Empirical Investigation and Assessment of Various Energy Sources for Sustainable Development of Energy Sector in India

THESIS

Submitted in partial fulfilment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

by

SANTOSH KUMAR SARASWAT

Under the Supervision of

Prof. Abhijeet K. Digalwar

&

Dr. Shyam Sunder Yadav

BIRLA INSTITUTE OF TECHNOLOGY & SCIENCE, PILANI

PILANI – 333031 (RAJASTHAN), INDIA

2022

……dedicated

to

my family……

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Birla Institute of Technology & Science, Pilani
Pilani Campus

CERTIFICATE

This is to certify that the thesis titled **"Empirical Investigation and Assessment of Various Energy Sources for Sustainable Development of Energy Sector in India"** submitted by **Santosh Kumar Saraswat**, ID.No. **2017PHXF0012P** for award of Ph.D. of the institute embodies original work done by him under our supervision.

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SANTOSH KUMAR SARASWAT

Abstract

The rapidly growing population, unplanned urbanization, and industrialization in developing countries are currently the world's most pressing concerns. These challenges lead to an increase in the rate of energy consumption, fossil fuels, water, materials, and available natural resources. In addition to this, there is also extensive destructions caused to natural resources and fossil fuels. Therefore, there is a need to tap the 'sustainable energy sources' for global energy security and a cleaner environment. The importance of sustainable energy has been addressed on numerous global platforms and stages including the Brundtland Commission report of the United Nations (UN) in 1987, Agenda21 in 1992, the Kyoto Protocol in 1997, the UN Millennium Development Goals (MDGs) in 2000, Sustainable Energy for All (SE4ALL) in 2011, and finally, the UN Sustainability Development Goals (SDGs) in 2016. As a country, India has set ambitious future development goals and made international pledges to the country's and the world's sustainable development and progress. To achieve these goals, India must address a number of issues, including foreign fuel dependency, financial strain, greenhouse gas emissions, air pollution, water scarcity, electrical infrastructure, land acquisition, etc. In order to overcome or minimize these challenges, the aim of the current study is to classify and quantify the sustainable energy sources on a broad scale. This task is met by considering the following objectives: (i) identification of crucial and important sustainability indicators, (ii) evaluation of sustainable energy sources including multiple aspects, (iii) assessment of optimal energy mix scenario in India, (iv) assessment of potential sites for the installation of sustainable energy sources based on technical, economic, and socio-environment aspects, (v) estimation of exploitable sustainable power potential, and (vi) validation of findings via a case study.

Firstly, in order to assess the sustainability indicators in the Indian context, a survey is carried out including 93 indicators pertaining to 15 main categories. As a result, 442 responses are collected across the country. Further, these survey responses are analyzed to obtain the sustainability importance index (SII). Furthermore, the survey outcome is validated through statistical analysis. Finally, the study obtained the 26 indicators

pertaining to six categories of economic, technical, social, environmental, political, and flexible. As the study has to address multiple aspects, it is necessary to use a multi-criteria decision-making (MCDM) approach. In addition, seven key energy alternatives are considered after a thorough examination of the Indian energy sector: thermal (coal), gas, nuclear, hydro, solar, wind, and biomass energy. By utilizing the hybrid fuzzy MCDM approaches, the study identifies solar energy as the most sustainable energy source in India, followed by wind, hydro, biomass, and gas power. The outcome of the proposed approaches is validated by performing the sensitivity and correlation analysis. Further, to evaluate the optimal energy mix scenario in India, 14 distinct scenarios are developed by taking the anticipated growth rate in the top-five sustainable energy sources into account. Finally, the optimal energy mix scenario includes coal (49%), solar (14%), wind (13%), hydro (9%), nuclear (4%), gas power (4%), biomass (2%), small hydro (2%), and import-export (2%) in total electricity delivered to customers.

Further effort was put to identify the prospective locations for the installation of the most sustainable energy sources, those are the solar and wind energy. The study employed a one-of-a-kind combination of MCDM and geographical information system (GIS) for this objective. In this case, MCDM is used to assign importance to decision criteria, and a GIS technique is used to visualize prospective sites while assessing decision and limiting criteria. The study includes thirteen decision criteria for solar energy and twelve decision criteria for wind energy under the technical, economic, and socio-environmental categories. Due to this exercise, the resulting site suitability map is divided into five classes namely 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and finally 'not suitable'. Among these classes, the highly suitable category contains an area of 133874 km^2 for the solar and 29457 km^2 for the wind energy. On the other hand, Rajasthan is the leading state in terms of solar and wind energy. The study also calculated the geographical, theoretical, technical, economic, and environmental potentials of these highly suitable locations. In addition to that, the study found that 16 Indian states had greater potential than their present energy needs. Finally, a software-based case study is conducted on these highly suitable sites to analyze the economic viability, technical feasibility, and environmental sustainability of the project.

The findings of the present study will be valuable and useful to a variety of organizations at various levels as follows:

- ✓ Firstly, it will serve as a guiding light for international community and government agencies in developing standard or globally acknowledged sustainability indicators that are still at the nascent phase of development.
- ✓ In addition, the study will also assist researchers, academicians, governments, policymakers, and decision-makers in achieving the aim of sustainable development while adhering to international obligations.
- ✓ The outcome of the present study would also assist the government of India (GOI) in meeting international commitments and will also contribute to the country's GDP growth via expanding economic trade, property revenue, capital investment, and other factors.
- ✓ In addition to the above points, the study will assist in the proper utilization of renewable energy potential and infrastructure which will aid in boosting investment and attracting investors.
- ✓ It will also aid in the better management of power between power-rich and power-scarce states.
- ✓ All of these points will contribute to a better understanding of the techno-economics of different sites, reduce the likelihood of economic losses, reduce the related economic and environmental hazards, and clarifies the project's future vision.

