Evaluating natural resources volatility in an emerging economy: The influence of solar energy development barriers

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Abstract

The utilization of solar energy is helpful in overcoming the prevailing energy crises of India. However, the country is struggling to efficiently use solar energy resources to meet the growing energy demand. To solve this research issue, the current study has developed a systematic structure to prioritize barriers according to their importance. Firstly, based on an extensive review of literature and modified Delphi approach, we identified solar energy barriers. Twenty-nine barriers in total were identified, which were then categorized under six major domains including technological, transparency & accountability, COVID-19, financial, policy & regulatory, and infrastructure. Secondly, the weights and rankings of barriers and sub-barriers were determined using the Analytical Hierarchical Process. The findings show that the "technological" barrier is the top-ranked barrier, while the overall ranking reveals that "unreliable local technology" ranks highest among all sub-barriers across all categories. Finally, we took a further step by employing the Grey Preference by Similarity to Ideal Solution approach to rank the alternatives. The results show that "R&D" and "corruption-free system" are the best alternate solutions to overcome solar energy adoption barriers. The research findings would assist practitioners, policymakers, and scholars, concentrating their future efforts on solar energy in India.

Keywords: Solar energy barriers; COVID-19; Modified Dephi; AHP, G-TOPSIS; India

1. Introduction

COVID-19 has posed significant issues to the energy sector [1]. Potential new activities and societal formations being facilitated by the novel pandemic are having impacts on energy

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production and consumption [2]. Precautionary measures in the form of social isolation, lockdown, and quarantine have been taken to reduce the spread of coronavirus infection [3,4]. All economic activities, traffic movement, and the normal functioning of industries have almost ceased. Numerous industries have been impacted by the COVID-19 pandemic, including manufacturing, agriculture, education, healthcare, finance, sports, food, and tourism. The energy industry is not immune to these impacts [5]. According to the International Energy Agency (IEA) statistics and projections, the 2020 energy demand shock is the largest in the last 70 years. The global energy demand dropped by 6% in 2020 compared to 2019, a reduction seven times bigger than during the 2009 financial crisis [6]. While the fact that global energy demand dropped is straightforward, the ramifications may vary between different energy types and consumption patterns in different localities [7] [8].

The novel pandemic has changed the lifestyles of people. During the lockdown period, people typically stay at home and work from home [9]. With a huge population of 1.38×10^9, India is the second-largest country in terms of population [10]. This terrible situation poses new challenges for the power sector in the country [11]. Yet, discovering innovative and reliable methods of energy generation is always a challenging job. Being a developing country, fossil fuels (coal, oil, and gas) are India's primary energy generation sources [12]. The country fulfils 69% of its energy needs from these sources [13]. Due to overuse, fossil fuels are under high pressure of scarcity. The massive dependence on these sources would lead India to an unwanted state of fossil fuel depletion in the future. In the meantime, owing to the huge population and economic growth, the power demand and supply situation has worsened in the country. To cope with this situation, India is finding alternate sources to reduce the dependence on fossil fuels [14]. The Indian Government has announced several policies for maximizing the share of renewables in the total energy mix of the country. Out of different renewable sources, solar energy will not only improve the energy structure of the country but also has the capability to minimize carbon footprints and foster sustainable growth [15]. As a result of Government initiatives, entrepreneurs and investors have shown significant interest in solar energy development programs, and new solar parks have been established at different locations of the country [16].

Despite having enormous solar resources, several barriers are obstructing the smooth deployment of solar energy in India [17]. Scholars agreed that the fate of solar energy resources would remain unchanged in India unless these barriers are well identified and adequately discussed. Therefore, in order to formulate tailored solutions, it is imperative to recognize, evaluate and rate these barriers based on their significance. Several researchers have identified barriers related to renewable energy sources across different geographical locations and over time. Some of them even provided optimum solutions in different contexts [18,19]. However, these barriers may vary in almost all countries, depending on the economic, social, political, and technological situations. For instance, Irfan et al. [20] assessed solar energy barriers of Pakistan. The authors used semi-structured interviews with industry professionals to categorize major barriers. The work recognized twenty-three barriers in five major domains, including technological, economical, policy, social barriers, and information & human resources. They ordered economical and policy barriers at the top position followed by technological, information & human resources and social barriers.

Numata et al. [21] analyzed barriers for the deployment of renewable-based mini-grids in Myanmar by employing the Analytic Hierarchy Process (AHP) approach. They recognized twenty barriers and classified them within five main domains. The findings reveal that economic, technical, and regulatory barriers have a significant impact on the deployment of renewable-based mini-grids, while the social/cultural and financial barriers have less impact. Similarly, Mukeshimana et al. [22] examined barriers to biogas dissemination in Rwanda using the AHP approach. A total of twenty most significant barriers were identified under four major categories. Research outcomes disclosed that financial barriers are the most influential barriers, followed by institutional, technical, and socio-cultural barriers.

Similarly, some scholars have pinpointed and classified solar energy barriers in the Indian context. However, despite the longstanding interest of former scholars, studies dealing with the extent to which these barriers obstruct solar energy adoption in India are scarce, particularly during the COVID-19 outbreak. In this respect, understanding the extent of barriers before devising policies at the national level is of utmost importance. The absence of such studies motivated us to fill this research gap by conducting a comprehensive analysis and answer the following three research questions. (i) What are the significant solar energy barriers in India? (ii) How can they be prioritized in a way that could add value for both researchers and practitioners? (iii) What are the optimal solutions to overcome these barriers to successfully adopt solar energy in the country? By knowing solar energy adoption barriers, Government and policymakers would be in a better position to deploy solar energy quickly in the country. For this purpose, we use the AHP method to calculate the weights of the elements (dimensions, parameters and indicators). As a next step, the G-TOPSIS approach is used to get the ultimate ranking of the alternative nearest to the optimal solution. The major benefits of using the G-TOPSIS approach include flexibility, logic, and comprehensibility, which enables the relative success of alternatives to be calculated in a computational way. This study makes several contributions. Firstly, compared to other studies, we have employed the modified Delphi approach in the Indian solar energy context, which former researchers have neglected in the past. Secondly, the study offers contributions in the form of novel insights concerning solar energy barriers by including, for the very first time, the pandemic (COVID-19) as a new barrier in the Indian context. According to the best of the authors' knowledge, no study has used this barrier in the Indian solar energy context so far. Moreover, as we exposed new insights into meaningful sub-criteria, we find AHP outcomes as a basis for recognizing major barriers and sub-barriers for scholars and policymakers. Finally, further contributions come by using the application of novel G-TOPSIS, which would assist in expanding previous findings and prioritizing the best alternatives to overcome solar energy barriers for the successful adoption of solar energy in the country and confirm the coherence of study outcomes.

The rest of the research is carried out as follows: Section 2 establishes the research framework of the paper. Section 3 presents results and discussion using AHP and Grey-TOPSIS approaches. Finally, section 4 concludes the study and suggests essential policy propositions.

2. Research framework

The research framework of this study is depicted in Fig. 1. As a first step, an extensive review of literature is conducted to identify the significant solar energy barriers. In this context, journal articles, energy reports, official Government policy documents, and regulations were thoroughly consulted to have a deeper understanding of the barriers. Journal articles were searched from major databases, including Scopus, Web of Science, Google Scholar, IEEE Explore, and ScienceDirect. Published energy reports were reviewed from different organizations such as International Renewable Energy Agency (IRENA), World Bank, and Central Statistics Office (CSO). Policy documents and regulations were mainly gathered from various energy institutions in India, such as the Ministry of New and Renewable Energy (MNRE), Ministry of Statics and Program Implementation (MOSPI), Indian Renewable Energy Development Agency (IREDA), and Central Electricity Authority (CEA). Next, the modified Delphi method is used for finalizing and categorizing solar energy barriers with the help of experts' input. Later, the AHP approach is employed at the initial phase to measure the weights of major and sub-barriers by performing a pairwise comparison matrix. Finally, the G-TOPSIS approach is used to find out the best solution on the basis of five alternatives. A detailed description of these approaches is provided in the relevant sections.

