wind power 3000 MW. Similarly, the hydropower capacity will be increased to 3200 MW and bioenergy to 6700 MW [16]. With its abundant renewable sources of solar power, hydropower, and biomass energy, Thailand can develop its green hydrogen industry, not only to cut its reliance on oil imports, but also to improve the reliability of its energy system to accommodate a greater share of renewable sources. Unfortunately, Thailand has yet to draft its green hydrogen road map to develop plans and set targets for the development of this industry and encourage investments in this sector [17]. The potential assessment of green hydrogen will help Thailand develop its green hydrogen road map to define policies and targets for the development of the industry. It will also encourage investors to look for opportunities in investing in the green hydrogen industries based on the available potential.

Spatial analysis techniques have become a cost-effective, fast, and reliable tool for the potential assessment of renewable energy sources. Numerous studies have been carried out for the potential assessment of renewable sources like solar power, wind power, hydropower, biomass, etc., using spatial analysis tools like GIS. The review of studies carried out for the assessment of solar energy using GIS for mapping the sites, design, and planning of solar systems is presented in [18]. The GIS-based technique was used for the wind power potential assessment of the Cordoba province of Spain, which was previously considered unsuitable for such an assessment [19]. A hydrokinetic power potential assessment was completed for the U-Tapao river in Southern Thailand using GIS and SWAT analysis [20]. The estimation of biomass energy production from agriculture residue was carried out using GIS in India, where areas with huge agricultural residue were mapped to be used for the production of bioenergy [21]. The development of renewable energy sustainability is a coordinated effort of multiple stakeholders, ranging from the government's policymakers to the members of the communities. The involvement of multiple stakeholders, when not addressed properly, often leads to conflicts of interests, resulting in undermining the achievement of the intended targets. The consolidation of GIS with MCDM techniques provides an even more useful and effective tool for the assessment and sustainable development of renewable energy as it can involve multiple stakeholders in the decision-making process. The involvement of stakeholders in the decision-making process reduces the conflict of interests, which is vital for the sustainability of renewable energy development.

The GIS-MCDM has been used for the assessment of renewable energy through the selection of suitable sites throughout the globe. Suitable sites selection in the United Arab Emirates, using the GIS-AHP approach for concentrated solar power sites, was executed in [22]. A total of 17.53% of the Al-Qassim region in Saudi Arabia was identified as 'most suitable' and 'suitable' for the production of solar-based electricity using a GIS-AHP-based technique [23]. Areas of 524.5 km^2 and 147.2 km^2 were selected for the production of electricity from solar and wind power, respectively, in the Igdir province in Eastern Turkey using a GIS-AHP method [24]. The selection of wind-based green hydrogen production and hydrogen refueling station sites using GIS-AHP in the Adrar region of Algeria identified 2.95% of the region highly suitable, 54.9% moderately suitable, and 41.34% unsuitable for wind-based green hydrogen production [25]. The GIS-MCDM technique was used for the selection of utility-scale solar and wind farm sites considering multiple criteria in the Philippines [26]. The Andean region of continental Ecuador was selected as the most suitable site for wind farm installation using GIS-MCDM methods [27]. Similarly, the GIS-MCDM approach is also used for the assessment of solar- and wind-based green hydrogen but the study in this field is limited. A total of 31 major cities of Iran were assessed for the potential of green hydrogen, considering 14 criteria using the fuzzy multicriteria decision-making technique and GIS [28]. The GIS-MCDM method was employed for land suitability evaluation of solar-based green hydrogen using in Algeria [29]. A regional decision support system based on GIS-MCDM was used for the identification of green hydrogen production sites from renewable energies in the northern Italian region [30]. Hence, the combination of GIS-MCDM is a powerful and reliable approach for the assessment of renewable energies including green hydrogen, as evidenced by the above-mentioned studies.

This study is focused on the identification of highly suitable sites for solar-based hydrogen production in the 14 southern provinces of Thailand using a GIS-AHP-based approach, considering technical, economic, and environmental criteria. To the best of the authors' knowledge, it is the first study for the assessment of green hydrogen in tropical Southeast Asia including Thailand. Studies like these are very essential for the development of the green hydrogen road map of Thailand and the development of its green hydrogen sector.

2. Materials and Methods

2.1. Study Area

Southern Thailand is located between 5.789 to 11.026 to °N, 99.545 to 101.698 °E on the Malay Peninsula, bordering Malaysia to the south, as shown in Figure 1. The region covers a total area of 70,714 km^2 comprising 14 provinces, namely Chumphon, Nakhon Si Thammarat, Krabi, Narathiwat, Phang Nga, Phatthalung, Pattani, Phuket, Ranong, Satun, Songkhla, Surat Thani, Trang, and Yala. The region has a typical rainforest climate with temperatures averaging around 30 °C. December to May are the driest months with little or no rainfalls followed by a wet session from April to November with 1200–4500 mm of rainfall. The region has good solar power potential, with the majority of the areas having 5 kWh/m^2 horizontal irradiation [31] that can be utilized to produce green hydrogen.

Figure 1. Study area.

2.2. Methodology

A methodology using the consolidation of GIS and AHP was developed in this study for the selection of suitable green hydrogen production sites, as presented in Figure 2. Technical, economic, and environment considerations were selected as the three major criteria, with 10 sub-criteria as presented in Table 1, based on the literature [26,32–34], discussions with experts, and Thailand's environmental protection laws [35,36]. These criteria are in line with the standards followed around the world for the selection of green hydrogen sites and comply with Thailand's laws and regulations.

Table 1. Selected Criteria.

Main Criteria	Sub-Criteria
Technical	Hydrogen generation potential Proximity to major urban centers Slope Elevation
Economic	Distance to road Distance to transmission lines
Environmental	Distance to waterbodies Distance to protected areas Distance from residential areas Land type used

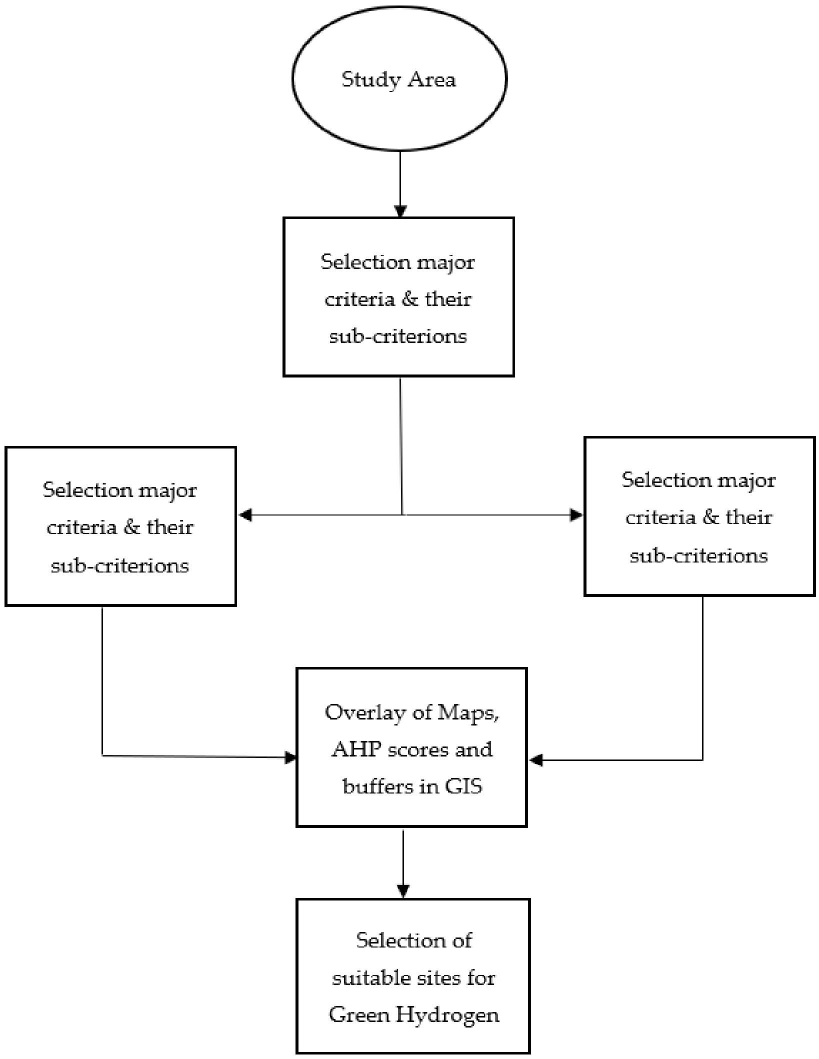

Figure 2. Methodology of the study.