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List of Abbreviations and Symbols

Symbol/Abbreviation	Description
AHP	Analytical Hierarchy Process
ANP	Analytic Network Process
ARAS	Additive Ratio Assessment
BWM	Best-Worst Method
CC	Closeness Coefficient
CEA	Central Electricity Authority
CI	Consistency Index
CR	Consistency Ratio
ELECTRE	Elimination and Choice Translating Reality
ESRI	Environmental System Research Institute
EU	European Union
FAHP	Fuzzy Analytical Hierarchy Process
FNIS	Fuzzy Negative Ideal Solution
FPIS	Fuzzy Positive Ideal Solution
GDP	Gross Domestic Production
GIS	Geographical Information System
GM	Geometric Mean
GOI	Government of India
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IESS	Indian Energy Security Scenario
IMD	Indian Meteorological Department
INDC	Intended Nationally Determined Contribution
IRENA	International Renewable Energy Agency
IWTMA	Indian Wind Turbine Manufacturer Association
JNNSM	Jawaharlal Nehru National Solar Mission
LCOE	Levelized Cost of Energy
MAUT	Multi-Attribute Utility Theory
Mtoe	Million tons of oil equivalent

Symbol/Abbreviation	Description
MCDM	Multi Criteria Decision Making
MDGs	Millennium Development Goals
NAPCC	National Action Plan on Climate Change
NIWE	National Institute of Wind Energy
NLDC	National Load Dispatch Center
NHPC	National hydroelectric Power Corporation
NPCIL	Nuclear Power Corporation of India Ltd.
NREL	National Renewable Energy Laboratory
OWA	Order Weighted Averaging
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
RES	Renewable Energy Sources
RI	Random Index
SDGs	Sustainable Development Goals
SE	Sustainable Energy
SJVN	Satluj Jal Vidhyut Nigam
SWARA	Step-wise Weight Assessment Ratio Analysis
SWPP	Solar and Wind Power Potential
TERI	The Energy and Resources Institute
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TSPP	Theoretical Solar Power Potential
TWPP	Theoretical Wind Power Potential
USD	United States Dollar (currency)
WASPAS	Weighted Aggregated Sum Product Assessment
WISE	World Institute for Sustainable Energy
WPM	Weighted Product Model
WSM	Weighted Sum Model

Greek Symbols

Q_i	Fuzzy VIKOR Index
S_i	VIKOR Usefulness
R_i	VIKOR Discomfortness
φ^+	PROMETHEE Leaving Flow
φ^-	PROMETHEE Entering Flow
φ	PROMETHEE Net Flow
A_i	Weighted Normalized Matrix
n	Number of Factors or Criteria
W_l, W_m, and W_u	Lower, Middle, and Upper Triangular Fuzzy Numbers
$\lambda_{max.}$	Maximum Eigen Value
r_{SR}	Spearman's Rank Difference
r_{KP}	Karl's Pearson Correlation Coefficient
SR	Solar radiation intensity (kWh/m^2/day)
CA_s	Geographical suitable land area for solar energy (km^2)
AF_s	Area factor for solar energy (%)
η	Efficiency (%)
TA_w	Available highly suitable land area for wind energy (km^2)
AF_w	Area factor for wind energy (%)
n	Operational life of technology ($/kW)
I_t	Investment cost ($/kW)
O & M_t	Operation and maintenance cost ($/kW/year)
F_t	Expenditure on fuel ($/kW/year)
r	Discount rate (%)
E_t	Amount of electricity generated per year (kWh/year)
US ₵	US cents (currency)
₹	Indian Rupees (currency)

CHAPTER – 1

INTRODUCTION

This chapter provides an overview, research motivation, objectives and scope of the study, methodology, significance of the study and thesis organization.

1.1 INTRODUCTION

The world's fastest-growing population, urbanization, and industrialization are the world's most pressing concerns, especially for India. These challenges lead to an increase in the rate of energy consumption of resources, fossil fuels, water, material, and accessible natural resources. In addition to this, there is extensive destruction caused to natural resources and fossil fuels [1]. Therefore, energy security, availability of food and water, and a clean environment have become the real concerns of the current century for the fulfillment of the life of world communities. Furthermore, for energy security and a clean environment, there arises a need to tap ‘sustainable energy sources’ on a large scale [2]. The fundamental concept of sustainable energy sources has now become a critical concept for the sustainable development of world communities, following a long and pressing necessity. At first, the Brundtland Commission of the United Nations (UN) explains the concept of sustainable development in its 1987 report, "Our Common Future," which recognizes energy as a fundamental component [3]. Furthermore, both the UN Conference on Environment and Development's endorsement of ‘Agenda 21' in 1992 and the ‘Kyoto Protocol' in 1997 emphasized the necessity of achieving sustainable development while reducing greenhouse gas emissions [4–6]. Finally, in 1997, the UN General Assembly acknowledged for the first time the importance of sustainable energy for global community development [7].

Furthermore, the UN Millennium Development Goals (MDGs) were introduced in the year 2000 without any discussion or consideration of the energy goals and challenges [8]. On the other hand, energy-related issues are still gaining traction at international venues such as the 2001 ‘Energy for Sustainable Development’ summit and the 2002 ‘World Summit on Sustainable Development' [9,10]. Finally, in 2011, Ban Ki-moon, the former UN secretary-general, expanded on the theme of sustainable energy by launching the Agenda Sustainable Energy for All (SE4ALL), with the vision statement "Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive. Development is not possible without energy, and sustainable development is not possible without sustainable energy" [11] The concept of sustainable energy development has traditionally been centered on emissions and energy security only [12].

To increase electrification in rural and slum regions, to provide a safe and economical cooking system, to mitigate the climate catastrophe, and to regulate greenhouse gas emissions, there is a need to focus on sustainable energy generation. Therefore, at the United Nations (UN) General Assembly meeting in 2016, the UN superseded the MDGs with the Sustainable Development Goals (SDGs), with the goal of "achieving a better and more sustainable future for all by 2030" [13,14]. Among the 17 SDGs, the 7th SDG, "Ensure access to affordable, reliable, sustainable and modern energy for all" was derived from the goals of SE4ALL [13]. At last, with the establishment of SDG 7, sustainable energy was viewed as a vital principle for achieving long-term sustainable development.