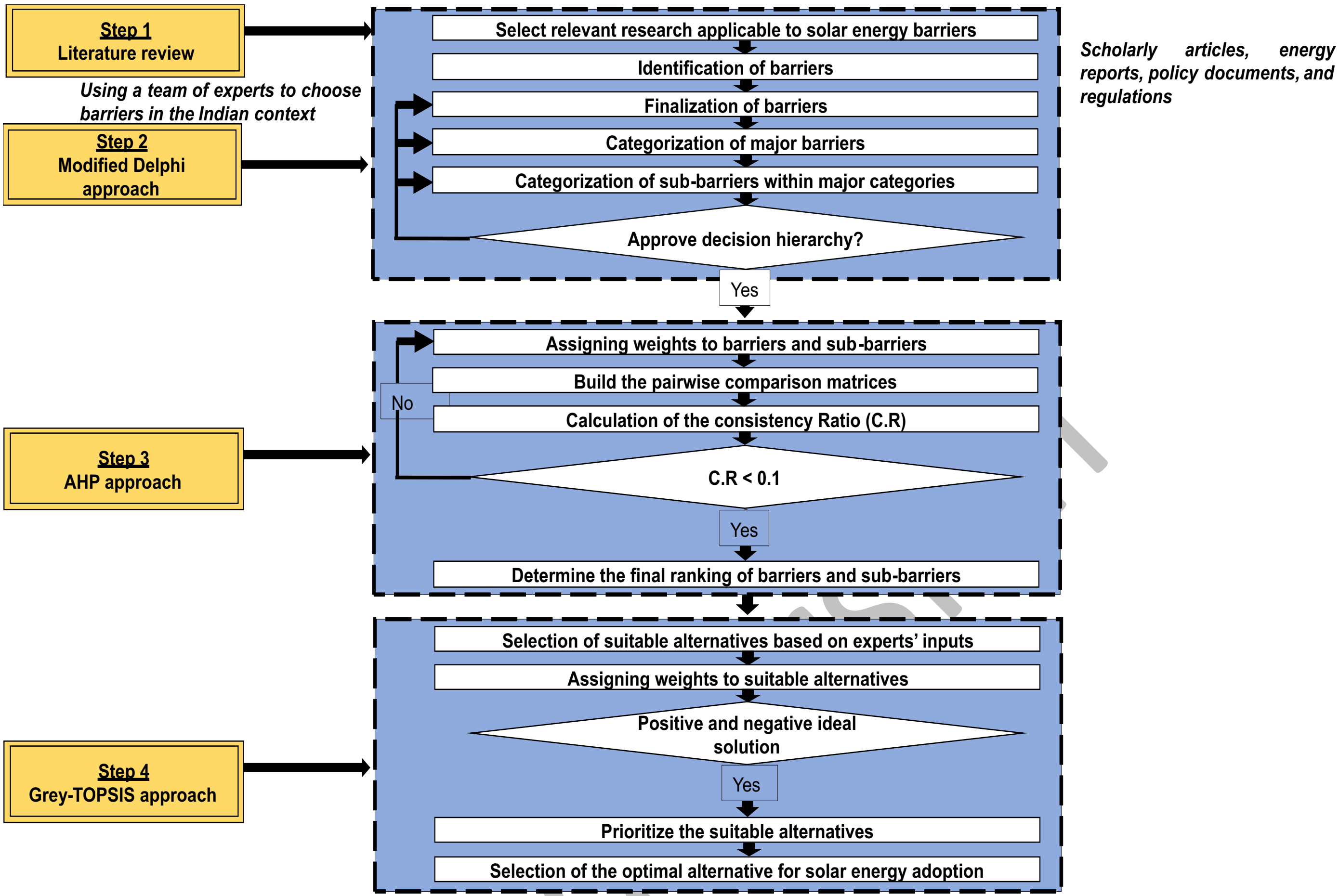

Fig. 1. Research framework.

2.1 Modified Delphi method

The modified Delphi method is used for the finalization and categorization of solar energy barriers. This method systematically gathers input from experts through discussions and questionnaires. Experts from related fields make shared inferences by exchanging their ideas, expertise, perspectives and skills [23]. The method consists of five essential steps, namely the selection of experts; the second and third step includes a double round of questionnaires surveys; the compilation of experts' feedback; and ranking the barriers [24].

Studies have suggested that there is no particular criterion for selecting experts in this method. However, Shah et al. [25] surveyed sixteen experts in their post-COVID-19 green economic recovery study. Zare et al. [26] took feedback from five experts, whereas, Solangi et al. [27] surveyed twelve experts in their analysis. Due to the countrywide lockdown situation, we conducted an online survey with thirteen experts (related to industry and academia) and incorporated their inputs using the modified Delphi approach. More specifically, we collected data from experts during the second COVID-19 lockdown in India (15 April – 3 May, 2020). The data collection process was divided into three phases. During the first phase, fifteen experts were approached through emails and their consent was asked regarding this research. The purpose of the study was briefly discussed with them at this stage. The following criteria were considered for recruiting experts. (1) Top-level professionals, i.e., lecturers, assistant/associate, and full professors (from academia) and chairman, secretary, and directors (from industry). (2) Experts should have more than ten years of professional experience in the relevant fields. (3) The qualification of the experts should be not less than bachelor's level. Thirteen experts agreed to provide their feedback by keeping in view how critical roles barriers can play in obstructing the adoption of solar energy in India. In the light of former studies, this sample (thirteen experts) is sufficient to conduct this research. During the second phase, the agreed experts were given a time period of one week to complete their responses. A detailed description of every question was provided to obtain accurate and meaningful results. During the third phase, responses were received from experts after one week and included for empirical analysis. Experts provided scores based on grey linguistic variables and triangular fuzzy number (TFN) to tackle solar energy barriers. The profiles of experts are provided in Appendix-A.

Recently, as the economic recovery is occurring to some extent and the solar industry is revitalizing, we performed a second round of Delphi data collection during 1 – 10 June, 2021 from same experts using the above-mentioned criteria to see how barriers changed from first round of data collection until now. The analysis has provided some interesting findings (see results section).

2.2 Analytical Hierarchy Process

AHP is one of the most adaptable MCDM techniques to solve complicated decision-making problems. This approach was first introduced by Thomas L. Saaty in the 1970s [28]. According to Wang et al. [29], AHP's key constituents encompass pairwise comparisons, thus creating comparison matrices for which their accuracy can be properly tested and sustained. The approach assists decision-makers in choosing and prioritizing complex issues correctly. Saaty [30] proposed the following main phases of the AHP approach.

Phase 1. Development of the hierarchical pattern of the decision problem.

Phase 2. Decision-problem's pairwise comparison matrix by employing Saaty's 1-9-point scale development,

Phase 3. The calculation of Consistency Index (CI).

During this phase, the consistency of the pairwise comparison matrix is calculated by using CI [31] and is represented as:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

Here, λ_{max} denotes the eigenvalue and n denotes the no. of major criteria

Phase 4. The calculation of the Consistency Ratio (CR)

$$CR = \frac{CI}{RI} \tag{2}$$

Here, RI indicates the random index and is reported in Table 4. One main criterion which must be considered during pairwise comparison is that CR should be within the threshold of 0.1. If it surpasses the suggested threshold level, the results would be inaccurate [32]. The weights of the key criteria and sub-criteria after the completion of all phases have been given by the AHP approach.

Table 4
Random Index *(RI)*.

n	1	2	3	4	5	6	7	8	9	10
RI	0.00	0.00	0.058	0.90	1.12	1.24	1.32	1.41	1.45	1.49

2.3 Grey system theory

Professor Julong Deng developed the principles of Grey system theory in 1982 [33]. The theory addresses and solves the discrete and incomplete data ambiguity problems with an objective to overcome the gap between natural and social sciences. Grey systems are named based on the transparency amount of data. If the system data is completely known, then it is called the white system, and if the system data is entirely unknown, the black system is called. The term white system is used when there is full recognition of system data, while the term black system is used when there is no recognition of system data [34]. On the other hand, the system is called a grey system if some portion of the system data is recognized, and the rest portion is unrecognized [35]. Because of the arbitrary and ambiguous opinion of researchers, the present study has employed the G-TOPSIS approach. This approach yields satisfactory results by utilizing inconsistent input data. Table 5 displays the TFNs classification system mostly used in MCDM issues.

Table 5
Linguistic variables grey number.

Number	Linguistic Variables	TFNs
1	Highly unfavorable (HU)	(0.0, 0.2)
2	Unfavorable (U)	(0.2, 0.4)
3	Neutral (N)	(0.4, 0.6)
4	Favorable (F)	(0.6, 0.8)
5	Highly Favorable (HF)	(0.8, 1.0)

2.4 Grey numbers

Grey number is defined as the interval of specified and unspecified value. The interval usually contains missing system data. The ⊗ symbol is used to denote the grey numbers. Grey numbers have multiple categories [36]; however, the present study has proposed three categories as follows:

Category (1): A grey number is called a lower bound if it is only measured by its lower bound and is denoted by $\otimes A = [\,\underline{A}\,, \infty)$.

Category (2): A grey number is called an upper bound if it is only measured by its upper bound and is denoted by $\otimes A = (\,\infty\,, \overline{A}\,]$.

Category (3): A grey number is called an interval grey number if it is measured by both lower and upper bound and is denoted by $\otimes A = [\,\underline{A}\,, \overline{A}\,]$.