The identification of suitable green hydrogen sites was done using the following multi-step procedure.

- Selection of major criteria and their sub-criteria from literature, discussions with experts, and Thailand's environmental protection laws.
- Calculation of weight (importance) of each criterion using the AHP. Experts in the field related to renewable energy, green hydrogen, Thai government departments, etc., were asked to fill out a questionnaire designed for the pairwise comparison of the selected criteria. Based on their scoring, the weights of each criterion were calculated using the AHP.
- Maps of the selected criteria were collected from different sources and modified using GIS to be used in our study.
- Finally, the maps of different criteria were overlaid, incorporating their weights calculated through AHP and the suitable buffer areas to identify the most suitable sites for green hydrogen production.

2.3. Data Description

The required data were obtained from the relevant government departments, websites, etc., as summarized in Table 2, and were modified to be used in this study.

Table 2. Description of Data.

Data Layers	Format	Spatial Resolution	Source
Digital elevation model (DEM)	Raster Grid	100 M	Royal Thai Survey Department (RTSD), 2002
Land use map	Vector	1:50,000	Land-Development Department, 2012
National parks, protected forest map	Vector	1:50,000	Department of Environmental Quality Promotion, 2010
Road map	Vector	1:50,000	Department of Environmental Quality Promotion, 2010
Transmission line map	Vector	1:50,000	Provincial Electricity Authority, 2018
Residential area Map	Vector	1:50,000	Land Development Department, Sentinel Satellite 2020
Solar radiation Map	Vector	1000 M	Solargis, 2020
Elevation	Vector	30 M	USGS, 2010
Waterways and waterbodies	Vector	1:50,000	Department of Environmental Quality Promotion, 2018

2.4. Definition of Buffers for the Criterions

Buffer ranges with suitability scores were defined for each criterion, as shown in Table 3, to use for the selection of green hydrogen sites. The score of 3 represents high suitability, progressively reducing towards 0, which shows the buffer range is not suitable for the selection of sites.

Table 3. Buffer ranges for the criteria.

Score	Distance to Roads &Rail-way Lines (Km)	Distance to Trans-mission Lines (Km)	Distance to Water Bodies & Ways (km)	Distance to Protected Areas (Km)	Hydrogen Generation Potential (Kg/Km^2/Year)	Land-Type Used	Distance to Resi-dential Areas (km)	Proximity to Major Urban Centers (km)	Slope (%)	Elevation (m)
3	0.5–2	0.5–2	0.5–2	>3	>6000	Baren land, old mining areas etc.	>1.5	1–5	0–5	>100
2	2–5	2–5	2–4	2–3	5500–6000	Agriculture (low value)	1–1.5	5–10	5–10	75–100
1	5–10	5–10	4–5	1–2	5000–5500	Agriculture (High Value)	0.5–1	10–20	10–15	50–75
0	<0.5, >10	<0.5, >10	<0.5, >5	< 1	>5000	Residential, Protected forests etc.	<0.5	> 20	>15	<50

3 = High suitability, 2 = Moderate suitability, 1 = Low suitability, 0 = Not Suitable.

2.5. Technical Criteria

The technical criterion was selected as one of the major criteria. Technical assessment is vital for the assessment of any renewable energy project, including green hydrogen. Four sub-criteria were selected for the technical assessment of suitable green hydrogen sites.

2.5.1. Hydrogen Generation Potential

This study is focused on the assessment and selection of solar-based green hydrogen sites in the southern region of Thailand. The solar radiation map of Southern Thailand, shown in Figure 3, was used to calculate the green hydrogen production potential of the region. The region's solar radiation is between 3–5 kWh/m^2/day.

A monocrystalline photovoltaic solar panel with a module efficiency of 20.5% and peak power output of 530 watts was used for the calculation of annual solar energy production. The annual energy produced by the solar panel was calculated using Equation (1) [37].

$$E_{Pv} = \eta_{Pv} \times \eta_{PG} \times G \tag{1}$$

where $\boldsymbol{G}$ is the annual horizontal solar irradiation, kWh/km^2/year, $\boldsymbol{\eta_{Pv}}$ is the module reference efficiency (%), and $\boldsymbol{\eta_{PG}}$ is the power conditioning efficiency (%)

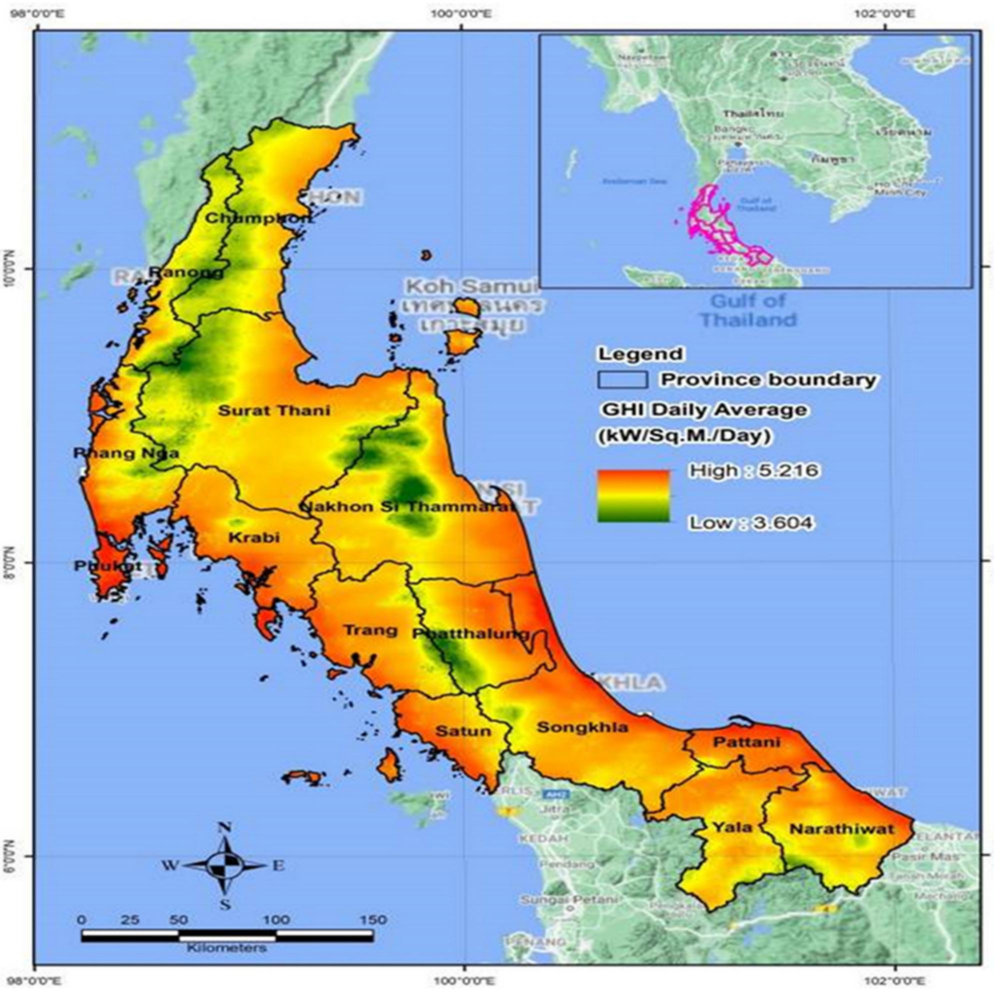

Figure 3. Solar radiation map of Southern Thailand.

