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Analysis of solar and wind farm area using technique for order of preference by similarity to ideal solution

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Abstract. Solar and wind are considered the type of renewable energy source that can power a clean energy revolution especially for the upstream process of the Green Hydrogen Supply Chain (GHSC). The GHSC, in particular, is concerned with the electrolysis technique, in which water and electricity from renewable energy sources like solar and wind are used. In this study, our aim is to assess the strategic location of solar and wind farm area under diverse criteria using a case study in Thailand. In particular, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is applied, in which criteria data for air temperature, terrain elevation, direct normal irradiation, photovoltaic power, wind speed, and power density relevant to solar and wind efficiency are collected. The TOPSIS technique is used to evaluate alternatives from the district areas using a case study at Ubonratchathani, Thailand. Our results suggest the ranking list for potential district areas to investigate further for projects involving renewable energy investment connected to the GHSC. The obtained results will be further used as input data for our ongoing work on the model and analysis of the GHSC network.

1 Introduction

Recent evidence shows that fossil fuel energy significantly contributes to the increase in greenhouse gas emissions and thus is not sustainable [1-3]. Therefore, increased attention to renewable energy has also been observed. The global renewable energy market is also expected to continue its upward growth, in which the market will reach over two trillion U.S. dollars by 2030. Solar and wind, in particular, are the types of potential renewable energy sources that can power a clean energy revolution and are considered a sustainable option [4].

Solar and wind energy are also one of the most sustainable ways reported for producing hydrogen energy by using produced electricity to split water into hydrogen and oxygen via the electrolysis technique, which is known as the green hydrogen concept. The market and demand for hydrogen prevail in several applications. According to the IEA 's sustainable development scenario [5], pure hydrogen demand could reach 90 million metric tons by the end of 2030 and over 500 million metric tons by 2070. Although the current application shows that the transportation sector is currently only a minor consumer, it is expected to become the largest sector in 2050 and so on **(Fig. 1)**. Considering the expected growth of hydrogen demand, proper evaluation of the complex issues related to the infrastructure for GHSC is essential.

In this study, given that diverse locational areas can hypothetically selected as potential areas to invest for renewable energy, our research aim is to examine the strategic locational decision for solar and wind farm areas at the upstream process in the green hydrogen supply chain (GHSC) context with multiple criteria. Initially, criteria data relevant to both solar and wind farm efficiency are collected for air temperature, terrain elevation, direct normal irradiation, photovoltaic power, wind speed, and power density. Then, the case study of Ubonratchathani province in Thailand is evaluated, which comprises the main 25 districts in the province. The problem is then modeled and examined using one of the well-known Multi-Criteria Decision Analysis

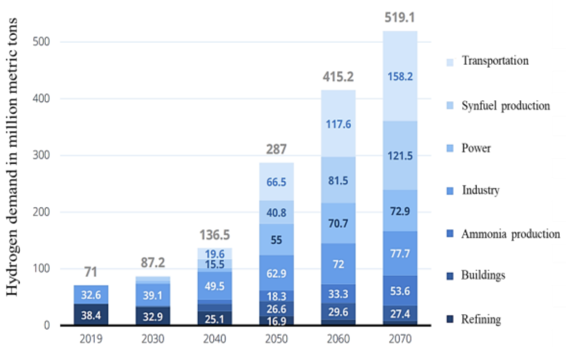

Fig. 1. Expected global demand for hydrogen sector [5]

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(MCDA) called the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) to evaluate the best district (i.e., alternative) under assessment.

We note that the current assessment is our ongoing study to further evaluate and model the network of GHSC next. The structure of the manuscript is followed by the related literature review and methodology in Section 2, the case study under evaluation in Section 3, and the conclusion in Section 4, respectively.