Arithmetic functions could be done on two grey numbers having values $\otimes A = [\,\underline{A}\,, \overline{A}\,]$ and $\otimes B = [\,\underline{B}\,, \overline{B}\,]$ and shown in Equations 3–6 as follows:

$$\otimes A + \otimes B = \left[\,\underline{A} + \underline{B}, \overline{A} + \overline{B}\,\right] \quad (3)$$

$$\otimes A - \otimes B = \otimes A + (-\otimes B) = [\,\underline{A} - \overline{B}, \overline{A} - \underline{B}\,] \quad (4)$$

$$\otimes A \times \otimes B = \left[\,Min\,\{\underline{AB}, \overline{AB}, \overline{A}\underline{B}\,, \underline{A}\overline{B}\,\}, Max\,\{\underline{AB}, \overline{AB}, \overline{A}\underline{B}\,, \underline{A}\overline{B}\,\}\,\right] \quad (5)$$

$$\frac{\otimes A}{\otimes B} = \otimes A \times \otimes B^{-1} = \left[\,Min\left\{\frac{\underline{A}}{\underline{B}}, \frac{\underline{A}}{\overline{B}}, \frac{\overline{A}}{\underline{B}}, \frac{\overline{A}}{\overline{B}}\right\}, Max\left\{\frac{\underline{A}}{\underline{B}}, \frac{\underline{A}}{\overline{B}}, \frac{\overline{A}}{\underline{B}}, \frac{\overline{A}}{\overline{B}}\right\}\right] \quad (6)$$

Equation 7 provide the length of grey number $\otimes A = [\,\underline{A}\,, \overline{A}\,]$ as:

$$L(\otimes A) = \overline{A} - \underline{A} \quad (7)$$

If $\otimes A = [\,\underline{A}\,, \overline{A}\,]$ and $\otimes B = [\,\underline{B}\,, \overline{B}\,]$ are two grey numbers; then the greyness degree is obtained between them by using Equation (8) [37].

$$P\{\otimes A \leq \otimes B\} = \frac{Max\{0, L^{*} - Max(0, \overline{A} - \underline{B}\,)\}}{L^{*}} \quad (8)$$

Here $L^{*} = L(\otimes A) + L(\otimes B)$

2.5 G-TOPSIS approach

Yoon and Hwang developed the TOPSIS approach in 1981 [38]. The method assesses n alternatives by using the m parameters. The core logic of this method determines the optimal positive and negative solutions. An optimal alternative is the one with the least distance from the optimal positive solution and the highest distance from the optimal negative solution. The grey theory takes into account inconsistencies, as the data are not consistent sometimes. The different phases of the Grey Group TOPSIS approach are presented in the following stages [39].

Stage 1: During stage 1, the weight of all criterion should be decided by decision-makers. The views of experts can be articulated in grey theory based on linguistic variables. Suppose that k is the number of decision-makers, then the weight of criterion j is determined by the following Equation.

$$\otimes w_j = \frac{1}{k}\left[\otimes w_j^1 + \otimes w_j^2 + \cdots + \otimes w_j^k\right] \tag{9}$$

Stage 2: To assess the position of all study alternatives in the criteria, the linguistic variables are utilized. If k represents the number of decision-makers in criterion j, then the value of alternative i is determined as:

$$\otimes G_{ij} = \frac{1}{k}\left[\otimes G_{ij}^1 + \otimes G_{ij}^2 + \cdots + \otimes G_{ij}^k\right] \tag{10}$$

Stage 3: This stage intends the grey decision matrix and is represented by the following Equation.

$$D = \begin{bmatrix} \otimes G_{11} & \otimes G_{12} & \dots & \otimes G_{1n} \\ \otimes G_{21} & \otimes G_{22} & \dots & \otimes G_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes G_{m1} & \otimes G_{m2} & \dots & \otimes G_{mn} \end{bmatrix} \tag{11}$$

Here, $\otimes G_{ij}$ articulates the significance of the alternative i in the criterion j.

Stage 4: In this stage, the matrix of grey decision is standardized and denoted by Equation 12 as:

$$D^* = \begin{bmatrix} \otimes {G_{11}}^* & \otimes {G_{12}}^* & \dots & \otimes {G_{1n}}^* \\ \otimes {G_{21}}^* & \otimes {G_{22}}^* & \dots & \otimes {G_{2n}}^* \\ \vdots & \vdots & \vdots & \vdots \\ \otimes {G_{m1}}^* & \otimes {G_{m2}}^* & \dots & \otimes {G_{mn}}^* \end{bmatrix} \tag{12}$$

If the criteria are benefit attributes, then equation 13 is utilized for normalization as:

$$G^*{}_{ij} = \left[\frac{\underline{G}_{ij}}{G_j^{max}}, \frac{\overline{G}_{ij}}{G_j^{max}}\right] \; Where \; G_j^{max} = max_{1\le j\le m}\{\overline{G}_{ij}\} \tag{13}$$

If the criteria are cost attributes, then the following Equation is used for normalization.

$$G^*{}_{ij} = \left[\frac{G_j^{min}}{\overline{G}_{ij}}, \frac{G_j^{min}}{\underline{G}_{ij}}\right] \; Where \; G_j^{min} = min_{1\le j\le m}\{\underline{G}_{ij}\} \tag{14}$$

Energy matrix values would be within the range of [0, 1] after normalization.

Stage 5: A grey-weighted normalized decision matrix is devised and shown in the following Equation.

$$V = \begin{bmatrix} \otimes V_{11} & \otimes V_{12} & \dots & \otimes V_{1n} \\ \otimes V_{21} & \otimes V_{22} & \dots & \otimes V_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \otimes V_{m1} & \otimes V_{m2} & \dots & \otimes V_{mn} \end{bmatrix} Where\ \otimes V_{ij} = \otimes G_{ij}^{*} \times \otimes w_j \quad (15)$$

Stage 6: By using Equations 16 and 17, the optimal positive and negative solutions are computed during this stage as:

$$S^{max} = \{[max_{1\le j\le m} \underline{V}_{i1}, max_{1\le j\le m} \overline{V}_{i1}], [max_{1\le j\le m} \underline{V}_{i2}, max_{1\le j\le m} \overline{V}_{i2}], \dots, [max_{1\le j\le m} \underline{V}_{in}, max_{1\le j\le m} \overline{V}_{in}]\} \quad (16)$$

$$S^{min} = \{[min_{1\le j\le m} \underline{V}_{i1}, min_{1\le j\le m} \overline{V}_{i1}], [min_{1\le j\le m} \underline{V}_{i2}, min_{1\le j\le m} \overline{V}_{i2}], \dots, [min_{1\le j\le m} \underline{V}_{in}, min_{1\le j\le m} \overline{V}_{in}]\} \quad (17)$$

Stage 7: The potential greyness degree between optimal and alternative solutions is determined during this stage using Equation 18.

$$P\{S_i \le S^{max}\} = \frac{1}{n}\sum_{j=1}^{n} P\{\otimes V_{ij} \le \otimes G_j^{max}\} \quad (18)$$

Step 8: The alternatives are arranged in ascending order according to the values obtained in stage 7. Higher priority is given to the alternative with the minimum greyness degree.

3. Results and discussion

3.1 Results of AHP approach

The analysis begins by conducting a comprehensive literature review. Next, the authors used a group-based method of decision-making to give weights to solar energy barriers and sub-barriers. Based on an extensive literature review and experts' inputs, six major barriers were identified for the AHP model analysis. These barriers include technological, transparency & accountability, COVID-19, financial, policy & regulatory, and infrastructure. Next, we performed a pairwise AHP comparison matrix to measure individual weight scores by utilizing a geometric mean [40]. The weights of the major barriers were obtained in the first phase of AHP analysis, while twenty-nine sub-barriers were evaluated in the second phase. Fig. 2 depicts the hierarchical structure of solar energy barriers.