To produce green hydrogen from electrolysis, a Polymer Electrolyte Membrane (PEM) electrolyzer with 75% efficiency and an electrolytic rate of 52.5 kWh/kg of hydrogen was considered [29]. Solar energy transferred to the electrolyzer to produce green hydrogen is presented by Equation (2).

$$\boldsymbol{E_{H_2}} = \boldsymbol{\eta_1} \times \boldsymbol{\eta_2} \times \boldsymbol{E_{Pv}} \tag{2}$$

where $\boldsymbol{\eta_1}$ is the electrolyzer operation efficiency (%), $\boldsymbol{\eta_2}$ is the electrolyzer losses (%), and $\boldsymbol{E_{Pv}}$ is the solar electric source production, kWh/km^2/year.

Finally, the annual solar-based hydrogen production was calculated using Equation (3) [38].

$$\boldsymbol{MH_2} = \frac{\boldsymbol{E_{H_2}}}{\boldsymbol{HHV_{H_2}}} = \frac{\boldsymbol{\eta_{Elec} E_{Pv}}}{\boldsymbol{HHV_{H_2}}} \tag{3}$$

where $\boldsymbol{MH_2}$ is the annual hydrogen production [kg/km^2/year], $\boldsymbol{E_{H_2}}$ is the hydrogen energy produced [kWh/km^2/year], $\boldsymbol{HHV_{H_2}}$ is the hydrogen higher heating value (39.4 kWh/kg), and $\boldsymbol{\eta_{Elec}}$ is the efficiency of the electrolysis system.

The annual solar-based green hydrogen production was calculated using the above formula in an Excel spreadsheet and mapped, as shown in Figure 4, for each point of the study area.

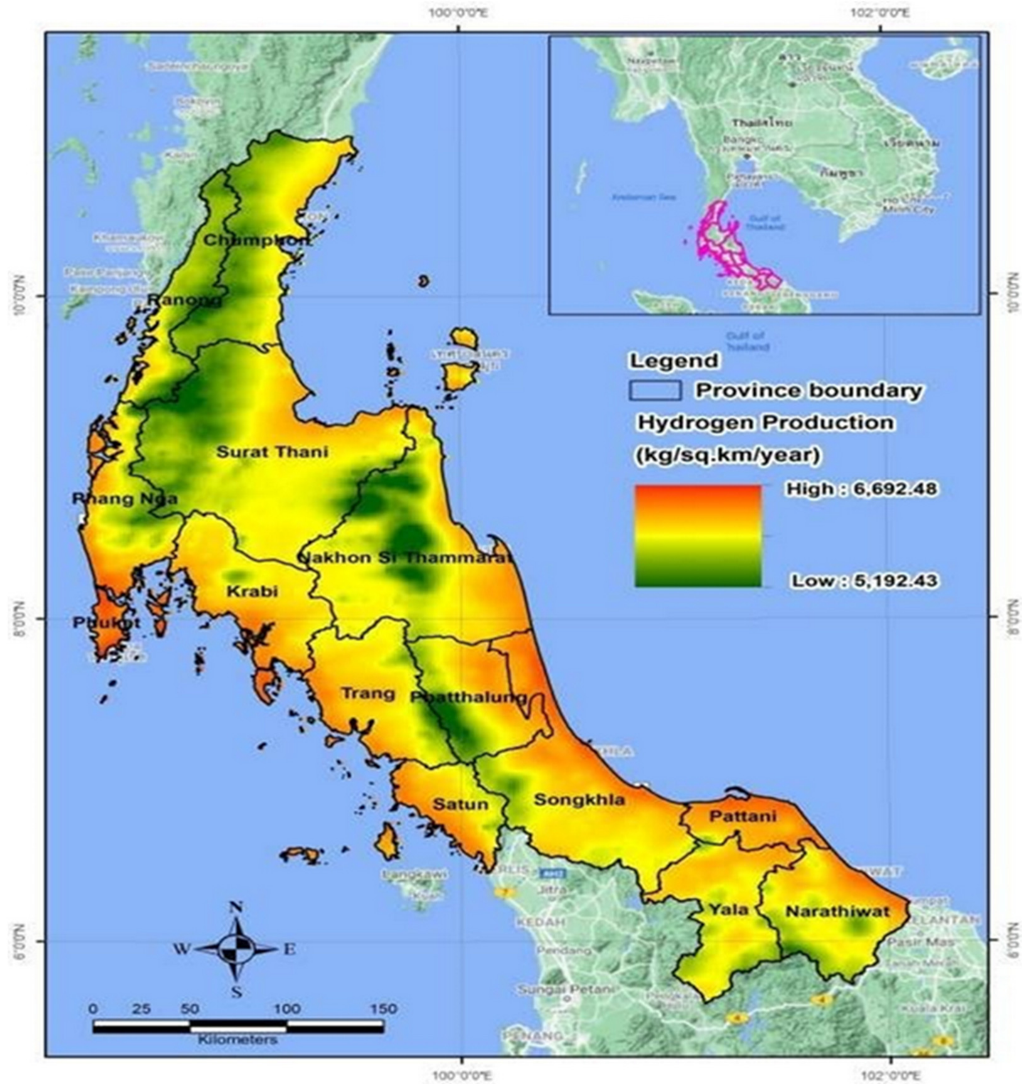

Figure 4. Solar-based hydrogen production.

2.5.2. Proximity to Major Urban Centers

The demand for hydrogen as fuel will be an important factor for the development of green hydrogen as an industry. Major urban centers, with their transport, industries, residential, and other economic sectors, will be the major venues for the use of green hydrogen as a fuel source. The proximity of green hydrogen production sites to major urban centers will play an important role in the logistics, as well as the economy of hydrogen production and transport.

A map of major cities and towns in Southern Thailand was extracted, as shown in Figure 5, and the buffer ranges are defined as shown in Table 3.

2.5.3. Slope

Areas with steep slopes are not suitable for the construction of PV solar plants and hydrogen production sites due to the challenges they pose for accessibility, as it would be difficult for trucks and other modes of transportation to reach the site, increasing the costs and technical challenges [32,33]. As a result, areas with flat terrain were given higher suitability scores. The digital elevation model (DEM), shown in Figure 6, was used to calculate the slope of the study area.