2 Methodology

2.1 Related Literature

Modeling and analyzing the GHSC presents significant challenges. The GHSC process generally begins with renewable energy sources and ends at demand areas, with multiple alternatives available at each stage of the infrastructure network. Regarding hydrogen supply sources, green hydrogen production involves the electrolysis technique, where water and electricity from renewable energy sources such as solar and wind are utilized. Electrolysis is particularly promising for extensive deployment due to its potential for a low-carbon footprint in the energy system. However, its economic feasibility remains a concern, as the process is still relatively costly [6-7]. The hydrogen produced can then be distributed through various modes depending on its physical form and the energy demand profile. For example, liquefied hydrogen can be transported by tankers via roads and railways, while gaseous hydrogen can be distributed through pipelines. Additionally, storage decisions are a crucial aspect of the GHSC and are complicated by the different physical forms of hydrogen (**Fig. 2**).

Several studies in the literature suggest challenges in operational, tactical, and strategic-level decisions for hydrogen networks (e.g., [8 - 10]). Liu and Ma [8] suggest some research gaps and directions for GHSC. According to the authors, many problems have yet to be resolved from a technical perspective, such as the efficient storage of hydrogen, the economic benefits engendered by market demand that could accelerate technological upgrades, and the introduction of a hydrogen energy system that can address human health, political conflict, and energy shortages to estimate and budget for its tangible benefits. Ransikarbum et al. [9] introduce an integrative MCDA tool designed to evaluate weighted criteria and sourcing alternatives based on data gathered from a group of selected experts in Thailand. Their study assesses a range of criteria related to sustainability paradigms and sourcing decisions for the potential use of hydrogen energy. Riera et al. [10] conducted a review of HSC and suggested lacking aspects in the literature. The authors point out that research gaps exist for production sources, international cases, and methodology. In addition, it is suggested to take an international perspective to allow decision-makers to more accurately model geopolitical climates.

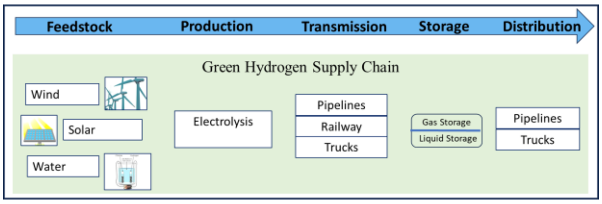

Fig. 2. The schematic of the green hydrogen supply chain

Several studies have also discussed the strategic advantages of green hydrogen to promote sustainable development when compared to other methods of producing hydrogen in the literature (e.g., [11 - 13]. That is, green hydrogen can serve as a core strategy to promote the widespread adoption of renewable energy in an energy system. The integration of green hydrogen projects with the existing grid infrastructure also offers an opportunity to provide low-cost clean energy to local communities. Moreover, the flexibility of the electrolyzers can also facilitate the balancing of electricity systems during peak demand of electricity and surplus electricity. In addition, the development of hydrogen production capacity from renewable sources can also foster the growth of a skilled local workforce, the access to cutting-edge technologies related to solar panels and wind turbines.

2.2 TOPSIS Methodology

We next discuss the TOPSIS technique, which is one of the well-known MCDA techniques and is applied in several studies [14 – 16]. The method relies on the idea that the optimal choice should be the one with the shortest geometric distance to the positive ideal solution (PIS) (i.e., A+) and the longest geometric distance from the negative ideal solution (NIS) (i.e., A-), as depicted in **Fig. 3**. Specifically, the PIS represents an option with the highest scores across all criteria, while the NIS represents an option with the lowest scores among all the criteria considered. In this study, the equal weight consideration is used to lessen the dependency issue of the judgment for criteria. That is, secondary data are initially collected based on existing sources related to Geographic Information System (GIS) and then recorded and analyzed using Microsoft Excel to obtain TOPSIS-based ranking list.