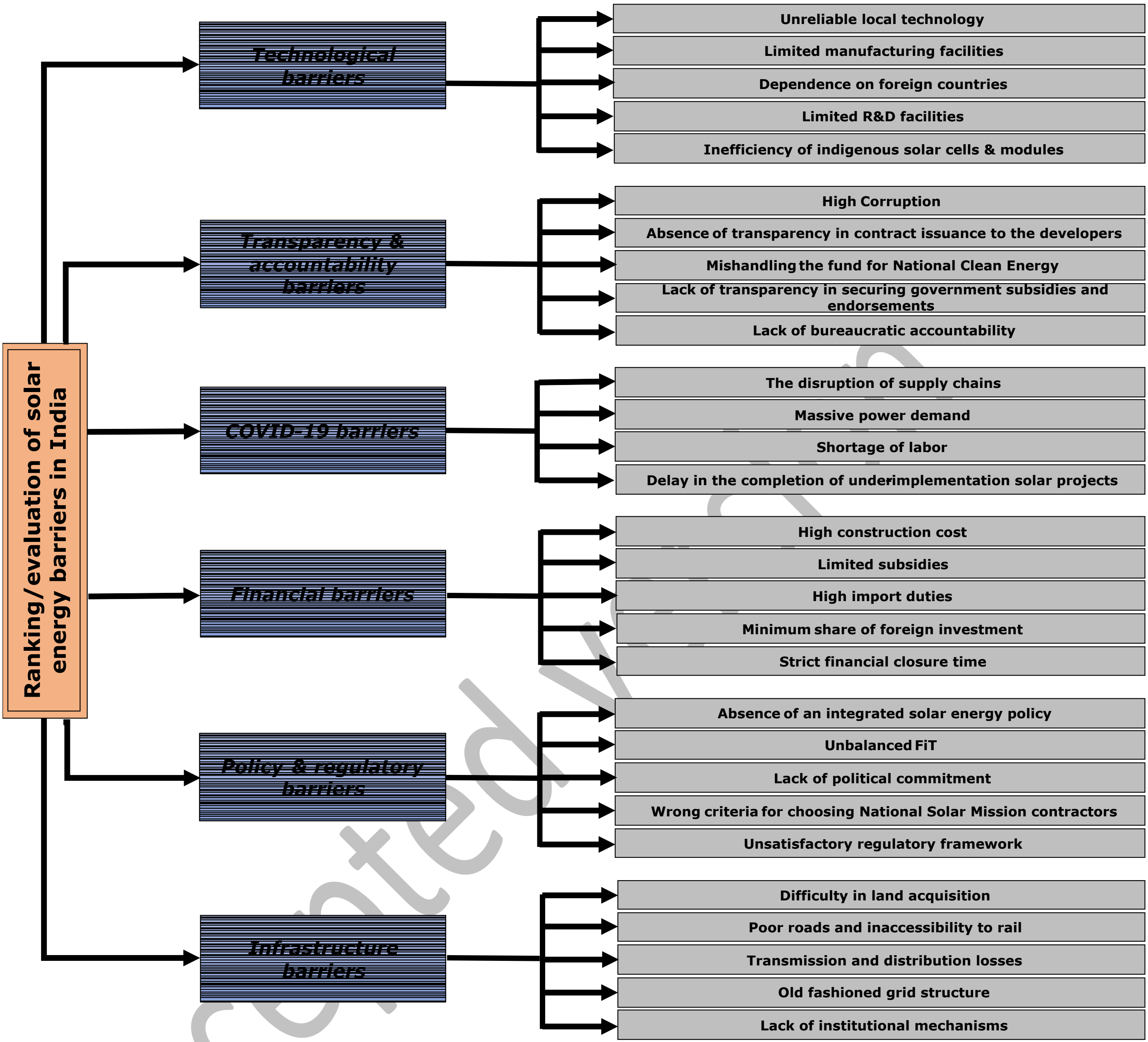

Fig. 2. The hierarchal structure of solar energy barriers.

3.1.1 Ranking of major barriers

The AHP method hierarchically measured the weights of all major barriers (see Table 6). It is evident from table 6 that the technological barrier is the most influential barrier, having a weight of (0.383). Transparency & accountability barrier ranks second with a weight of (0.260), followed by COVID-19 (0.143), financial (0.097), policy & regulatory (0.061), and infrastructure (0.056) barriers respectively. Fig. 3 represents the detailed weights of each major barrier. Based on the weight estimations of the major barriers, the top priority is given to the technological barrier in this study. Solar technology is still associated with high risks because this is not a developed technology in India. The country has limited production facilities and is dependent on foreign countries for key parts and equipment to establish mega-scaled solar energy parks [41]. The second priority is given to the transparency & accountability barrier.

Lack of implementation of transparent rules and regulations, unchecked bureaucracy powers, high taxation, and the monopoly of Government institutions are the root causes of the transparency & accountability barrier [42].

The recent COVID-19 pandemic is the third most significant barrier to the solar energy sector, impacting the overall solar industry and the solar energy development projects [43]. The financial barrier is turned out to be the fourth most influencing barrier after COVID-19 [19]. Owing to the latest advancements, new guidelines and enforcement parameters continue to be the significant problems for the solar industry. The industry, therefore, needs to regularly adopt new protocols to allow more sustainable practices and comply with them. The solar sector is confronting policy & regulatory barriers. The absence of an integrated solar energy policy and regulatory mechanisms affects the rapid development of the solar industry in India. Besides, some Government policies (i.e., [1]RPO, FiT, accelerated depreciation and net-metering policy) need amendments with the passage of time [44]. Finally, the least significant barrier is infrastructure barrier, which obtained the least weights estimated by the fuzzy AHP method in the context of solar energy, impeding the continuous deployment of solar energy in the country [45].

Table 6
Ranking of major barriers.

Major barriers	Code	Weight	Rank
Technological	TECH	0.383	1st
Transparency & accountability	TRA	0.260	2nd
COVID-19	COV	0.142	3rd
Financial	FIN	0.097	4th
Policy & regulatory	POLR	0.061	5th
Infrastructure	INF	0.056	6th

CR = 0.064

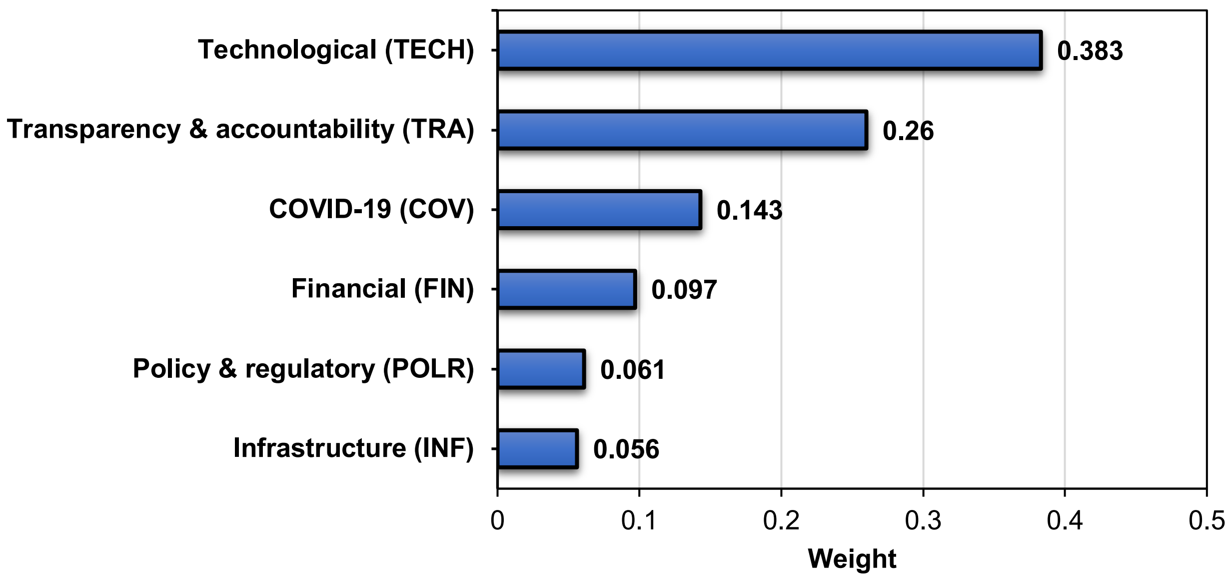

Fig. 3. The ranking of major barriers.

[1] RPO: Renewable purchase obligations, FiT: Feed-in tariffs.

3.1.2 Ranking of sub-barriers

A pairwise comparison matrix of sub-barriers is established after developing the hierarchical structure in Appendix B (see Tables B1–B6). The results of sub-barriers are discussed in this section.

Technological:

According to the results shown in Fig. 4, the sub-barriers in the technological category are ranked as follows: TECH-4 > TECH-5 > TECH-2 > TECH-1 > TECH-3. Unreliable local technology (TECH-4) is the most significant sub-barrier within this category by obtaining the highest weight of 0.457. Solar technology is new in the Indian subcontinent and hence there are high risks associated with this technology. The country lacks state-of-the-art solar technology to manufacture solar equipment and the equipment produced locally is unreliable [46]. The availability of solar irradiation data is necessary for the establishment of solar parks. However, some developers in the country merely use data obtained from the National Renewable Energy Laboratory (NREL), satellite modelled data (with only 70–80% confidence level) of the National Aeronautics and Space Administration (NASA) or assign external organizations to determine on-ground data. The dispatch of newly established solar parks is below projections due to the unavailability of proper solar irradiation data [47].

Limited manufacturing facilities (TECH-5) ranked second by obtaining a weight of 0.299. Literature supported this fact as almost every advanced country is developing its solar sector by building large manufacturing facilities. According to the Ministry of New and Renewable Energy, the manufacturing capacity of solar cells and modules is just 1,212 MW and 5,620 MW, respectively, in India [48], whereas countries such as the USA, China, Malaysia, and Germany have already achieved multi-gigawatt productions. Dependence on foreign countries (TECH-2) obtained a weight of 0.094 and is on the third number in this category. Due to unreliable local technology and limited manufacturing facilities, India relies on foreign countries for key equipment used in the construction of solar farms [49]. The import of these components from foreign countries not only results in high cost but also slows down the domestic growth of the solar industry.