1.2 OVERVIEW OF THE ENERGY SECTOR

The world is continuously making progress towards the adoption of SDGs. Among all the goals, the adoption of goal 7 (Affordable and clean energy) is considerably and encouragingly increasing due to fulfilling the aim "to provide widely and sustainably power to all." The UN quoted "to generate clean and sustainable energy will be the major challenge in the coming decade as well as sustainable energy generation will be an opportunity that will transforms lives, economics, and the planet." UN elaborated the SDG 7 into 5 targets and 6 indicators [2, 3]. In addition, improving sustainable energy access (SDG 7) allows progress on other objectives such as SDG 1 (bring people out of poverty), SDG 2 (reduce hunger), SDG 3 (promote good health and well-being), SDG 6 (providing clean water and sanitation), and SDG 13 (climate actions), among others [15,16]. The progress toward SDG 7 is measured in three interconnected sub-areas: SDG 7.1: Access to electricity and clean cooking, SDG 7.2: Renewable energy share, and SDG 7.3: Energy efficiency and international financial support to developing countries in support of clean energy.

On a global scale, 23398 TWh of electricity were consumed in 2018. Coal energy generates 35.1% of total energy, followed by gas power (23.4%), hydro energy (16%), nuclear (10.1%), and oil (2.8%). Whereas, wind energy as renewable energy has the largest share in overall electricity generation at 5.9%, followed by solar (3.2%), geothermal, biomass, and other renewables (2.6%). Whereas, in terms of countries, China is the leading country, accounting for approximately 32% (7500 TWh) of global energy generation, followed by the United States (17%). In addition, India is the world's third-largest producer and generator of energy. India contributes around 6.7% (1547 TWh) of the world's total energy generation, followed by Russia (4.12%), Japan (3.8%), Brazil (2.5%), Canada (2.3%), South Korea (2.25%), Germany (2.23%), and France (1.92%) [17].

Further, the Indian energy sector is the most diversified and expanding energy sector in the world. Energy demand in the country is continuously rising with the growth of the Indian economy and it is expected to have a further increase in the future due to government policies such as “24 x 7 Power for All,” “The Saubhagya Scheme,” and “Pradhan Mantri Sahaj Bijli Har Ghar Yojana” [18]. The installed capacity of India is increased by two hundred times from 1713 MW in 1950 to 349 GW in 2019. It represents an overall compound annual growth rate of 9% over a span of seventy years [19]. Similar trends of growth were witnessed in demand where per capita electricity consumption rises from 18 kWh in the year 1950 to 1181 kWh in the year 2019. Energy sector planning, development, execution, and monitoring were carried out in the five-year plans made by the planning commission or NITI aayog of India. The Indian energy sector was grown into twelve different five-year plans and six annual plans [20]. The brief details about India's energy plans, including highlights, solutions, and accomplishments are included in Appendix – I.

The growth rate of the installed capacity of energy resources reflects the trend of the growth of the Indian economy. Fig. 1.1 shows the year-wise growth in installed capacity of energy resources in India. As of September 2021, the total installed capacity of India has been reached 387953 MW, consisting of 234023 MW (60%) for thermal energy, 46512 MW (12%) for hydro energy, 6780 MW (2%) for nuclear energy, and 100637 MW (26%) for renewable energy resources [19].

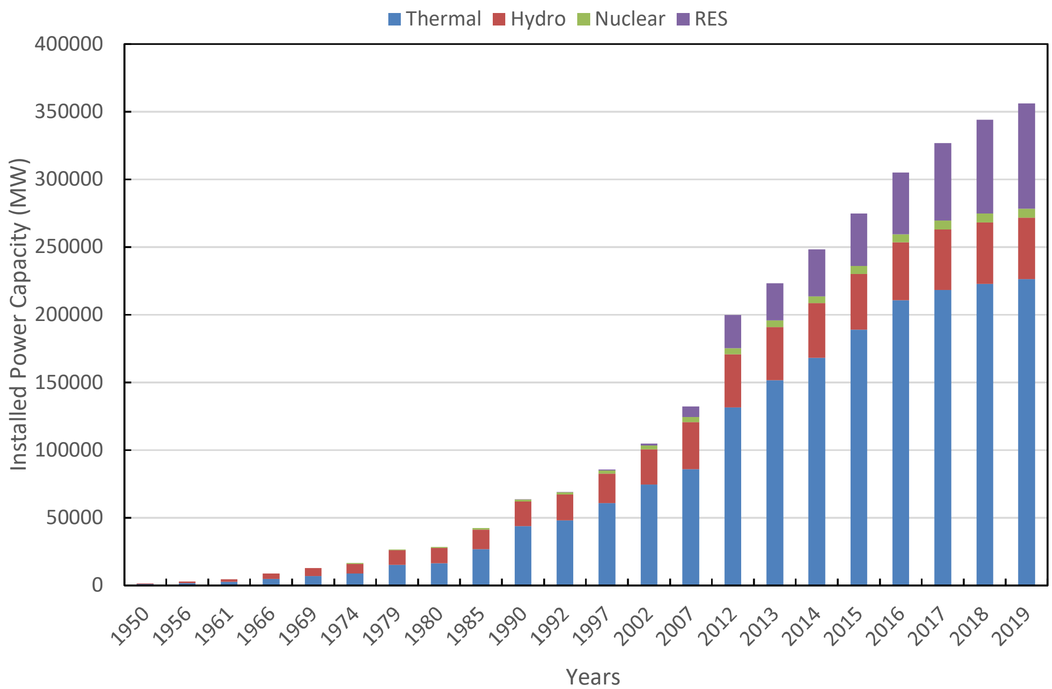


Fig. 1.1: Growth of installed power capacity in India [19]

The Government of India is also fully committed to attaining these SDGs through increasing electrification, investing in clean energy sources, increasing energy efficiency, and reducing transmission and distribution losses, energy deficits, and greenhouse gas emissions. The Indian energy sector is currently the most developed and diversified, but it is nevertheless plagued by serious issues, such as the fact that 5.5 million people are still without electricity. Furthermore, 656 million people still do not have access to clean cooking. In terms of SDG 13, India is liable for 2.3 Gt CO_2 emissions in the year 2019, accounting for 7% of total global CO_2 emissions. According to SDG 3, 1.2 million people will die prematurely as a result of energy-related ambient and household air pollution [21].