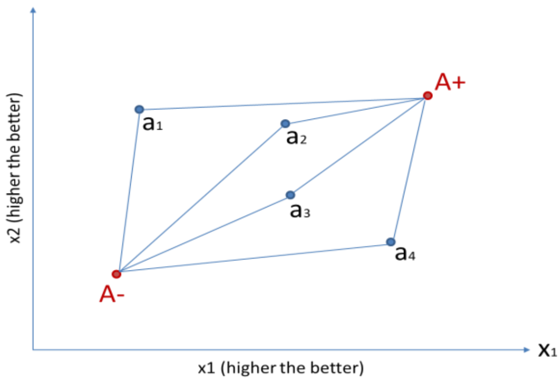

Fig. 3. The illustrated concept of TOPSIS

In addition, the methodological flowchart of the TOPSIS technique is presented in **Fig. 4**. That is, the procedure starts with creating a decision-making matrix and then normalizing the matrix (r_{ij}) to be unitless as shown in Equation (1). Then, based on the relative criteria weight, the next step is to compute the weighted normalized decision matrix (v_{ij}) as presented in Equation (2). The next step is to compute the PIS (i.e., A^*) and NIS (i.e., A') values, as shown in Equations (3) and (4), respectively. Next, the separation measure can be computed for each alternative under consideration, where S_i^* is the separation measure from the PIS and S_i' is the separation measure from the NIS as shown in Equations (5) and (6), respectively. Finally, the relative closeness value (C_i^*) can be computed as shown in Equations (7) and the value will be between 0 and 1. In particular, the 0 value represents the alternative solution that has the worst, while the 1 value represents the best alternative as shown in Equation (8).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \tag{1}$$

$$v_{ij} = w_j r_{ij} \tag{2}$$

$$A^* = \{v_1^*, \ldots, v_n^*\} \ ; v_j^* = \begin{matrix} \max(v_{ij}) \text{if } j \in J \\ \min(v_{ij}) \text{if } j \in J' \end{matrix} \tag{3}$$

$$A' = \{v_1', \ldots, v_n'\} \ ; v_j' = \begin{matrix} \min(v_{ij}) \text{if } j \in J \\ \max(v_{ij}) \text{if } j \in J' \end{matrix} \tag{4}$$

$$S_i^* = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j^*)^2} \tag{5}$$

$$S_i' = \sqrt{\sum_{j=1}^{n} (v_{ij} - v_j')^2} \tag{6}$$

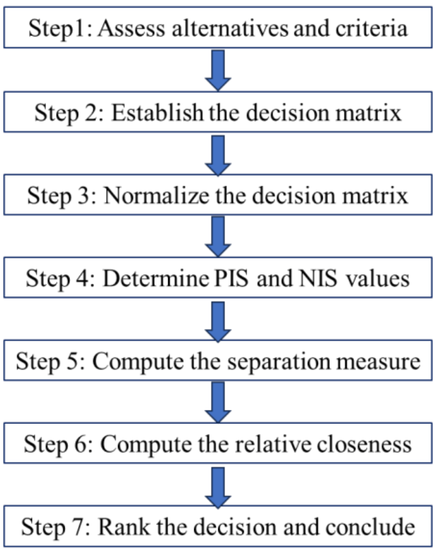

Fig. 4. The methodological flowchart of the TOPSIS

$$C_i^* = \frac{S_i'}{S_i^* + S_i'} \tag{7}$$

$$C_i^* = \begin{matrix} 1 \ \ if \ A_i = A^* \\ 0 \ \ if \ A_i = A' \end{matrix} \tag{8}$$

3 Results and Discussion

3.1 Case Study

We next discuss the case study for evaluating the upstream-strategic decision for solar and wind farm areas in the GHSC context. The alternatives and criteria are next presented as follows.

3.1.1 Alternatives

In this study, Ubonratchathani province is illustrated as a case study, which comprises 25 governmental districts as presented in **Table 1**. These 25 districts are then used as alternatives for the evaluation of potential solar and wind farm areas. In addition, **Fig. 5** presents the illustrated case study.