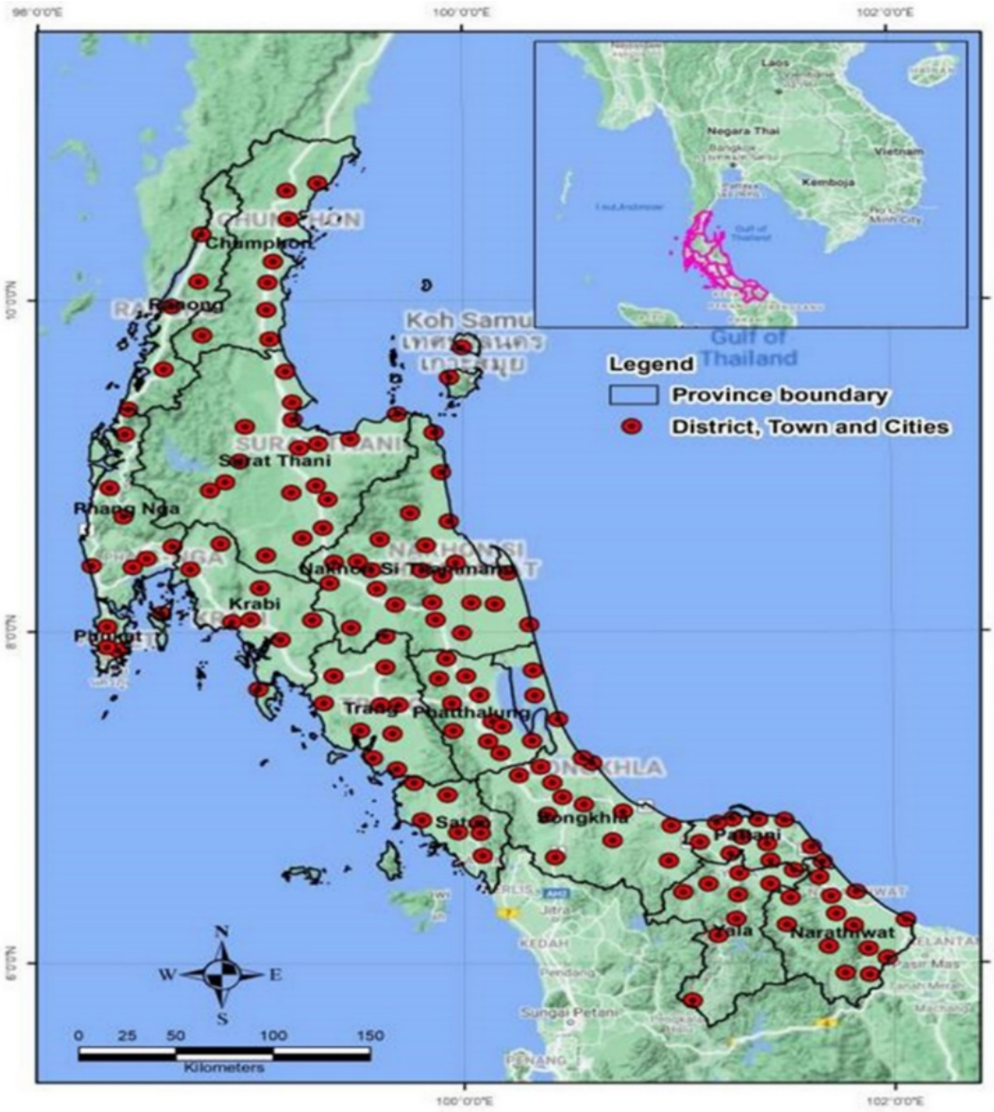

Figure 5. Major cities and towns of Southern Thailand.

2.5.4. Elevation

The efficiency of PV solar panels is much better at higher elevations due to temperature levels increasing the energy production [33,39], which can increase green hydrogen production as well. Higher elevation areas were considered more suitable for the selection of suitable areas for solar-based green hydrogen production due to the advantages they offer for PV solar panels. A 30 m resolution DEM of the study area was extracted and used as shown in Figure 6.

2.6. Economic Criteria

Economic feasibility is one of the most important criteria that need to be considered for the development of any project. The distance to roads and railway networks and transmission lines are considered the two sub-criteria for the economic assessment of suitable green hydrogen sites in the study area.

2.6.1. Distance to Roads and Railway Lines

Road and railway accessibility are vital for both the construction of infrastructures and transportation related to green hydrogen. Being close to roads and railway networks will significantly bring down the construction and transport costs as the construction of new roads and railways can be avoided. Areas in the proximity of existing roads and railway lines were given high suitability scores [26,40]. The map of existing roads and railway lines in Southern Thailand is shown in Figure 7.

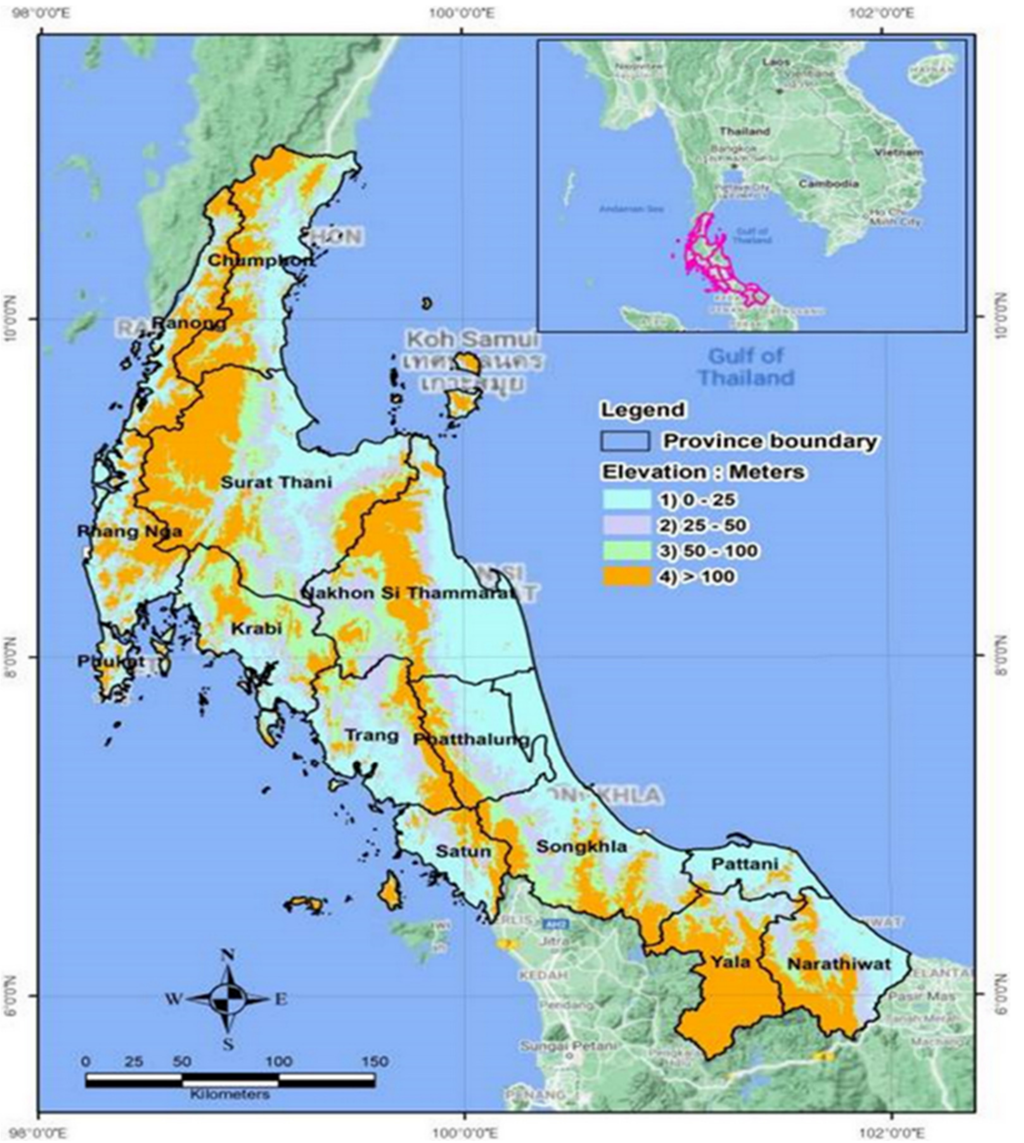

Figure 6. DEM of study area.

2.6.2. Distance to Transmission Lines

Distance to transmission lines is also a major cost factor for the selection of green hydrogen sites. Areas near the transmission line networks will incur a lower cost and line losses [33,41]. Existing transmission lines can also be used to supply surplus renewable energy from other regions for the production of green hydrogen, further adding value to the available renewable energy sources. The site suitability of areas near existing transmission lines was given higher scores compared to areas further away from them. The network of transmission lines in the study area is shown in Figure 8.

2.7. Environmental Criteria

Without considering environmental criteria, sustainable development of any project is deemed incomplete. Thailand has some very strict environmental protection laws, which are very essential for the development of any project [35]. Four sub-criteria were selected under the environmental criterion to assess the environmental suitability of the green hydrogen sites.