The government of India (GOI) is trying to attain the SDGs through the establishment of NITI aayog. Whereas, to achieve the SDGs, GOI launched the supportive schemes i.e., Deen Dayal Upadhyaya Gram Jyoti Yojana, Saubhagya Scheme, National Clean Energy and Environmental Fund (NCEEF), Unnat Jyoti by Affordable LEDs for All (UJALA), Indian Cooling Action Plan (ICAP), Pradhan Mantri Ujjwala Yojana (PMUY), Nation Clean Air Programme (NCAP), and National Solar Mission. The following schemes were implemented through the Ministry of Power (MoP), Ministry of New and Renewable Energy (MNRE), and Ministry of Petroleum and Natural Gas [4].

Although, prior to assessing the sustainable energy sources, it is essential to select the appropriate sustainability indicators, as it provides a clear and deeper understanding of the concepts [7]. To begin, the requirement for indicators to evaluate progress toward sustainable development was outlined in ‘Agenda 21' [4]. As a result, in 1996, the United Nations Department of Economic and Social Affairs (UNDESA) published a set of 134 indicators for sustainable development, which were then refined and updated into a final set of 96 indicators over the next decade [22]. Further, in 2005, a group of international organizations and agencies collaborated to produce a report titled "Energy Indicators for Sustainable Development: Guidelines and Methodologies," which includes 30 energy indicators divided into three categories: economic, environmental, and social, for the long-term development of nations and societies [23].

As a consequence of SDGs, the assessment of sustainable energy sources, in addition to economic, social, and environmental concerns, will have to include some additional future factors such as climate change, safety, and human health, water availability, financial strain, land requirement, and so on [24]. This will enhance the understanding of the serious challenges of the future and facilitate the assessment and adoption of sustainable energy sources. In addition, a better knowledge of these critical aspects will benefit governments, policymakers, shareholders, and researchers in their perceptions of the adoption and development of sustainable energy sources. A number of researchers also have offered their perspectives on how the concept of sustainability may be applied to energy for example Paz et al. [25], Kaygusuz et al. [26], Waisman et al. [27]. Despite the fact that no single interpretation has yet gained widespread acceptance.

1.3 RESEARCH MOTIVATION

The global population surpassed 7 billion in 2018 and is anticipated to reach 9.7 billion by 2050, with an annual growth rate of 0.8%. Similarly, the global gross domestic product (GDP) is expected to rise from US$ 86.139 trillion in 2018 to US$ 252 trillion in 2050, with promises for increased productivity and wealth in communities around the world [28]. Energy access is intimately linked to economic success and prosperity. So, according to the business-as-usual scenario, global electricity consumption was 26700 TWh in 2018, and it will be 41235 TWh in 2050. In overall global scenarios, India is the leading contributor, with the world's second-largest population (1.38

billion), third-largest energy consumer (1383 TWh), and sixth-largest economy ($ 3.050 trillion) [17].

As a country, India is the world's second most populated country, and it is on track to overtake China as the most populous country by the mid of the current decade, based on its average yearly population growth rate. In the next two decades, India's urban population is predicted to surpass 270 million people. In addition, in terms of nominal GDP, India has been one of the world's fastest-expanding economies in recent years, ranking sixth after the United States, China, Japan, Germany, and the United Kingdom. Industry, service, and agriculture sectors account for 30 percent, 54 percent, and 16 percent of India's GDP, respectively [29]. India has also achieved some positive growth standards as a result of these developments, including (i) quadrupling of per capita yearly income since 1991 to $8100 (Purchasing Power Parity) in 2019, (ii) a reduction in poverty headcount ratio from 48% in 1993 to 13% in 2015, and (iii) an increase in India's human development index value from 0.43 in 1990 to 0.65 in 2018. All of these variables represent increases in life expectancy, educational access, and income. In addition to all of this, India's 900 million residents have access to electricity in 2019 [21].

On the other hand, according to the Vision Case of India, India's power demand has surged over the last two decades, from 369 TWh in 2000 to 1383 TWh in 2020, and is anticipated to be 3433 TWh in 2040 [17]. To meet the ever-increasing power demand, India relies heavily on fossil fuels. Among all of these fossil fuels, coal continues to be a major source of energy. Therefore, India is the world's second-largest coal importer, while having the world's fifth-largest proven coal reserves. As a result, India spent $21 billion on coal imports in 2019, a 21-fold increase since 2000 [21]. This will impose a significant financial burden on the country. Apart from that, coal is also responsible for 70% of India's energy sector CO_2 emissions while meeting 45% of the country's primary energy needs. In addition, by 2020, the Indian power sector will have used more than 20 billion cubic meters (bcm) of water for cooling and washing of coal power plants. India, on the other hand, is the world's most water-scarce country, with only 4% of the world's resources for an 18% population [21]. Furthermore, the Indian energy sector is also responsible for the three major air pollution emissions which are Sulphur dioxide emission (SO_2), nitrogen oxides (NOx), and particulate matter emission (PM2.5). India, like coal, is the world's largest importer of oil and natural gas as well. In order to lessen the economic burden, the administration has also announced a reduction in fossil fuel imports. Renewable energy capacity has developed at a remarkable rate over the last five years, particularly solar energy capacity, which has increased by 60% on average, and wind capacity, which has increased by 10%. Simultaneously, renewable energy sources also have some obstacles and limits, such as population displacement and resettlement related to the development of hydroelectric plants. Whereas, in the case of solar and wind power project installations, however, investors must contend with a number of problems, including the weak financial status of many states' distribution companies, difficulties in acquiring land, difficulties in securing financing, grid congestion, and concerns over grid infrastructure development. Apart from that, India has a slew of other issues, including a lack of land utilization due to its dense population, and a society that cannot afford high energy prices [21]. Finally, India's ultimate goal is to provide a secure and sustainable energy future for its citizens by formulating and implementing a variety of policies and measures.

During the last two decades, researchers are focusing on several levels of sustainability assessment such as the evaluation of sustainability indicators [1,30–34], evaluation of renewable or conventional energy sources with single or multiple factors [35–40], the estimation of the potential of a particular renewable or conventional power sources [41–46], and calculation of theoretical or any other particular power potentials [47–51], etc. have been the subject of independent research. Whereas, hardly any studies are found which have done sustainability assessment of the energy sector sequentially with numerous influencing factors.