Table 1. Alternatives for the case study

Alt.	Description	Coordinate
A1	Mueang	15.228889, 104.854167
A2	Si Mueang Mai	15.495278, 105.278611
A3	Khong Chiam	15.318889, 105.495556
A4	Khueang Nai	15.389444, 104.551389
A5	Khemarat	16.042179, 105.223583
A6	Det Udom	14.903056, 105.076389
A7	Na Chaluai	14.521389, 105.246111
A8	Nam Yuen	14.489167, 105.000833
A9	Buntharik	14.756667, 105.411389
A10	Trakan Phuet Phon	15.612222, 105.021944
A11	Kut Khaopun	15.791667, 104.996667
A12	Muang Sam Sip	15.510833, 104.726389
A13	Warin Chamrap	15.2025, 104.8675
A14	Phibun Mangsahan	15.244444, 105.228889
A15	Tan Sum	15.315556, 105.155
A16	Pho Sai	15.825833, 105.260833
A17	Samrong	15.008333, 104.782222
A18	Don Mot Daeng	15.37903, 105.02786
A19	Sirindhorn	15.201667, 105.398333
A20	Thung Si Udom	14.733333, 104.91
A21	Na Yia	15.059444, 105.060278
A22	Na Tan	15.89749, 105.29318
A23	Lao Suea Kok	15.406667, 104.923333
A24	Sawang Wirawong	15.241389, 105.092222
A25	Nam Khun	14.583333, 104.925

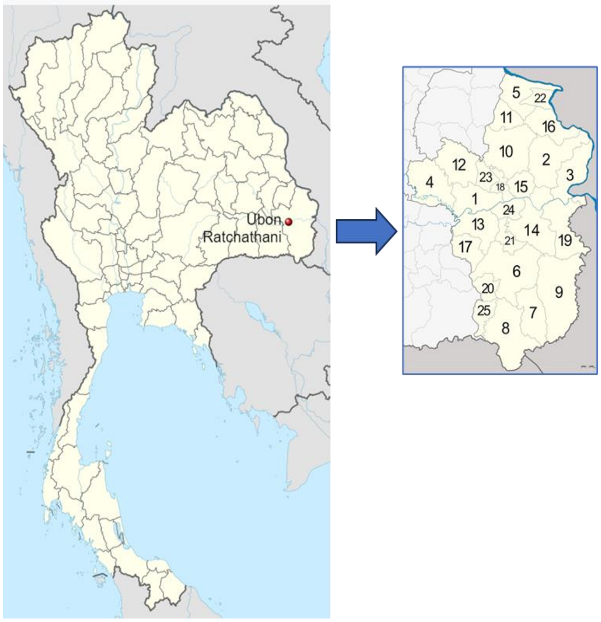

Fig. 5. The case study map of Ubonratchathani province in Thailand

3.1.2 Criteria List

We next discuss the criteria list related to the evaluation of solar and wind farm areas in the GHSC context. In particular, criteria are chosen based on the literature review related to the renewable source (i.e., solar and wind) for electrolysis technique to produce green hydrogen [17 - 20]. Rather than focusing on a particular renewable type, we focus on both solar and wind types since they are known to be currently connected to the grid infrastructure of the GHSC in many countries. In particular, data related to the six criteria related to the air temperature, terrain elevation, direct normal irradiation, photovoltaic power, power density, and wind speed are obtained from Global Solar Atlas and Global Wind Atlas.

C1) Air temperature (°C): This criterion represents the average monthly air temperature at 2 m above ground. The air temperature can affect solar panels such that when the temperature increases, the amount of energy a panel produces can be reduced. Additionally, If the temperature is high, the air density can decrease and will lessen the energy output from the wind turbine. Thus, this criterion is considered lower the better for both solar and wind evaluation.

C2) Terrain elevation (m): This criterion is the elevation of the terrain surface above or below sea level. Typically, more direct irradiation from the high elevation can help to increase the solar power output. Similarly, wind turbines situated on top of hill peaks can cause more power generation than those located on level ground. Regardless, it is noted that flat or sloping terrains should also be noted since they can affect the installation and maintenance. Thus, this criterion is considered higher the better for both solar and wind evaluation.

C3) Direct normal irradiation (kWh/m²): This criterion is computed using the average monthly sum of direct normal irradiation. Direct normal irradiation (DNI), in particular, is the amount of solar radiation received per unit area by a surface. Thus, the higher the irradiance, the greater the solar output current and the power generated. It is noted also that the distribution of solar uneven heating across the atmosphere together with irregular surfaces of the earth will correlatedly affect the wind patterns. Thus, this criterion is considered higher the better, especially for the solar evaluation.

C4) Photovoltaic power (kWh/kWp): This criterion is based on the monthly average values of photovoltaic electricity (AC) delivered by a photovoltaic (PV) system and normalized to 1 kWp of installed capacity. Thus, this criterion is considered higher the better, especially for the solar evaluation.