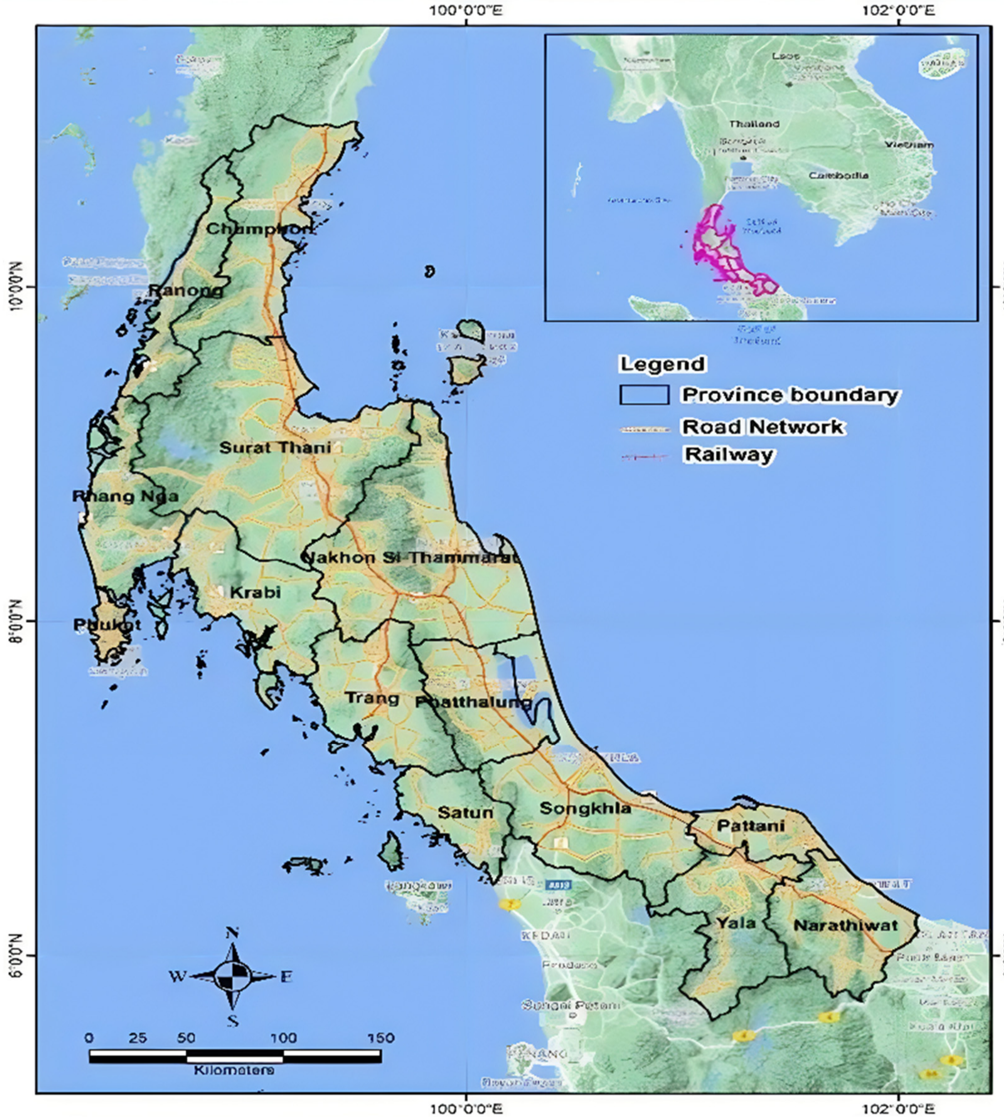

Figure 7. Roads and railway network.

2.7.1. Distance to Waterbodies

Water is a vital commodity in the electrolysis process that produces green hydrogen; therefore, the proximity of suitable sites to available waterbodies or waterways is of utmost importance. However, waterways are very protected in Thailand, with watershed classes 1 and 2 being completely off-limits for the development of any projects [36]. Therefore, the areas less than 0.5 km from waterbodies and waterways are considered unsuitable for the selection of green hydrogen production sites in order to avoid water contamination as well as provide protection from natural disasters such as floods, which are becoming commonly frequent in recent years due to climate change. Similarly, areas more than 5 km from available waterbodies were given lower scores to bring down the cost for the supply of water from a great distance. The available waterways and waterbodies in the study area are shown in Figure 9.

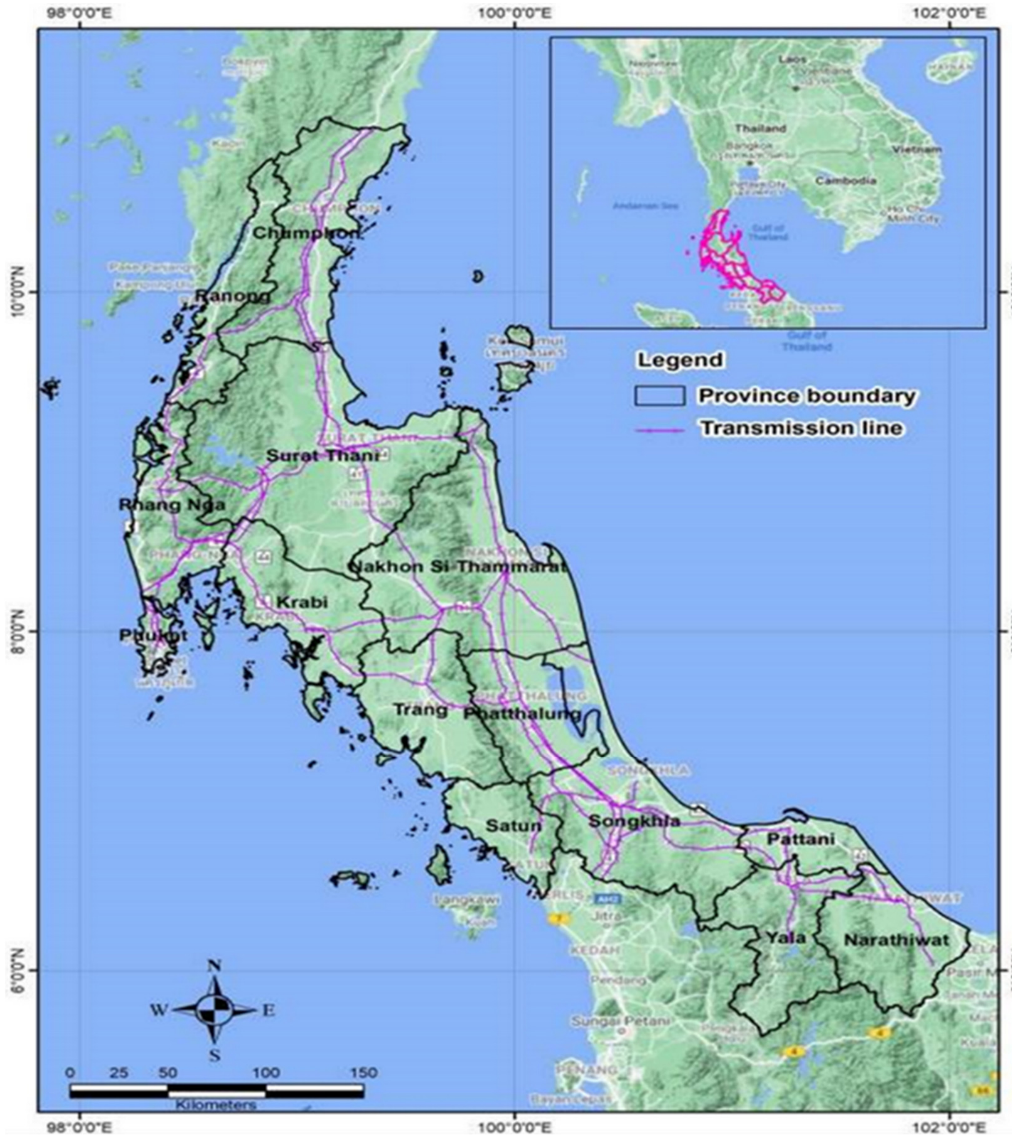

Figure 8. Power transmission network of Southern Thailand.