To bridge the research gap, there is a need to develop an integrated evaluation model that includes sustainability criteria, sustainable energy sources, feasible sites, and achievable power potential from the Indian context. The sustainability assessment takes into account a variety of elements and restrictions throughout, to draw more robust and accurate conclusions.

1.4 OBJECTIVES OF THE STUDY

The objectives of the study are:

- Identification of crucial and important sustainability indicators from the Indian economic and geographical context for the assessment of sustainable energy sources.
- Evaluation of sustainable energy sources in India using theoretically and empirically validated criteria.
- Assessment of optimal energy mix scenario in India for the time frame of the year 2030, considering only India's most sustainable energy sources.
- Assessment of potential sites for the installation of sustainable energy sources based on certain aspects.
- Estimation of feasible or exploitable sustainable power potential, taking into account multiple constraints.
- Prioritization of sustainable site alternatives and validation of their techno-economic feasibility.

1.5 METHODOLOGY

The following methodology has been adopted to achieve the objectives of the study:

- A thorough assessment of the literature on sustainable energy sources is conducted in order to identify the most critical and important sustainability indicators, as well as to track the progress in the evaluation of sustainable energy sources, potential sites, and exploitable power potential.
- A survey is constructed using 93 indicators corresponding to 15 categories and is pre-tested and validated by a panel of academicians before being distributed. Finally, a survey is conducted in both the online and offline mode and responses are collected.
- A total of 442 responses are collected and analyzed to determine their sustainability importance index (SII), and finally, 26 indicators relating to 6 categories of economic, technical, social, environmental, political, and flexible are selected. Furthermore, the survey results are statistically validated using the IBM-developed SPSS software.

- Thoroughly assessed the Indian energy sector to derive the alternatives and criteria for the assessment of sustainable energy sources. Further, using these suitable criteria, appropriate alternatives, and robust multi-criteria decision making (MCDM) approaches, finally, assessed the sustainable energy sources in India.
- Determined the optimal sustainable power mix scenario for the time frame of the year 2030 by using the five most sustainable energy sources and 14 distinct scenarios.
- Further, using a geographical information system (GIS) and MCDM techniques, create a site suitability map for the installation of sustainable energy sources (solar and wind energy). The site's suitability map carries five classes, namely highly suitable, suitable, moderately suitable, less suitable, and not suitable.
- The site suitability map is also examined to determine the highly suitable land area for India's various states and union territories. In addition, to determine the results' robustness, a sensitivity analysis is performed.
- Furthermore, the geographical, theoretical, technological, economic, and environmental potential for solar and wind power technologies are evaluated at these highly suitable sites, taking into account multiple constraints. In addition, the demand-potential scenario for different states, union territories, and the country is assessed.
- To obtain conspicuous sites, these highly suitable sites are regarded as alternatives and prioritized in a sequential order using the MCDM techniques. Finally, a case study is performed at the conspicuous site using the RETScreen software to techno-economically validate the results.

The above methodology is extensively discussed in the subsequence chapters of the thesis which is shown in Fig. 1.2 graphically.