C5) Power density (W/m^2): This criterion is the mean wind power density, which is also a measure of the wind resource. Generally, higher mean wind power densities indicate better wind resources. Thus, this criterion is also considered higher the better, especially for the wind farm evaluation

C6) Wind speed (m/s): This criterion is the mean wind speed, which is a measure of the wind resource. Higher mean wind speeds typically indicate better wind resources. It is also noted that the PV panel with wind speed is also suggested to correlatedly generate a higher output power than that without wind speed. However, caution is given for high wind events that may affect the system structure. Thus, this criterion is considered higher the better, especially for the wind farm evaluation.

3.2 Data Collection and Results

3.2.1 Data Collection

We next collect data from the Global Solar Atlas (GSA) as well as the Global Wind Atlas (GWA) websites related to how different alternatives perform under each criterion under evaluation. In particular, the GSA is a map-based application that provides global information on solar resources and photovoltaic power potential. The GSA platform is provided by the Energy Sector Management Assistance Program, which is funded and administered by the World Bank and was developed under contract by Solargis. Additionally, the GWA is further developed as a web-based application for the identification of the high-wind areas for global wind power generation. The GWA platform was initially developed by the framework of the Clean Energy Ministerial led by Germany, Spain, and Denmark. Later, the platform is administered by the World Bank to update and bring it into line with the GSA that was launched by the World Bank [21 - 22].

In particular, **Fig. 6** illustrates the GIS-based heat map data for the air temperature (i.e., C1), terrain elevation (i.e., C2), direct normal irradiation (i.e., C3), photovoltaic power (i.e., C4), power density (i.e., C5), and wind speed (i.e., C6) for Ubonratchathani province, respectively. Then data are disaggregated at the district alternatives level and are collected as shown in **Table 2**.

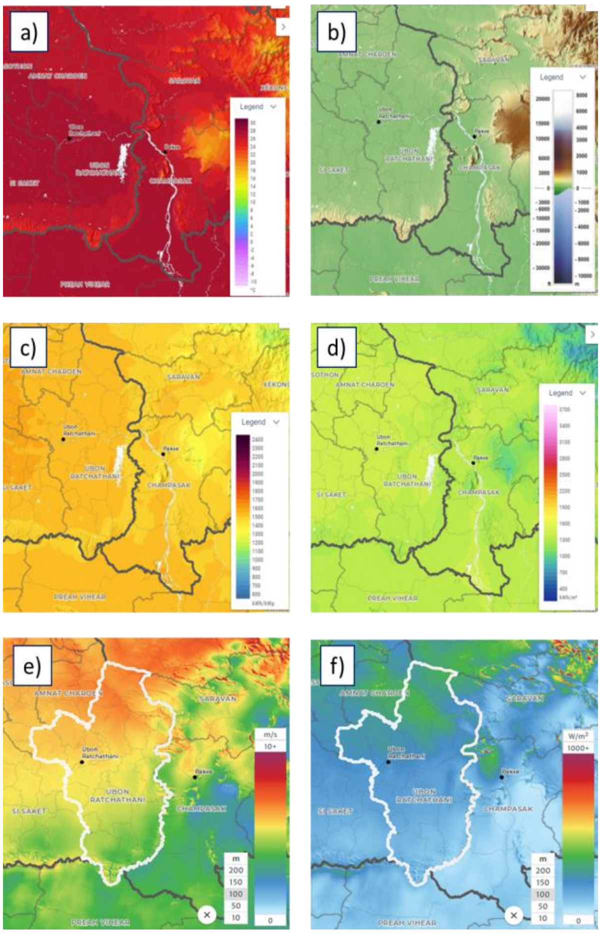

Fig. 6. Geographic Information System (GIS)- based heat map for a) C1, b) C2, c) C3, d) C4, e) C5, and f) C6

3.2.2 TOPSIS Results and Discussion

We next discuss results from applying the TOPSIS technique to evaluate the upstream-strategic decision for solar and wind farm areas in the GHSC context. Given that the TOPSIS technique highly depends on the criteria weight under evaluation. In this study, the equal weight consideration is used to lessen the dependency issue of the judgment for criteria. That is, all the criteria (i.e., C1 – C6) are provided an equally important weight, which is summed to 1 (i.e., 100%). The normalized data are shown in Table 3.