Limited research and development (R&D) facilities (TECH-1) ranked fourth in the list by obtaining a weight of 0.076. The solar industry is not developed in India compared to other renewable industries. To remain competitive and for the speedy growth of the solar sector, the country needs to invest more in R&D facilities on a priority basis [50]. The inefficiency of indigenous solar cells and modules (TECH-3) obtained a weight of 0.075 and got last place under the technological sub-barrier category.

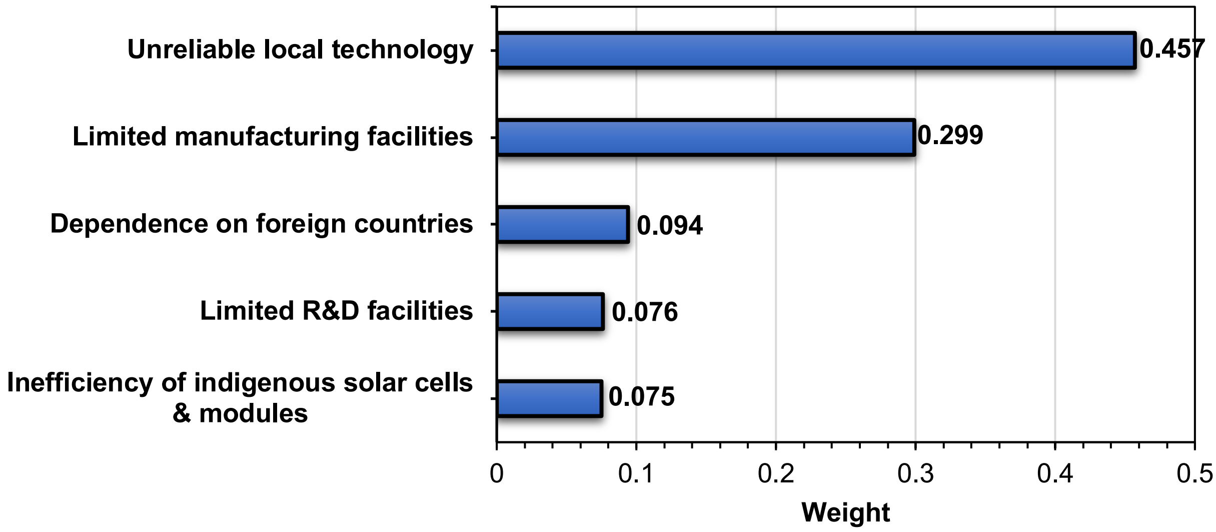

Fig. 4. The ranking of technological sub-barriers.

Transparency & accountability:

The ranking of sub-barriers under transparency & accountability group is as follows: TRA-4 > TRA-3 > TRA-2 > TRA-5 > TRA-1 and presented in Fig. 5. High corruption (TRA-4) is the most significant sub-barrier in this category, as it obtained the highest weight of 0.418. Researchers have widely reported this problem in their studies. For instance, [51] exposed that corruption is a primary barrier to the economic development of India. Spending on Government projects and schemes is the main corruption source in the country. Developers are forced to give bribes to officials during all phases of solar energy projects. The absence of transparency in contract issuance to the developers (TRA-3) is the second major sub-barrier in this category by obtaining a weight of 0.249. There are numerous cases when the Government did not follow the transparent laws in giving contracts to developers. One classic example of this lack of transparency is the "Coalgate" or Coal allocation scam. This incident happened in 2012 when the Government allotted 194 coal blocks to private companies without organizing the official bidding process [52].

Mishandling the fund for National Clean Energy (TRA-2) obtained a weight of 0.141 and got third place in this category. In 2010, the fund for *National Clean Energy* was established to boost renewable energy growth in the country. A major portion of this fund will be utilized for the R&D of solar PV. There have been concerns about the mishandling of this fund, as it is being used on the programs of other divisions and sectors rather than the solar industry [53]. Lack of transparency in securing Government subsidies and endorsements (TRA-5) is the fourth sub-barrier within this category, with a weight of 0.104. Local developers in India think that investing in solar energy development projects is difficult in the country as compared to foreign countries. The major reason is the lack of transparency in getting endorsements and financial assistance from the Government. Developers have the opinion that 60% of the solar energy project's overall time is spent on getting these approvals and subsidies. Moreover, according to the World Bank survey, India ranked 130 among 185 countries in ease of doing business index [54]. Consequently, local developers prefer to invest in foreign countries. Last in this category is the lack of bureaucratic accountability (TRA-1), with a weight of 0.089.

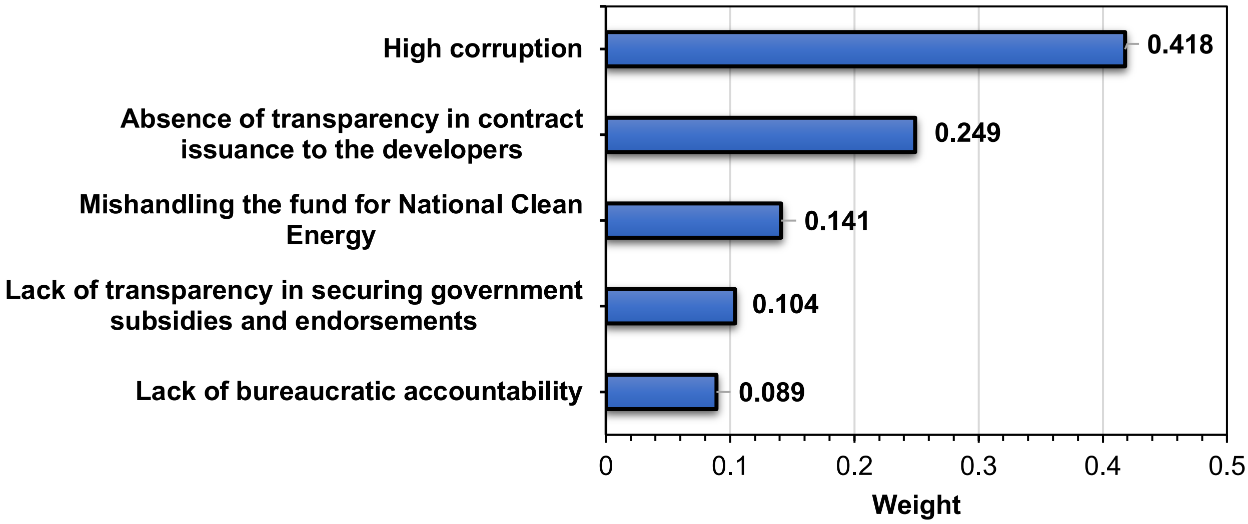

Fig. 5. The ranking of transparency & accountability sub-barriers.

COVID-19:

The results of the COVID-19 sub-barrier are shown in Fig. 6. The ranking of sub-barriers under COVID-19 (COV) group is as follows: COV-2 > COV-1 > COV-3 > COV-4. The disruption of supply chains (COV-2) is identified as the most significant COVID-19 sub-barrier with a weight of 0.410. The ranking is reasonable as Governments have imposed strict restrictions in the form of quarantine and social distancing policy [55]. Like other businesses, the supply chains of the solar industry have been severely influenced due to these restrictions. Accordingly, the production facilities of solar parks and power plants were considerably reduced [56]. Massive power demand (COV-1) is recognized as the second most significant barrier in this category by obtaining a weight of 0.403. India is the second-largest country in terms of population [10]. The novel pandemic has changed the lifestyles of people, as now people typically stay at home and work. Hence, there is a significant increase in residential power demand. This terrible situation poses new challenges for the power sector in the country [11].

Shortage of labor (COV-3) obtained a weight of 0.126 and ranked third in the COVID-19 sub-barrier category. The solar industry is facing immediate challenges as a consequence of COVID-19, such as the shortage of labor. The current labor force situation is in disarray due to the lockdown in all Indian states, which has resulted in a labor crunch, and the solar industry has not been left untouched by this unprecedented crisis [57]. One of the key contributors to the Government's attempt to attain clean energy goals, the solar sector has been left high and dry. Delay in the completion of under-implementation solar projects (COV-4) is placed at fourth position, as it received a weight of 0.060. The completion of under-implementation solar projects in India has been delayed, as modules and solar cells used in solar farms are mostly imported from China [58]. Due to the COVID-19 pandemic situation, China has closed borders with India and cancelled all consignments, for the time being, causing significant delays in the completion of ongoing solar projects.