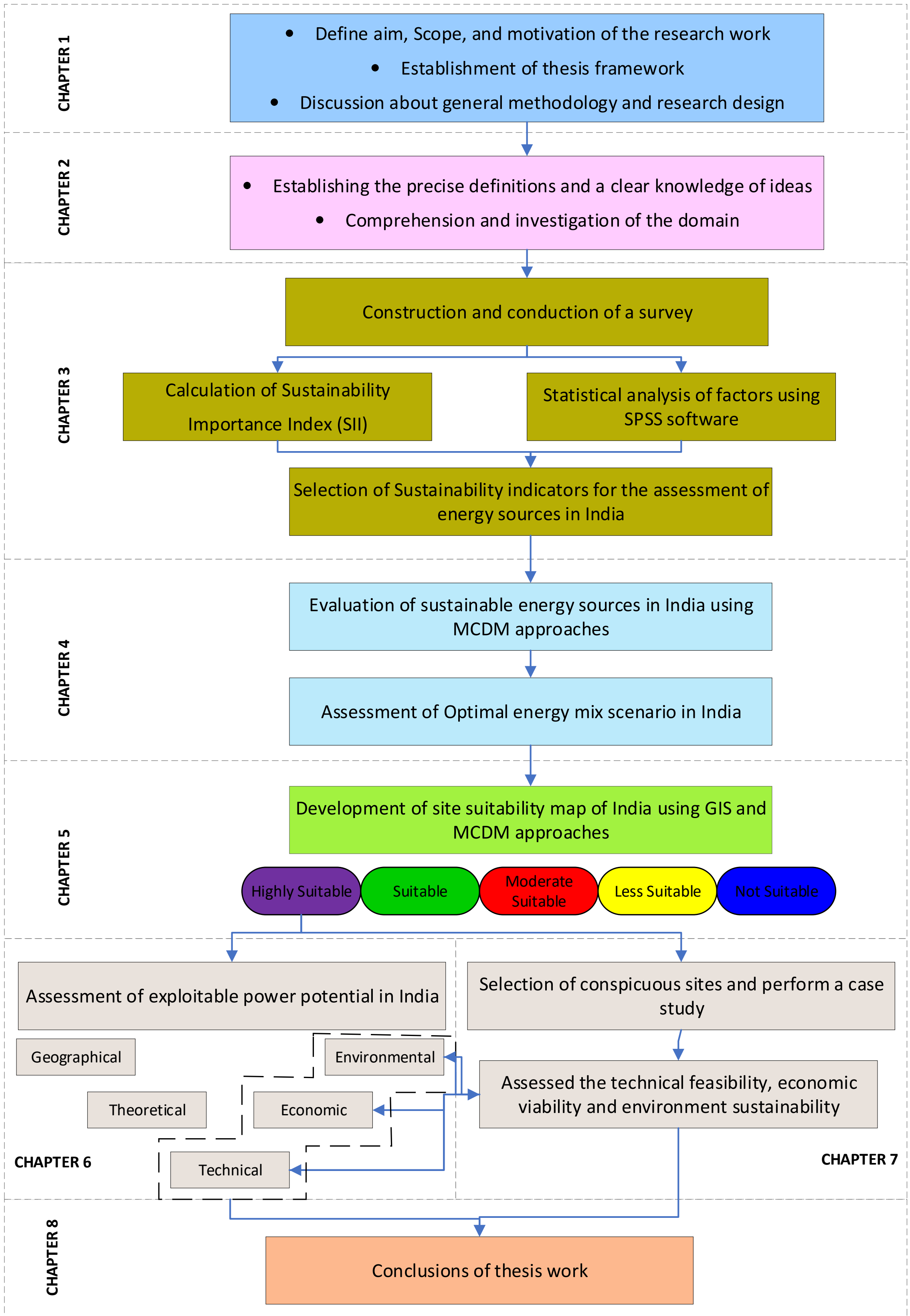


Fig. 1.2: Flow chart of the structure of the thesis

1.6 SIGNIFICANCE OF THE STUDY

The evaluation and utilization of sustainable energy sources have piqued the interest of researchers, policymakers, governments, and stakeholders all around the world. The Earth Summit (1992), Kyoto Protocol (1997), Doha Talks (2001), Copenhagen Deceleration (2009), and recent Paris Climate Change, as well as the UN's 17 SDGs, are just a few notable agreements or agendas that demonstrate the urgency and importance of adopting and achieving sustainable energy sources. While over there, rising economic burdens, water scarcity, land use constraints, GHG emissions, energy-generating reliability, and affordability all contributes to unsustainable development. Any recommendation or improvement in the adoption or exploitation of sustainable energy resources will make a substantial contribution to the nation's or world's long-term sustainability.

The systematic literature review can be utilized by researchers as a foundation for developing new research directions. The systematic literature review, as well as all other models produced in the thesis, will add to the existing body of knowledge, which is still in its infancy stage in terms of research, practice, and teaching. To begin, the survey results in the form of sustainability indicators will assist researchers and policymakers in assessing sustainable energy sources, which will be a driving factor in attaining sustainable development. In addition, it will serve as a beacon for international organizations and governments in the development of a set of universally acknowledged indicators for evaluating sustainable energy sources. In addition, evaluation of sustainable energy sources will also assist governments, researchers, policymakers, and decision-makers in achieving their aim of sustainable development as well as meeting their international commitments. Furthermore, evaluation of optimum energy mix scenarios will encourage and enlighten policymakers and the government to work tirelessly to attain these scenarios. Furthermore, in order to assist policymakers, private shareholders, and the government in meeting these objectives, the study will identify potential sites that are feasible in terms of economic, technological, environmental, and social factors. As a result, all the government has to do now is re-validate the results and buy the land for private players, the government, and private enterprises. In order to maximize their benefits, the study also estimated the theoretical and technical power potential available at these highly suitable sites, as well as validated their economic viability, technical feasibility, and environmental sustainability.

The findings of the thesis' analysis, empirical research, and case studies can be used to raise awareness of sustainability indicators, sustainable energy sources, and sustainable development among researchers, governments, the general public, private firms, policymakers, and decision-makers, as well as to persuade them to follow a sustainable path.

1.7 ORGANIZATION OF THE THESIS

Chapter 1 presents the outline of the thesis. Chapter 2 provides a rigorous literature review of sustainable energy sources. In Chapter 3, a survey is developed and carried out in different geographical areas across India, with a significant number of responses received. As a result, the SII for these survey replies is also calculated. Chapter 4 incorporated appropriate criteria, and energy alternatives, to assess the sustainable energy sources in India using the MCDM techniques. These sustainable energy sources are further used to assess the optimal energy mix scenario in India for the time frame of the year 2030. In Chapter 5, a site suitability map is created for these sustainable energy sources, with the five categories of highly suitable, suitable, somewhat acceptable, and less suitable. Whereas, chapter 6, assessed the geographical, theoretical, technical, economic, and environmental potentials incorporating the multiple constraints. In addition, a case study is conducted in chapter 7, to validate the obtained results techno-economically. Finally, chapter 8 provides the conclusions of the current research work with future direction and limitations of the study.

CHAPTER – 2

EVALUATION AND EXPLOITATION OF SUSTAINABLE ENERGY SOURCES: A SYSTEMATIC LITERATURE REVIEW

This chapter presents a comprehensive assessment of the literature on the identification, evaluation, and exploitation of sustainable energy sources. The objectives of the chapter are (i) to assess the sustainability indicators for the evaluation of sustainable energy sources in India, (ii) to assess the highly suitable sites for the installation of sustainable energy projects, and (iii) to calculate the exploitable power potential of sustainable energy sources.

2.1 RESEARCH METHODOLOGY

A literature search was carried out using online databases as access to the internet and online databases are a cost-effective and efficient method for conducting a literature search. Therefore, the study employed online literature search using Scopus, Web of Science, and Google Scholar because they all are capable of providing high-quality search results in the desired language. To discover relevant publications in the current study, the following keywords were used: "sustainable energy," "sustainable development," "decision making," and "India." Furthermore, from a glance at the articles, it was realized that there is a need to review in several stages to ascertain the sustainability or sustainable development of the energy sector. Finally, considering the aims and reviewing the papers led to the decision to undertake a two-fold literature review. The adopted two-fold research methodology for the comprehensive literature review is depicted in Fig. 2.1.

The first phase of the literature review focused primarily on the keywords "sustainable energy," "decision making," and "India." Furthermore, a review of the literature reveals that the research community has used the terms multi-criteria decision making, sustainability, sustainable development, alternative energy, and so on interchangeably. As a result, the search criteria are expanded to include "multi-criteria decision making," "sustainability," "sustainable development," "alternative energy," and "energy planning." Similarly, in Phase-II, the final keywords are "decision making," "geographical information system," "renewable energy," "analytical hierarchy process," "solar energy," and "wind energy," using actual or interchangeable phrases.