Then, the separations are further computed for each alternative under consideration for both the separation measure from the PIS and the separation measure from the NIS, respectively. Finally, the relative closeness value can be computed as shown in Table 4. The obtained relative closeness values will be between 0 and 1, which is based on the importance of separations of each alternative from the PIS and the NIS. That is, the district alternatives can be ranked based on their relative closeness to these ideal solutions (i.e., the higher, the better rank).

The obtained results suggest the ranking list for all the district alternatives under evaluation. In particular, the top five alternatives are found to be A11 (i.e., Kut Khaopun district), followed by A16 (i.e., Pho Sai district), A22 (i.e., Na Tan district), A2 (i.e., Si Mueang Mai district), and A5 (i.e., Khemarat district), respectively. We further note that the obtained relative closeness scores are quite close for some alternatives and thus other alternatives of the districts are also worth exploring. Additionally, the obtained results also depend on the criteria list under evaluation. That is, if the criteria are further added or deleted from the assessment, the obtained results may change depending on the applied criteria.

Table 2. Collected data for the alternatives concerning assessed criteria

	C1	C2	C3	C4	C5	C6
A1	27.3	125	1539.6	1394.3	242	5.89
A2	27	146	1520.1	1370.2	347	6.55
A3	27.3	114	1471.6	1298.1	304	6.13
A4	27.3	127	1549.2	1406.1	239	5.86
A5	26.7	138	1506.5	1367.8	357	6.95
A6	27.3	137	1529.6	1376.5	160	5.21
A7	26.6	196	1488.9	1308.1	113	4.58
A8	26.8	186	1503.3	1338.6	184	5.37
A9	27	159	1506.7	1344.7	155	4.99
A10	27	135	1533.5	1392.7	359	6.66
A11	26.8	154	1534.6	1394.1	360	6.84
A12	27.1	142	1540.6	1392.3	262	6.01
A13	27.3	133	1535.4	1392.8	206	5.54
A14	27.3	128	1527.5	1383.5	196	5.43
A15	27.3	128	1520.8	1364.7	247	5.82
A16	26.7	160	1525	1387.7	335	6.77
A17	27.3	138	1541.1	1393.4	171	5.34
A18	27.2	126	1533.6	1388	229	5.79
A19	27.1	154	1518.6	1368.7	208	5.48
A20	27.1	162	1522.9	1363.7	148	5.09
A21	27.3	138	1524.4	1365	179	5.33
A22	26.6	147	1523.2	1390.1	352	6.84
A23	27.1	147	1539.5	1393.1	252	5.95
A24	27.2	138	1524.5	1369.1	214	5.59
A25	26.9	183	1507.8	1339	134	4.98

Table 3. Normalized data for the alternatives concerning assessed criteria

	C1	C2	C3	C4	C5	C6
A1	0.202	0.170	0.202	0.203	0.194	0.202
A2	0.200	0.199	0.200	0.200	0.278	0.224
A3	0.202	0.155	0.193	0.189	0.243	0.210
A4	0.202	0.173	0.203	0.205	0.191	0.201
A5	0.197	0.188	0.198	0.199	0.286	0.238
A6	0.202	0.186	0.201	0.201	0.128	0.179
A7	0.197	0.267	0.196	0.191	0.090	0.157

Table 3 (cont.). Normalized data for the alternatives concerning assessed criteria