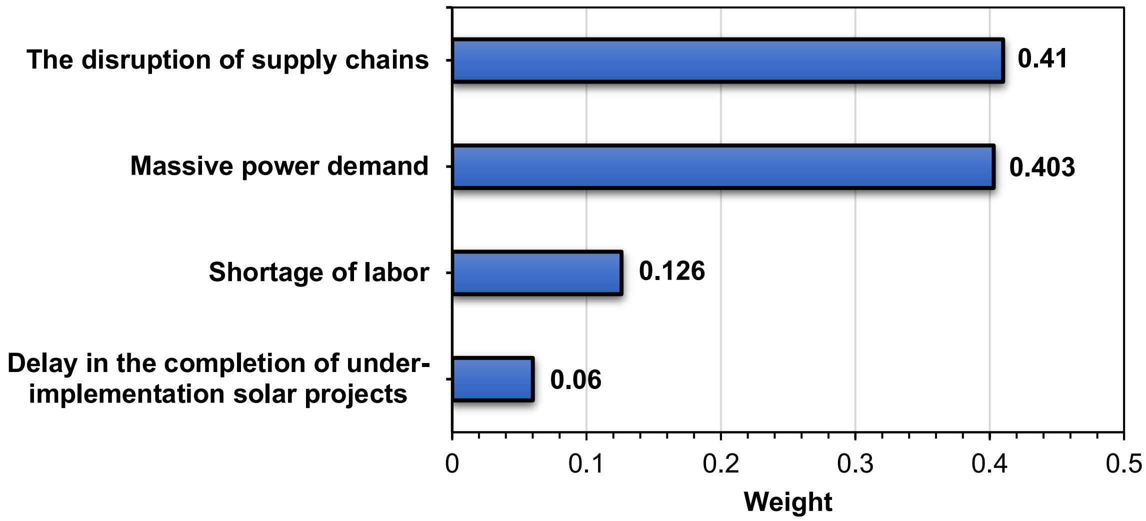

Fig. 6. The ranking of COVID-19 sub-barriers.

Financial:

The ranking of the sub-barrier under financial (FIN) category is as follows FIN-4 > FIN-5 > FIN-1 > FIN-2 > FIN-3 and can be seen in Fig. 7. High construction cost (FIN-4) is the most significant sub-barrier in this category with 0.408 weight. Previous literature also supported this argument, as [59] revealed in their study that high cost is a major barrier in solar energy development because the construction of solar energy parks requires high capital cost. Though the cost of solar energy technology has considerably reduced over the years, it is still high in developing countries like India, which supports the use of fossil fuel-based thermal energy [60].

Based on weight allocation, limited subsidies (FIN-5) is the second most significant sub-barrier having a weight of 0.386. Contrary to thermal electricity, solar energy has no confirmed track record. Consequently, it is difficult for new ventures to receive subsidies from the Government. Monetary organizations have limited investment exposure against solar energy due to the fact that a vast capital has already been extended for thermal power sources [61]. As a result, the solar sector is confronting with teething pains. High import duties (FIN-1) obtained a weight of 0.091 and took third place in this category. Solar energy programs have become uneconomical due to the high import duties, whereas the provincial Government of Madhya Pradesh has waived electricity duty on wind power projects for five years [62]. The Government has imposed heavy duties on the import of solar PV, which has resulted in the high capital costs of PV plants [63].

Minimum share of foreign investment (FIN-2) with a weight of 0.064 is another significant barrier that got a fourth place under the financial sub-barrier category. As the interest rate for solar power programs is very high, foreign developers are reluctant to invest in the Indian solar sector [64]. Strict financial closure time (FIN-3) turned out to be the last sub-barrier in this category with a weight of 0.051. The "National Solar Mission" allocated a time frame of three months for financial closure. It was further publicized that the contractors will be fined if they fail to manage projects during this time period [65].

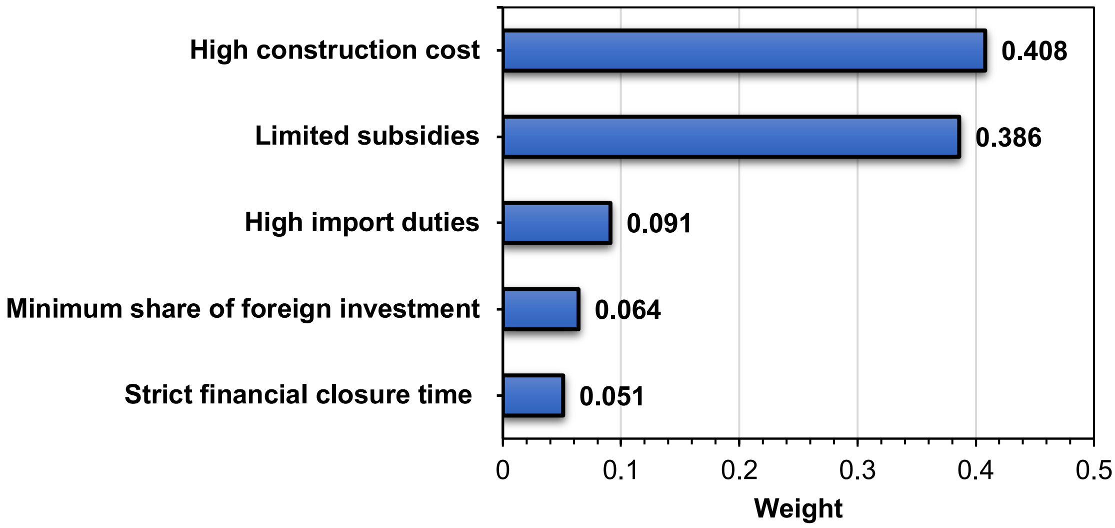

Fig. 7. The ranking of financial sub-barriers.

Policy & regulatory:

The ranking of sub-barriers under 'policy & regulatory' (POLR) category is as follows: POLR-2 > POLR-5 > POLR-4 > POLR-3 > POLR-1 as depicted in Fig. 8. The absence of an integrated solar energy policy (POLR-2) is the most significant sub-barrier with a weight of 0.441 in this list. Various studies have reported that the absence of clarification on existing and future policies for the growth of solar power capacity, infrastructure, and the establishment of grids continues to deter stakeholders [66,67]. Unbalanced FiT (POLR-5) placed second in the list by obtaining a weight of 0.257. The State Electricity Regulatory Commissions have specified FiT in all states. Nevertheless, FiT, governed by a cost-plus strategy within a rate of return mechanism, restrains the full use of solar power and never provides the cost reduction benefits. This prevalent form of cost-plus FiT has severely overlooked economic efficiency [68].

Lack of political commitment (POLR-4) obtained a weight of 0.177 and was placed at the third position in this list. India has abundant solar energy potential. Without a strong political commitment, this potential cannot be exploited. Political instability and Government intrusion in local markets are hindering the deployment of solar energy in the country [69]. The wrong criteria for choosing National Solar Mission contractors (POLR-3) is next in the sub-barriers list by obtaining a weight of 0.091. Currently, the benchmark for selecting contractors for

Jawaharlal Nehru National Solar Mission is based on minimum to maximum capability instead of track record and financial status, which should be changed [70]. Unsatisfactory regulatory framework (POLR-1) got the last place within the category of policy & regulatory barriers by obtaining a weight of 0.032.

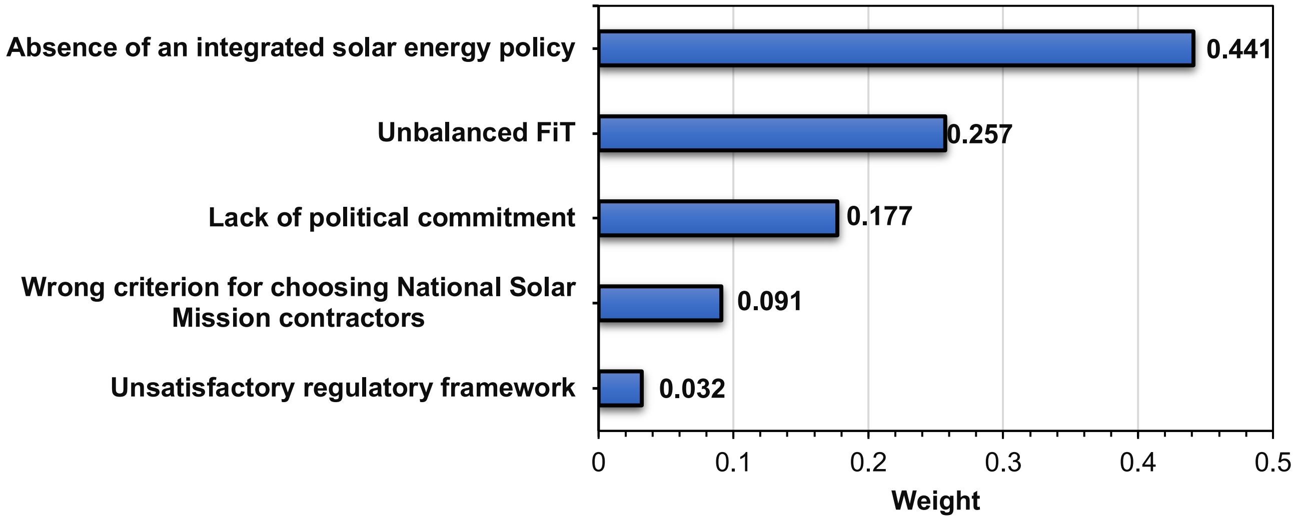

Fig. 8. The ranking of policy & regulatory sub-barriers.