2.7.2. Distance to Protected Areas

National forests, animal reserves, and other forested areas are very well-protected under Thai environmental protection laws like the National Forest Act (1969), the Wild Animal Reservation and Protection Act (1960), and cabinet resolutions that strictly protect the forests and national parks of Thailand. Development of any sort in these areas needs special permissions, which are very hard to come by. Therefore, areas in proximity to the protected areas shown in Figure 10 are given the lowest suitability scores.

2.7.3. Land Type Used

The construction of solar farms and green hydrogen production structures requires a significant amount of land. The selection of land type will have a great impact on the surrounding environment as well as on the economics of the project. The use of forested areas for the projects will lead to deforestation, whereas the use of agricultural land might lead to land use conflicts. Therefore, the selection of land use is vital for the environmental benefits and for the prevention of conflicts of interest among stakeholders. For this study, barren, unutilized lands such as old mining sites, etc., were given higher suitability scores while residential, agricultural, forested, and commercial areas were given lower suitability scores. The map of land use in the study area is presented in Figure 11.

Figure 9. Available waterways and water bodies in the study area.

2.7.4. Distance from Residential Areas

Distance from residential areas is very necessary to avoid inconveniences caused to the residents from noise pollution and visual intrusions. Distance from residential areas has been given similar importance in many renewable energy studies [34,39,40]. Therefore, a 500 m buffer is defined as an exclusion zone with the minimum suitable score defined to avoid any site selection for green hydrogen production near residential areas, as shown in Table 3. Figure 12 shows the map of the residential areas in the study area.

2.8. Calculation of Weights Using AHP

AHP, introduced by Saaty [42], has been vastly used in studies for the assessment of renewable energies involving multiple criteria due to its effectiveness and simplicity [43]. AHP reduces complex decision problems into simpler hierarchical structures and utilizes the judgment of experts through a pairwise comparison technique to determine the relative importance of involved criteria in the form of scores assigned to each of them [44]. The criteria are selected based on the objective of the research, which, in the case of this study, is the selection of suitable solar-based green hydrogen sites in Southern Thailand using technical, economic, and environmental criteria, and the hierarchy of the criteria are defined as shown in Table 2. The AHP also uses a method to check the consistency of experts' scoring to eliminate any personal bias [45]. The pairwise comparison of criteria by the experts is completed using a scale defined by Saaty, which is shown in Table 4; the scale helps experts score the relative importance of criterion compared to each other.

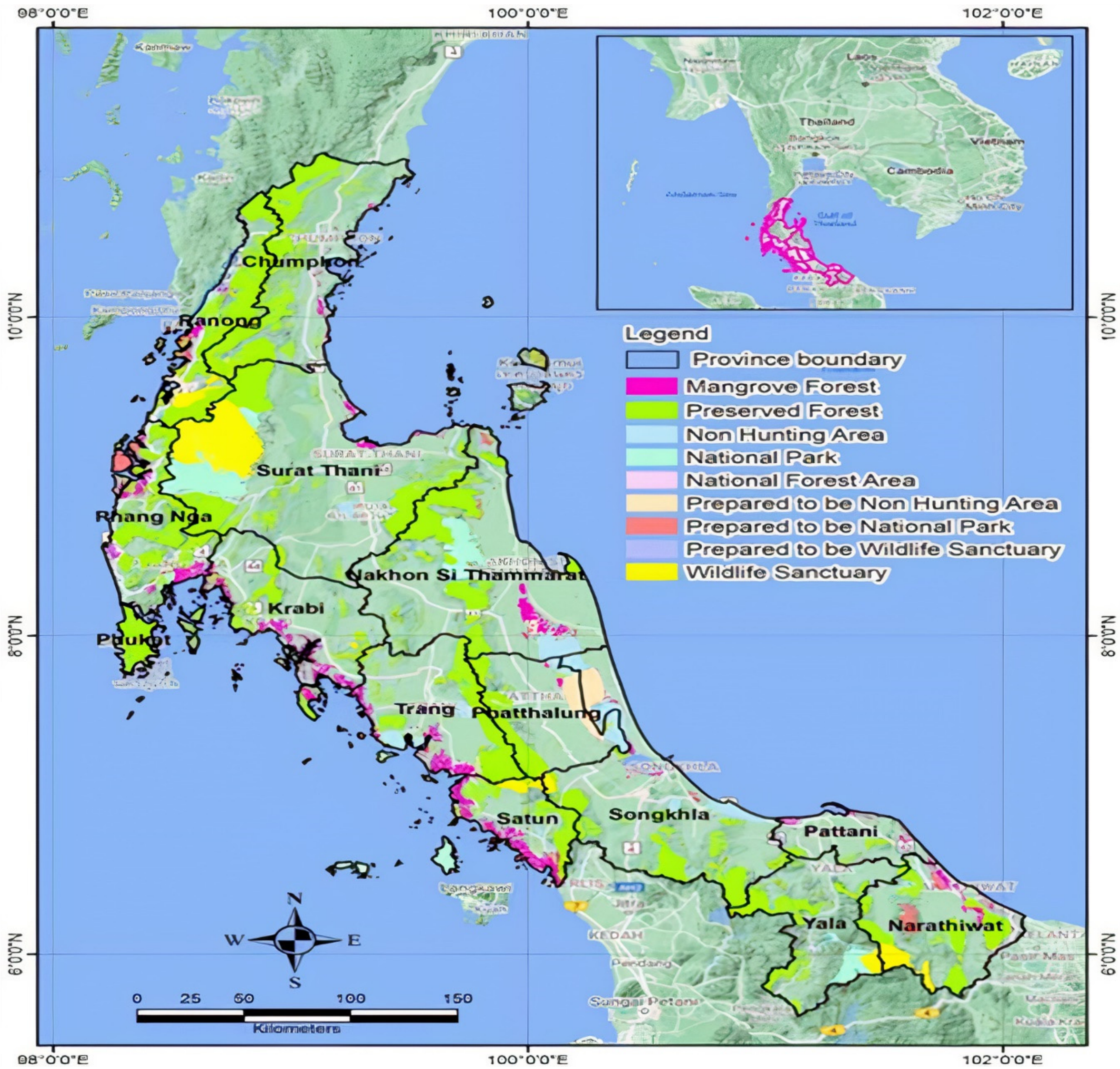

Figure 10. Protected areas of Southern Thailand.

Table 4. Pairwise comparison scale for AHP.

Score	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Judgment slightly favors one activity over another
5	Strong importance	Judgment strongly favors one activity over another
7	Very strong importance	An activity is favored very strongly over another
9	Extreme importance	Favoring one activity over another is of the highest affirmation
2,4,6,8	Intermediate values	When compromise is needed
Reciprocals	If one activity, i has one of the above activities assigned to it when compared with activity j, then j has the reciprocal value when compared with i (i.e., 2 = $\frac{1}{2}$ or 0.500)	