	C1	C2	C3	C4	C5	C6
A8	0.198	0.253	0.197	0.195	0.147	0.184
A9	0.200	0.216	0.198	0.196	0.124	0.171
A10	0.200	0.184	0.201	0.203	0.287	0.228
A11	0.198	0.210	0.202	0.203	0.288	0.234
A12	0.200	0.193	0.202	0.203	0.210	0.206
A13	0.202	0.181	0.202	0.203	0.165	0.190
A14	0.202	0.174	0.201	0.202	0.157	0.186
A15	0.202	0.174	0.200	0.199	0.198	0.199
A16	0.197	0.218	0.200	0.202	0.268	0.232
A17	0.202	0.188	0.202	0.203	0.137	0.183
A18	0.201	0.171	0.201	0.202	0.183	0.198
A19	0.200	0.210	0.199	0.200	0.166	0.188
A20	0.200	0.220	0.200	0.199	0.118	0.174
A21	0.202	0.188	0.200	0.199	0.143	0.183
A22	0.197	0.200	0.200	0.203	0.282	0.234
A23	0.200	0.200	0.202	0.203	0.202	0.204
A24	0.201	0.188	0.200	0.200	0.171	0.192
A25	0.199	0.249	0.198	0.195	0.107	0.171

Table 4. Normalized data for the alternatives concerning assessed criteria

	Separation Measure from the PIS	Separation Measure from the NIS	Relative Closeness Score	Ranking list
A1	0.02333	0.01912	0.450	11
A2	0.01176	0.03401	0.743	4
A3	0.02083	0.02695	0.564	7
A4	0.02334	0.01881	0.446	12
A5	0.01323	0.03570	0.730	5
A6	0.03146	0.00920	0.226	25
A7	0.03570	0.01862	0.343	18
A8	0.02531	0.01945	0.435	13
A9	0.03075	0.01196	0.280	23
A10	0.01395	0.03530	0.717	6
A11	0.00956	0.03661	0.793	1
A12	0.01871	0.02256	0.547	8
A13	0.02629	0.01448	0.355	17
A14	0.02815	0.01272	0.311	20
A15	0.02255	0.01957	0.465	10
A16	0.00891	0.03388	0.792	2
A17	0.02989	0.01077	0.265	24
A18	0.02453	0.01735	0.414	14
A19	0.02395	0.01653	0.408	15

Table 4 (cont.). Normalized data for the alternatives concerning assessed criteria

	Separation Measure from the PIS	Separation Measure from the NIS	Relative Closeness Score	Ranking list
A20	0.03119	0.01235	0.284	21
A21	0.02903	0.01137	0.281	22
A22	0.01120	0.03528	0.759	3
A23	0.01908	0.02164	0.531	9
A24	0.02477	0.01576	0.389	16
A25	0.03235	0.01612	0.333	19

4 Conclusion

Many countries around the globe have taken a variety of strategic policies aiming at meeting energy needs more sustainably. Hydrogen energy demand has grown remarkably to support commercial, transport, and residential applications. The hydrogen supply network is complex due to the production source, the types of products obtained, the storage decision, and the distribution channels. The hydrogen network based on the green hydrogen concept called GHSC is an emerging concept that utilizes electricity from a renewable energy source such as solar and wind renewable energy and water via the electrolysis technique to produce hydrogen with low emission impact. The upstream process of the GHSC was assessed in this study to investigate potential district areas for installing solar and wind farms using a case study of Ubonratchathani province in Thailand.

This study provides a practical assessment for policymakers and decision-makers involved in renewable energy as well as green hydrogen projects. Our analyzed results suggest that the district alternatives can be properly ranked, in which the top five alternatives are found to be Kut Khaopun District, followed by Pho Sai District, Na Tan District, Si Mueang Mai District, and Khemarat District, respectively. We also note future research directions as follows. That is, given that the obtained results depend on the criteria list under evaluation. Thus, other criteria may be added to further reflect economic and social criteria. Second, besides the equal weight combination provided in this study, the sensitivity analysis may be further performed to reflect both objective and subjective weight from diverse policymakers and stakeholders using group decision-making techniques. Third, given that the trend of MCDA research is to combine varied MCDA tools to overcome shortcomings of a particular tool used, the integrated MCDA tools should be further applied. That is, other MCDA tools can be used to compare with the obtained results to enhance the model robustness. The validity of the results can also be enhanced with governmental plans, if any. In addition, uncertainty relevant to the scope of decision analysis such as fuzzy theory and robust analysis can also be incorporated. Finally, we note that this study is the first phase of our ongoing research framework to model and analyze GHSC to integrate the upstream, midstream, and downstream operations further.

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