Infrastructure:

The ranking of sub-barriers within the ‘infrastructure’ (INF) group, exhibit the following pattern as: INF-2 > INF-5 > INF-4 > INF-3 > INF-1 (see Fig. 9). Difficulty in land acquisition (INF-2) is the top sub-barrier under the infrastructure domain by obtaining a weight of 0.435. Land acquisition for setting solar energy projects is always lengthy and time-consuming and differs in every state. Nearly one year is needed to acquire land, and in some circumstances, even one year is insufficient. Approval from different Government departments is also required for this purpose. Due to these difficulties, many solar energy projects have become delayed or even relocated to other places. Thus, the acquisition of land has become a very tedious process for solar energy programs in the country [71].

Poor roads and inaccessibility to rail (INF-5) rank second in the category by obtaining 0.258 weight. Sometimes, solar parks are established in remote rural areas, far away from national highways and do not have accessibility to rail. In these conditions, the transportation of PVs and related equipment to the target site is a challenging task. Even in some cases, the costly solar power equipment breaks during transportation, which results in delaying the normal function of solar power development programs [72]. Transmission and distribution (T&D) losses (INF-4) is the third major sub-barrier in this list, as it has obtained a weight of 0.180. T&D losses were 13% more in India than USA [73]. Poor management, less monitoring and electricity theft are the common reasons for T&D losses. The national grid is India's high-voltage electricity transmission network, connecting power plants and main substations and assuring that electricity generated anywhere in the country can be used to fulfil demand in other parts of the country [74]. The national grid is maintained and owned by the Power Grid Corporation of India and operated by the Power System Operation Corporation. The five regional power grids of India, namely Northern Region, Eastern Region, Western Region, North-eastern Region, and Southern Region grids, are interconnected to establish the national grid [75]. With 371.054 GW of installed electricity generation capacity, it is one of the world's largest functional synchronous grid [76]. While India's installed transmission capacity is only 13% of cumulative installed generation capacity, the ratio of transmission network availability is greater than 99%. The capacity of India's inter regional national grid is 61,150 MW [42].

Old fashioned grid structure (INF-3) obtained a weight of 0.092 and ranked fourth under the infrastructure barrier category. Literature supported this fact, as the Indian grid structure is old fashioned which is built for conventional thermal energy. Consequently, it only promotes thermal energy. Solar parks lack grid infrastructure in the country. [77] reported that the existing grid structure needs massive investment to support renewable energy technologies, including solar energy, in the long run. Finally, the lack of institutional mechanisms (INF-1) got the last position in the list by obtaining a weight of 0.033. There are no institutional mechanisms to offer after-sales services to support solar technology. Limited involvement of the private sector and associated initiatives cannot inspire the present institutional tools to adapt to new markets [78].

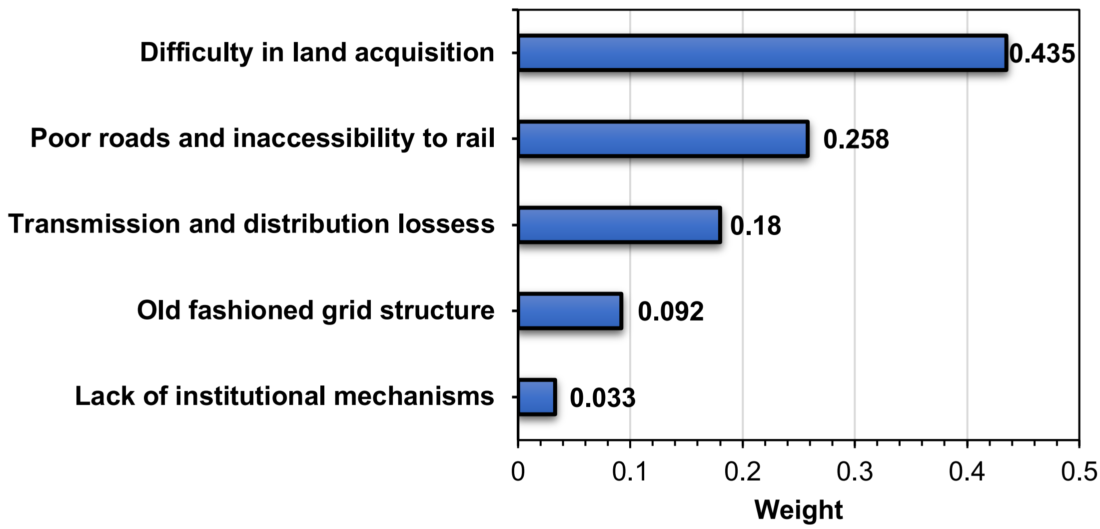

Fig. 9. The ranking of infrastructure sub-barriers.

3.1.3 Overall ranking of sub-barriers

We obtained the final weights of sub-barriers by multiplying the weight of every sub-barrier's respective category by its priority weight (see Table 7). Fig. 10 shows the schematic representation of the overall ratings of solar energy sub-barriers. The criterion is as follows: TECH-4 > TECH-5 > TRA-4 > TRA-3 > COV-2 > COV-1 > FIN-4 > FIN-5 > TRA-2 > TECH-2 > TECH-1 > TECH-3 > TRA-5 > POLR-2 > INF-2 > TRA-1 > COV-3 > POLR-5 > INF-5

> POLR-4 > INF-4 > FIN-1 > COV-4 > FIN-2 > POLR-3 > INF-3 > FIN-3 > POLR-1 > INF-1.

It is evident from Fig. 11 that "unreliable local technology" ranks highest among all sub-barriers by obtaining a weight of (0.1750), followed by "limited manufacturing facilities" (0.1145). "High corruption" and "the absence of transparency in contract issuance to the developers" are the 3rd and 4th most significant solar energy sub-barriers by getting weights of (0.1087) and (0.0647), respectively. The least significant sub-barriers are the old-fashioned grid structure (0.0052), minimum share of foreign investment (0.0049), unsatisfactory regulatory framework (0.0020), and the lack of institutional mechanisms (0.0019).

Table 7
Final weights and ranking of sub-barriers.

Major barriers	**Major barriers' weights**	**Sub-barriers' codes**	**Priority weight**	**Final weight**	**Overall ranking**
Technological (TECH)	0.383	TECH -1	0.076	0.0291	11
		TECH -2	0.094	0.0360	10
		TECH -3	0.075	0.0287	12
		TECH -4	0.457	0.1750	1
		TECH -5	0.299	0.1145	2
Transparency and accountability (TRA)	0.260	TRA -1	0.089	0.0231	16
		TRA -2	0.141	0.0367	9
		TRA -3	0.249	0.0647	4
		TRA -4	0.418	0.1087	3
		TRA -5	0.104	0.0270	13
COVID-19 (COV)	0.143	COV-1	0.403	0.0576	6
		COV-2	0.410	0.0586	5
		COV-3	0.126	0.0180	17
		COV-4	0.060	0.0086	23
Financial (FIN)	0.097	FIN-1	0.091	0.0088	22
		FIN-2	0.064	0.0062	24
		FIN-3	0.051	0.0049	27
		FIN-4	0.408	0.0396	7
		FIN-5	0.386	0.0374	8
Policy and regulatory (POLR)	0.061	POLR -1	0.032	0.0020	28
		POLR -2	0.441	0.0269	14
		POLR -3	0.091	0.0056	25
		POLR -4	0.177	0.0108	20
		POLR -5	0.257	0.0157	18
Infrastructure (INF)	0.056	INF -1	0.033	0.0019	29
		INF -2	0.435	0.0244	15
		INF -3	0.092	0.0052	26
		INF -4	0.180	0.0101	21
		INF -5	0.258	0.0145	19