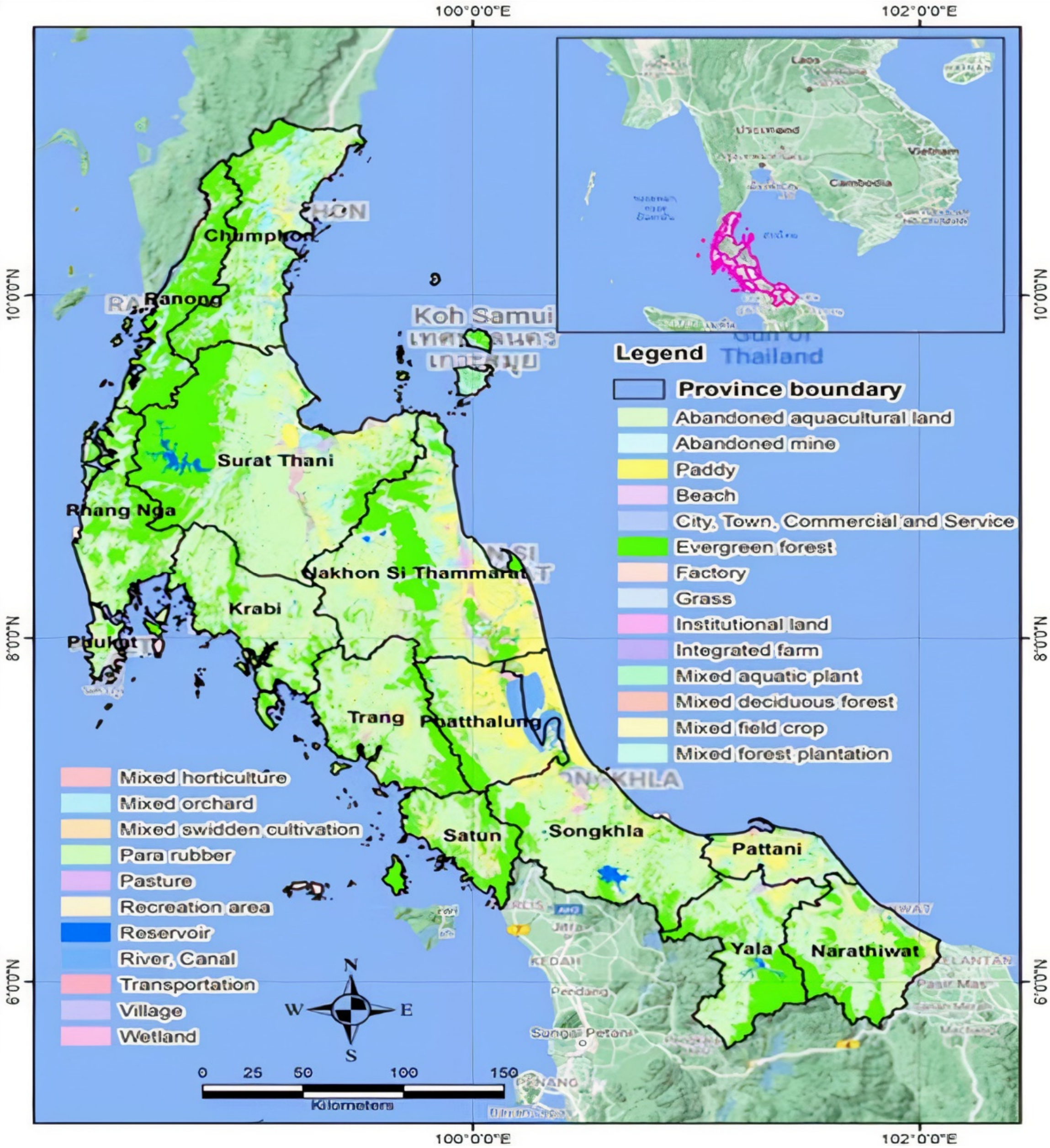

Figure 11. Land use map of the study area.

The scoring of six experts based on the scaling defined in Table 4 was used to construct the pairwise comparison matrix (M_x) for technical, economic, and environmental criteria and their sub-criteria as shown in Equation (4).

$$M_x = \begin{bmatrix} C_{11} & C_{12} & \cdots & C_{1n} \\ C_{21} & C_{22} & \cdots & C_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ C_{n1} & C_{n2} & \cdots & C_{nn} \end{bmatrix} \tag{4}$$

$M_x = |C_{ij}|\ \forall\ i,j = 1,2, \ldots, n$ for n criteria that influence the ultimate objective of the study, where C_{ij} demonstrates the relative importance of the criteria C_i over C_j and the reciprocal will be C_{ij} or $1/C_{ij}\ \forall\ i \neq j$ and $C_{ii} = 1$ [39]. After the formation of the pairwise comparison matrix, the final weights of the criteria were calculated by normalizing the individual eigenvectors associated with the maximum eigenvector of the reciprocal ratio matrix. Before finalizing the weights of the criteria, the consistency of the experts' scoring was checked using Equation (5).

$$CR = \frac{CI}{RI} \quad (5)$$

where CI is the consistency index calculated using Equation (6) and RI is the random consistency index whose value for different matrix sizes was selected from Table 5.

$$\mathbf{CI} = \frac{(\lambda max - \mathbf{n})}{(\mathbf{n} - 1)} \quad (6)$$

where **λmax** is the maximum eigenvalue and **n** is the size of the matrix.

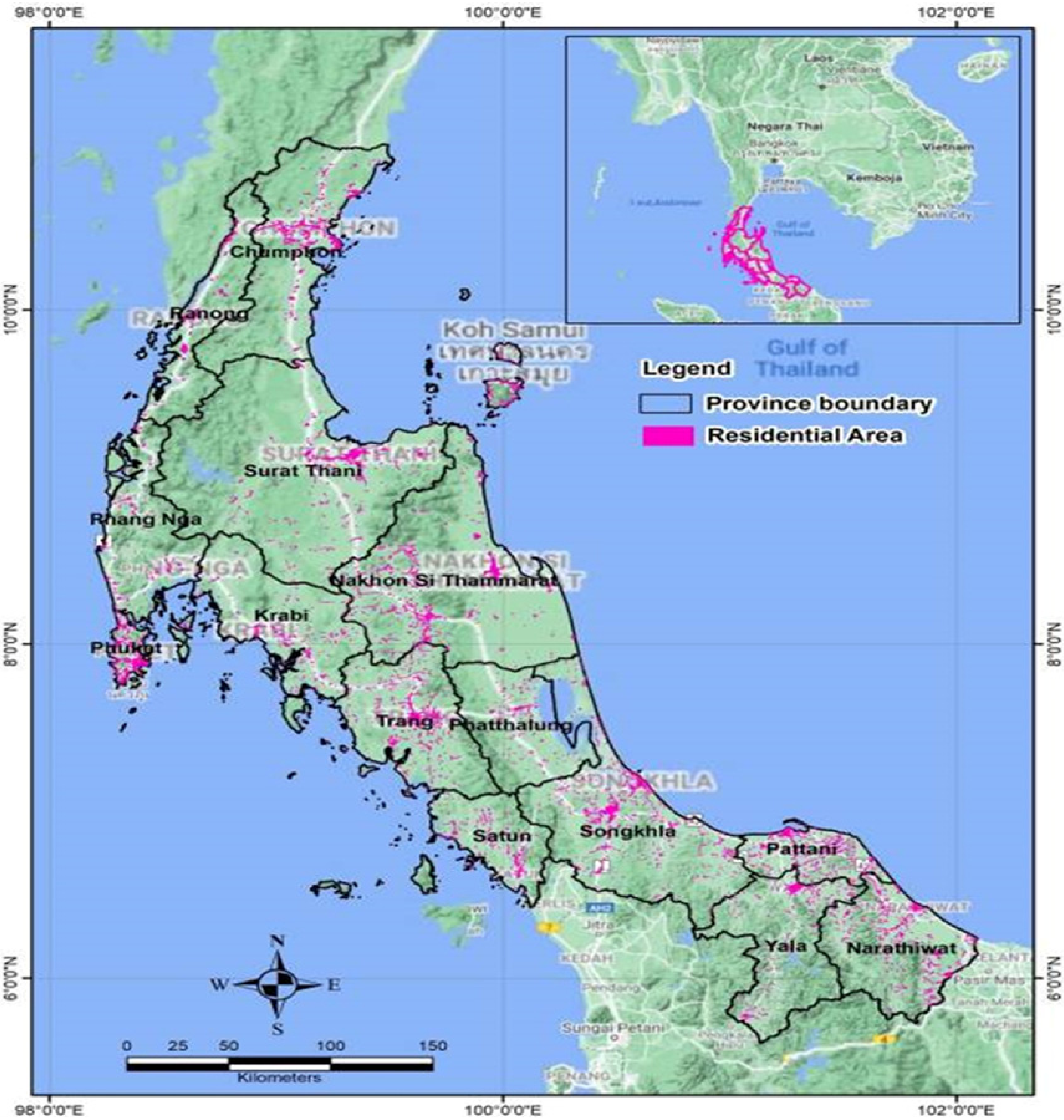

Figure 12. Map of Residential Areas.