Further, incorporating all these important keywords with “AND” and “OR” operators in the article title, keywords, or abstract, a total of 3728 and 2479 articles were identified. Since this resulted in a large number of articles, and therefore exclusion criteria based on a timeline, subject area, document type, keywords, source type, language, etc. were used to narrow down the articles as shown in Fig. 2.1. Finally, the peer-reviewed articles published and available online in the Elsevier, Springer, Emerald, Taylor & Francis, and Inderscience databases from the last two decades were collected. In Phases, I and II, a total of 126 and 154 papers were selected from these peer-reviewed journals, respectively. In addition, a snowball (forward and backward) technique was used to incorporate articles that were missed in the previous search but were discovered to be appropriate for the study.

According to the snowball method, 21 (8 in phase I and 13 in phase II) research articles or reports were found to be appropriate and were thus included in the review. The 21 articles featured in this collection have a high number of citations in the field of sustainable energy and come from a variety of organizations, conferences, and journals of international repute. This resulted in a list of articles to be reviewed and critiqued.

These 301 articles were evaluated to explain the study's goal, research gap, study limitations, research methodology, data collection method, resources employed in the study, results acquired, validation of findings, and conclusions reached; all of this will be discussed briefly in Section 2.2 and 2.3.

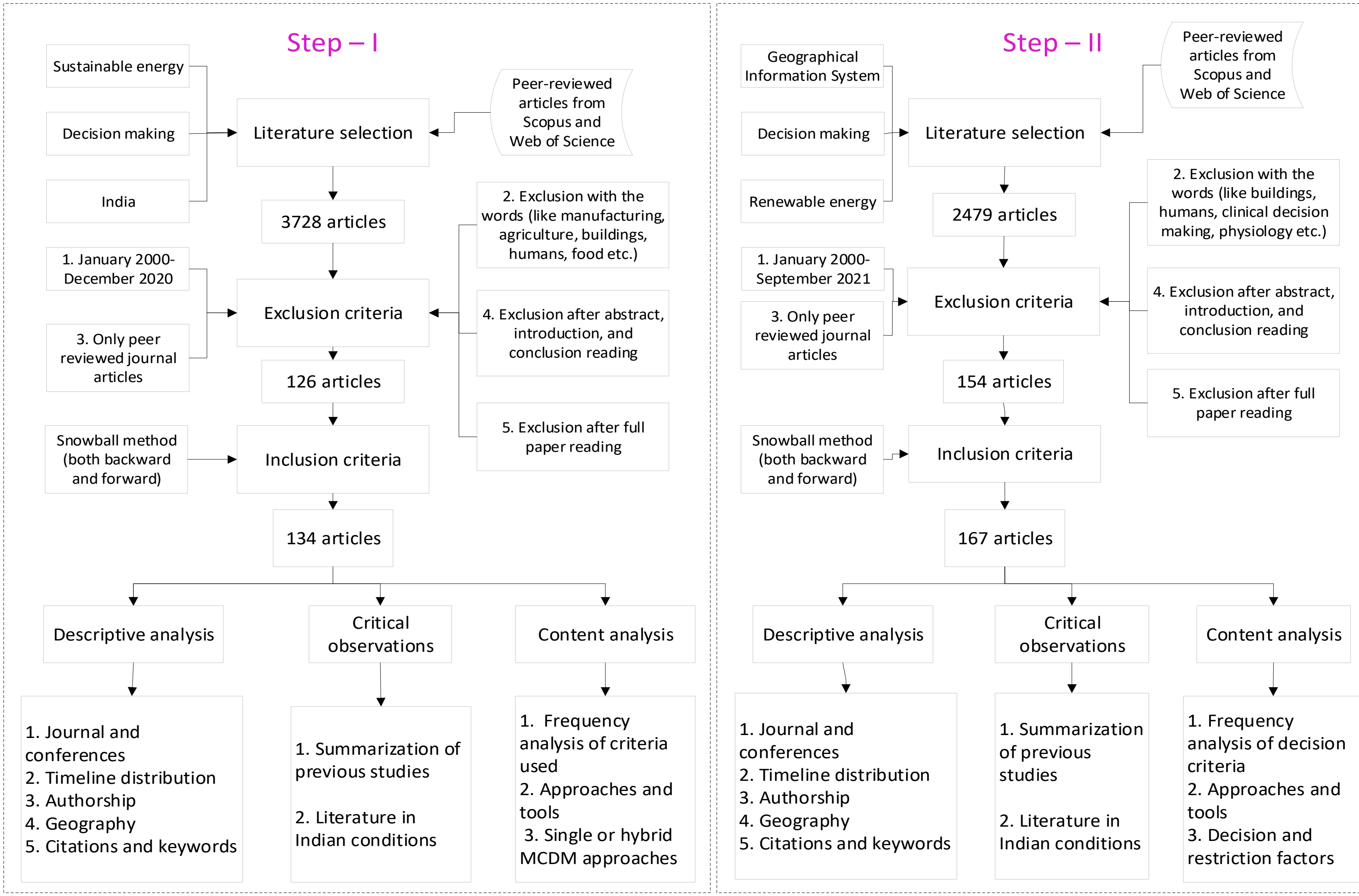


Fig. 2.1: Research methodology for systematic literature review

2.2 SYSTEMATIC LITERATURE REVIEW: PHASE-I

A systematic literature review typically consists of five consecutive steps: (i) defining the purpose of the research study, (ii) identifying relevant work, (iii) assessing the quality of work, (iv) summarising the evidence, and (v) interpreting the findings. The current study has already specified the purpose of the study and gathered relevant material; so, the current parts focus on the descriptive analysis, comprehensive analysis, and content analysis. The brief details are given in the following sections.

2.2.1 Descriptive Analysis

The descriptive analysis identifies the key characteristics of the collected articles. The descriptive analysis is primarily used to summarize the articles in terms of the journals and conferences that contributed to the gathered literature, as well as the temporal distribution, authorship, geography, keywords, and citations. This will encourage future scholars or researchers in the field to seek literature and publications from the current work. Articles publication timeline analysis is supposed to provide the chronological trend of the research's development to date. Whereas, authorship data reveals if this field's study is carried out by individuals or in collaboration with others. In addition, the geographical analysis will provide data for regions that have contributed to selected literature as well as the nations that have performed the empirical investigations.