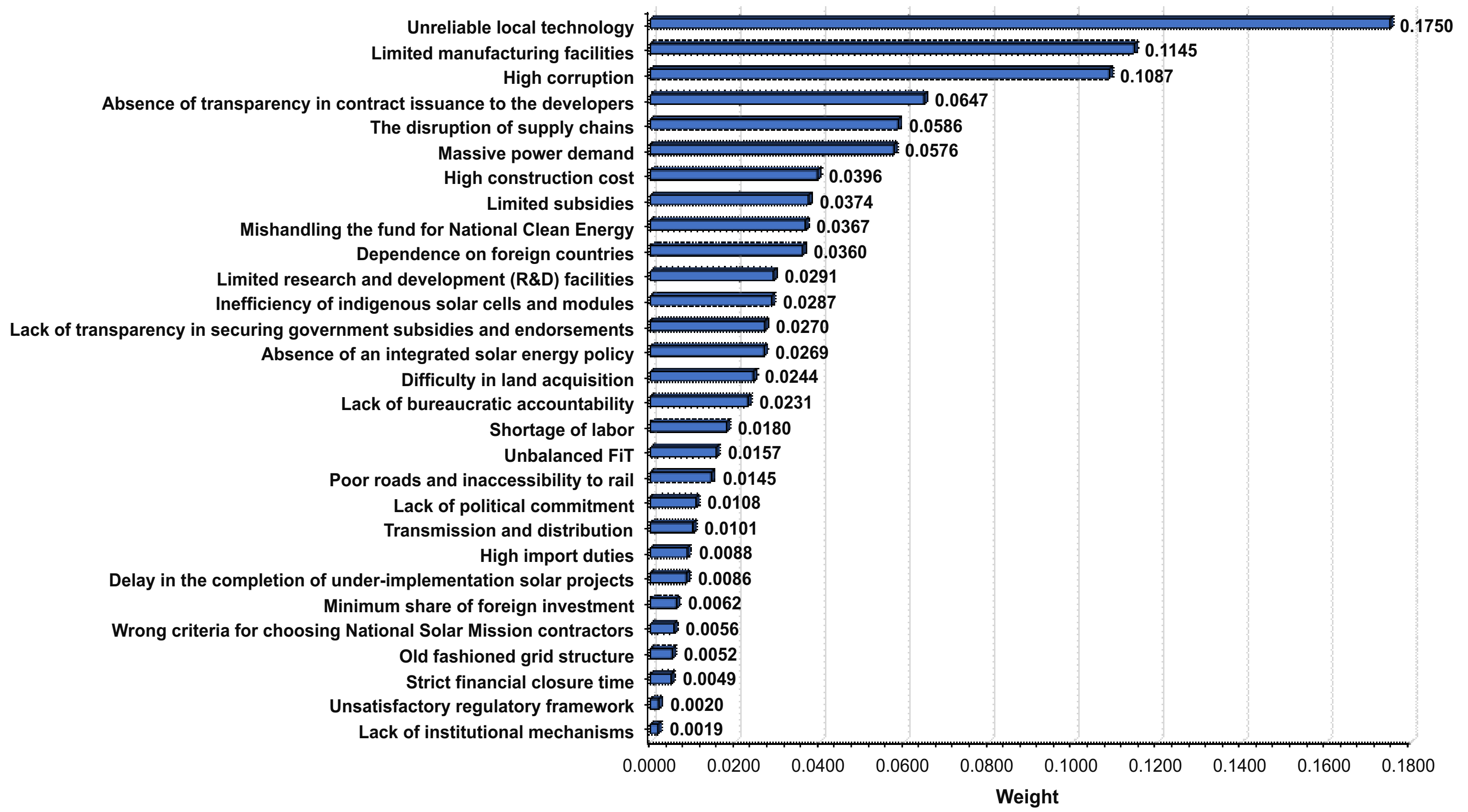

Fig. 10. The overall ranking of sub-barriers.

3.2 Results of G-TOPSIS approach

The G-TOPSIS approach enhances the precision of decision-making in uncertain situations. Consequently, we have employed this approach and selected the optimal solution to eradicate the barriers to the successful adoption of solar energy in the country. A group of thirteen experts provided their inputs regarding the key alternatives to overcome the solar energy adoption barriers. The five key alternatives such as human resources availability (A1), R&D improvement (A2), policy reformations (A3), corruption-free system (A4), and infrastructure development (A5) were chosen. Based on experts' inputs, we used the decision-making approach to determine the results. The inputs from the group of experts determined grey numbers and a grey evaluation matrix utilizing linguistic variables. The ranking matrix of linguistic variables was then established after comparing alternatives against each sub-barrier category. Table 8 presents the results of positive grey ideal solution and negative fuzzy ideal solution based on G-TOPSIS. Lastly, we measure the greyness degree between ideal solutions and alternatives. Equations 19–24 show the ideal solutions and alternatives.

$$P(S_1 \leq S^{max}) = 0.401 \tag{19}$$

$$P(S_2 \leq S^{max}) = 0.230 \tag{20}$$

$$P(S_3 \leq S^{max}) = 0.512 \tag{21}$$

$$P(S_4 \leq S^{max}) = 0.298 \tag{22}$$

$$(S_5 \leq S^{max}) = 0.600 \tag{23}$$

The ranking of alternatives is based on the possible degree of greyness values and provided in equation 24 as:

$$A_2 > A_4 > A_1 > A_3 > A_5 \tag{24}$$

The results of G-TOPSIS (reported in Table 8) show that R&D improvement is the best alternate solution to overcome solar energy adoption barriers by obtaining (0.230) weight. Corruption free system (0.298) ranks second in this category. Human resources availability, policy reformations, and infrastructure development are the least significant alternatives by obtaining weights of (0.401), (0.512), and (0.600), respectively.

Table 8
Grey TOPSIS-based final ranking of the alternatives.

Codes	Alternatives	S^{max}	S^{min}	possibility degree of greyness	Rating
A1	Human resources availability	0.495201	0.403214	0.401	3rd
A2	R&D improvement	0.61266	0.210241	0.230	1st
A3	Policy reformations	0.3922870	0.202358	0.512	4th
A4	Corruption free system	0.553201	0.30215	0.298	2nd
A5	Infrastructure development	0.250147	0.12021	0.600	5th

4. Conclusions and policy propositions

This study assesses and prioritizes barriers depending on the level to which they obstruct the solar energy sector in India. Several barriers were initially scrutinized from the previous literature and then refined with the assistance of experts. By employing the AHP method, twenty-nine barriers within six major categories were finalized, including technological, transparency & accountability, COVID-19, financial, policy & regulatory, and infrastructure. The weights of all these barriers were obtained by performing a pairwise comparison matrix. The contributions of this paper begin with the results of the AHP. The results reveal that the technological barrier is the top-ranked barrier, followed by transparency & accountability, COVID-19, financial, policy & regulatory, and infrastructure barriers, respectively. The ranking of sub-barriers has demonstrated that the "unreliable local technology" ranks highest among all sub-barriers. Further contributions and insights in the field are expanded by applying the G-TOPSIS approach, which have assisted authors to extend previous outcomes and prioritize the top five alternatives for enhancing and validating the accuracy of research outcomes. Based on the findings of the G-TOPSIS approach, R&D improvement is considered as the most effective solution to address the challenges of solar energy adoption, followed by a corruption-free system, human resources availability, policy reformations, and infrastructure development.

Solar energy can be a suitable energy choice for India, as every year, the country receives 5,000 trillion kWh of solar energy. However, the country is confronting with numerous barriers in achieving the highest potential of solar power sector. Accordingly, there is a significant difference between the present and the projected output of the solar industry. Research results revealed that R&D is an essential component of solar sector development. Nevertheless, the country has limited manufacturing facilities; the local solar technology is unreliable and mostly dependent on foreign countries. Therefore, it is proposed that R&D activities should be improved to minimize operating costs and reliance on foreign technology. Ample funds should be allocated to accelerate this process.

Dramatic changes caused by the novel COVID-19 have unprecedented implications for all industries and the solar industry is no exception. The unavailability of human resources due to the countrywide lockdown is one of the major challenges the solar industry faces. The role of Government is critical in this regard. There is a need to establish crisis management strategies, formulate comprehensive policies for remote as well as the hybrid working environment as a response to the current pandemic crises. The system should be free from corruption for the sustainable growth of solar industry. It should be regulated to ensure that all solar development programs have appropriate controls and balances, reduce bureaucracy powers, and devise an effective tax mechanism. Developers should be given tax holidays for establishing new solar parks and take benefit of accelerated depreciation.

The dream of quick deployment of solar energy is impossible without a robust policy framework. The Government should establish a comprehensive national solar energy policy in this regard. The old policy structure is usually meant for thermal energy sources and limited subsidies have been provided for the solar sector. Besides, massive investment is required for the construction and maintenance of solar parks. In this scenario, the old policy framework needs an amendment by giving enough subsidies to the solar power sector. Similarly, the benchmark used for selecting developers for the *National Solar Mission program* must be switched from minimum-maximum capability to financial status and track record basis. The solar energy infrastructure also requires major improvements. As the process of land acquisition for solar farms needs the approval of several Government agencies and is always time-taking; therefore, the Government should make efforts to make this process transparent and simplified. Reducing the involvement of too many Government agencies and following the transparent ways of land acquisition would be handy in this regard. The safe transport of PVs and relevant material to the construction sites should be supported by adequate roads and rail. Finally, the inefficient and obsolete T&D mechanism should be upgraded to mitigate T&D losses.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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