Table 5. Random consistency index values for different matrix sizes.

Matrix Size	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

A CR value of 10% (0.1) or below is acceptable whereas a value above 10% suggests major inconsistencies in the experts' scoring, requiring the reassessment of the pairwise comparison scorings [41]. The value of CR was below 10% in our study, which indicates an acceptable consistency of the scoring of our experts.

The final weights of major criteria and their sub-criteria, calculated using the AHP defined above, are shown in Table 6. An online AHP calculator [46] was used to perform the lengthy calculation step of AHP. These weights and suitability scores associated with buffer ranges for each criterion shown in Table 3 were used for the mapping of suitable green hydrogen sites in GIS.

Table 6. Final scores of the criteria.

Main Criteria	Score	Sub-Criteria	Score
Technical	0.2	Hydrogen generation potential	0.115
		Proximity to major urban centers	0.035
		Slope	0.026
		Elevation	0.017
Economic	0.17	Distance to road	0.058
		Distance to transmission lines	0.116
Environmental	0.63	Distance to Waterbodies	0.238
		Distance to protected areas	0.243
		Distance from residential areas	0.109
		Land type used	0.044
Sum	1	Sum	1

3. Results and Discussion

The selection of suitable sites for solar-based green hydrogen in Southern Thailand was carried out in this research, using the consolidation of a GIS and the AHP technique of MCDM. So far, this is the first study carried out for the assessment of green hydrogen potential in the tropical ASEAN region. The AHP was used to compute the weights of the involved criteria using the pairwise comparison method and the mapping of suitable sites using the weights and buffers of criteria were executed using ArcGIS software.

The environmental criteria scoring 0.634 was considered the most important of the major criteria by the experts, followed by the technical criteria with 0.2 and economic securing with 0.17. Among the sub-criteria, the distance to protected areas under environmental criteria turned out to be the most important with a weight of 0.243, distance to waterbodies with a score of 0.238 was ranked second, and the distance to transmission lines under the economic criteria was considered more important than distance to roads and railway networks, with a weight of 0.116. Similarly, the hydrogen generation potential in the technical criteria was top-ranked with a score of 0.115. The AHP scores of the major criteria and their respective sub-criteria are shown in Table 6.

Finally, the suitable sites were mapped in ArcGIS software overlaying the AHP scores of the criteria and the buffers defined for each sub-criteria presented in Table 3. The buffer ranges with the suitability score of 0 were considered to be exclusion zones for the selection of green hydrogen sites, while the ones scoring 3 were considered to be highly suitable. Employing the above-mentioned consolidation of GIS and AHP, areas of high, moderate, and low suitability for the solar-based green hydrogen were mapped as shown in Figure 13.

Figure 13. Map of Suitable Solar-based Green Hydrogen Sites.

The 4302 km^2 area is highly suitable to produce green hydrogen from solar energy in Southern Thailand, with the province of Surat Thani having the largest suitable area of 877 km^2, closely followed by Nakhon Si Thammarat with 845.12 km^2 and Songkla with 838 km^2. Phuket is the only southern province with no highly suitable area for green hydrogen production. The region also has a 3350 km^2 area of moderate suitability and a 321 km^2 area of low suitability for green hydrogen production, distributed among the 14 provinces shown in Table 7.

The different suitable areas indicated with different colors on the map are mostly located in the central and eastern regions of Southern Thailand. These regions are where the major cities and towns are located and have the bulk of roads, railways, and power transmission networks. Some of the highest solar-radiated regions are also located on the eastern coasts of Southern Thailand. The western parts of the study area, particularly the northwestern parts, have mountain ranges, high slope areas with difficult terrains, and the most highly protected watersheds, national parks, and forests, making it the least suitable area for green hydrogen production.

Table 7. Details of suitable areas for green hydrogen production in Southern Thailand.

Province	High Suitability (km^2)	Moderate Suitability (Km^2)	Low Suitability (km^2)
Chumphon	287.93	297.98	24.81
Krabi	206.57	400.46	68.84
Nakhon Si Thammarat	845.31	607.07	69
Narathiwat	60.07	102.07	11.15
Pattani	200.71	153.07	8.65
Phang Nga	35.28	124.09	12.00
Phatthalung	549.12	235.77	5.86
Phuket	-	0.10	0.07
Ranong	0.29	8.72	0.11
Satun	7.97	37.77	0.57
Songkhla	837.74	495.75	20.59
Surat Thani	876.99	771.81	76.01
Trang	212.99	222.26	15.78
Yala	181.07	93.94	7.95
Total	**4302.06**	**3550.37**	**321.36**

The global demand for green hydrogen is estimated to reach 500 million tons (Mt) by 2050, with a yearly export market worth US$ 300 billion and 400,000 jobs created in the renewable energy and green hydrogen sector [47]. China, Japan, and Korea are major importers of LNG, importing a combined 55% of global LNG imports, and these countries have ambitious future plans to become major green hydrogen importers to meet their energy demands [48]. Thailand possesses very favorable conditions to develop its green hydrogen industry. With domestic oil and gas reserves depleting fast, Thailand needs to quickly obtain alternative domestic energy sources to ensure energy security and avoid expensive fossil fuels imports. Green hydrogen can offer a lucrative alternative. Thailand has both the renewable energy and water sources to produce green hydrogen to meet its domestic demand and export it to countries like China, Japan, and Korea. Thailand possesses high solar radiation areas covering much of its northeast and central region, providing it with abundant sunshine to produce green hydrogen. Thailand has the potential to produce 17 GW of wind energy [49]. These renewable resources combined with abundant freshwater resources, available sea ports, and proximity to major importers of green hydrogen makes Thailand a green hydrogen hotspot that can be developed to ensure its own energy security, create jobs, and earn valuable foreign exchange. To promote the green hydrogen industry, the development of a road map is necessary and studies like this are vital to estimate the green hydrogen potential to develop an effective road map.

4. Conclusions

Sustainable development of renewable energy sources like green hydrogen is not merely a technical endeavor but also involves economic and environmental criteria. The participation of multiple stakeholders makes the task more complex because when the involvement of multiple stakeholders is not addressed properly, a conflict of interests jeopardizes the sustainability goals of the project.

In this study, a method using the consolidation of GIS and MCDM was developed to effectively address the participation of multiple stakeholders in the selection of suitable sites for solar-based green hydrogen in Southern Thailand, by involving them in the decision-making process. To select suitable green hydrogen sites, technical, economic, and environmental criteria with their respective sub-criteria were selected. The AHP method of MCDM was employed for the weight calculation of the involved criteria and the mapping of suitable sites was performed using ArcGIS software by overlaying the AHP scores and buffer zones defined for each criterion. Finally, three categories of suitable sites deemed high, moderate, and low were selected. From the total 70,714 km^2 area of Southern

Thailand, 4302 km^2 is highly suitable for solar-based green hydrogen production, with the provinces of Surat Thani, Nakhon Si Thammarat, and Songkhla having the most suitable sites. Apart from this, the region also has a 3350 km^2 area of moderate suitability and a 321 km^2 area of low suitability to produce green hydrogen. Overall, Southern Thailand is a well-suited region for the production of solar-based green hydrogen sites with a favorable number of suitable sites. Other than suitable sites, this region is ideal for the export of green hydrogen in the future due to its large coastlines and seaports to countries like South Korea, Japan, and China, which are predicted to become the major importers of this commodity.

Studies like these are very important for Thailand as accurate assessments are vital to developing its green hydrogen road map. The development of such preparations will help promote investments in the green hydrogen sector to establish the industry, not only to meet the country's energy demand via renewable energy sources and improve energy security, but also to export it to earn valuable foreign reserves. The development of the green hydrogen industry will add more value to Thailand's renewable resources like solar energy and create new jobs that promote economic development. The method developed in this study can also be applied to other regions for the assessment of suitable green hydrogen sites.

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