2.2.1.1 Journals and conferences

The study analyzed a total of 135 items, with 131 being research articles and four being conference papers. These 131 articles were selected from 35 reputed journals, with the publication 'Renewable and Sustainable Energy Reviews (RSER)' carrying the most, followed by 'Energy (EN),' and 'Renewable Energy (RE)'. The remaining details about the number of articles published in the journals are visually depicted in Fig. 2.2. Furthermore, reputable publishers such as Elsevier, Springer, Emerald, and Taylor & Francis publish these publications. Furthermore, the papers are collected from significant journals with brief abbreviations, such as Energy Policy (EP), Journal of Cleaner Production (JCP), Energy Sources Part B: Economics, Planning and Policy (ESP), Energy Conversion and Management (ECM), Energy Procedia (Eproc), Applied Energy (AE), Sustainable Energy Technologies and Assessment (SETA), and Expert Systems with Applications (ESA).

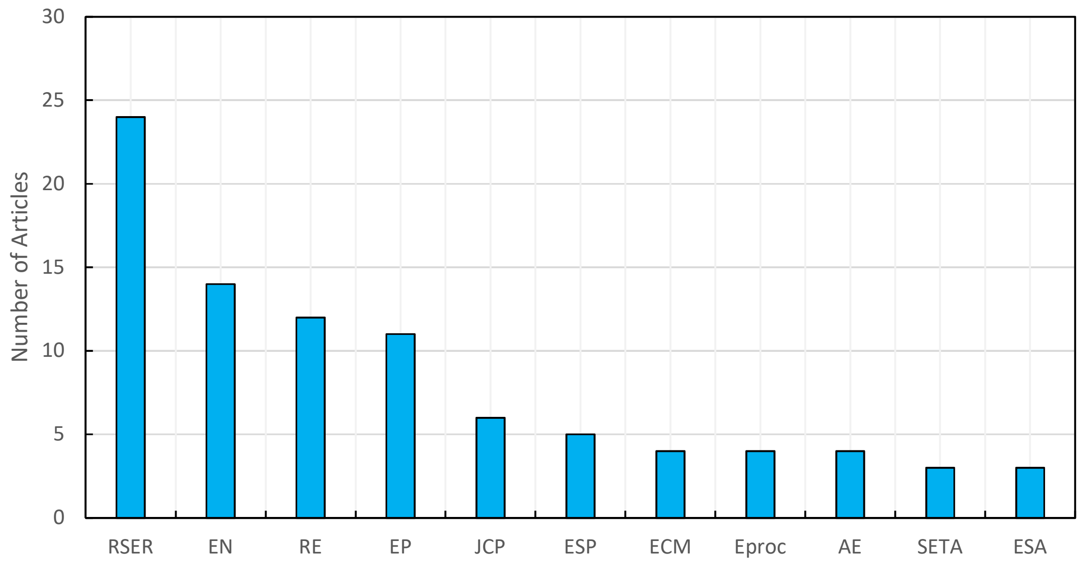


Fig. 2.2. List of journals with the number of published articles among the collected phase-I literature

2.2.1.2 Timeline distribution

The timeline distribution of Phase-I articles is depicted in Fig. 2.3. After 2011, the number of articles appears to be increasing in the graph below. With a large number of articles published recently, the study field is currently garnering attention. In this case, most articles are collected in the year 2019, and the literature survey is conducted until December 2020. The article's rising tendencies indicate that the current issue is gaining traction and will be a promising research topic in the future.

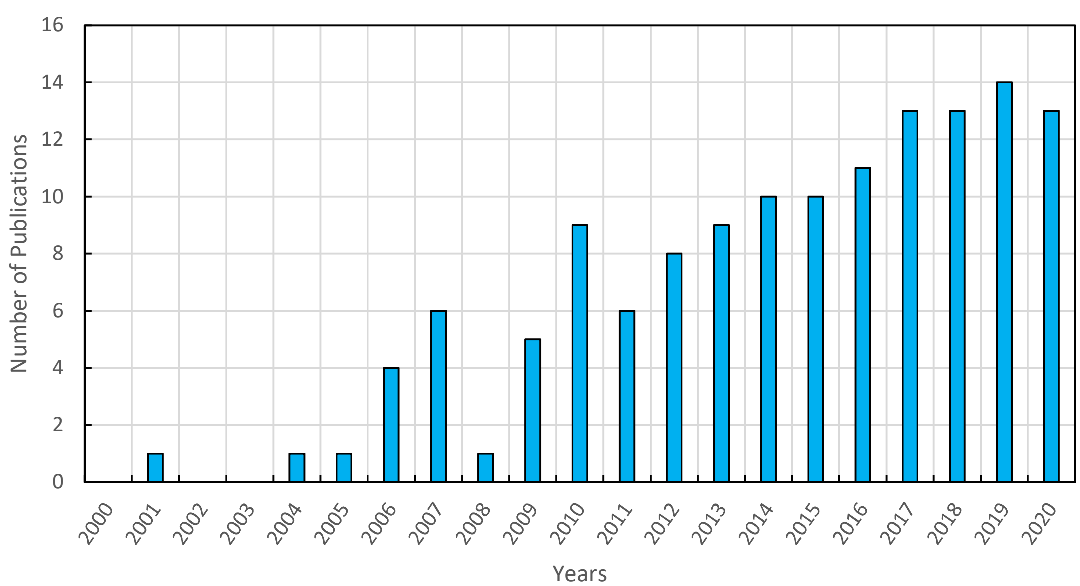


Fig. 2.3: Timeline distribution of selected articles

2.2.1.3 Authorship

The authorship analysis reveals whether the research was carried out independently or in collaboration with others. When it comes to authorship, the maximum number of publications with two writers is 41. Three authors wrote the second-highest 37 articles, while four authors together wrote the second-highest 28 articles. The 11 and 13 articles, on the other hand, claimed one or five authors, respectively. The three and two articles with the most authors each have six and seven authors. In addition, more than 91% of the works have multiple authors, and the collaboration is not just between academicians from the same institute/university, but also between academicians from other institutes/universities and countries. Further, International collaborations are also seen in about 30% of the papers. The findings show that academics and practitioners, both in India and overseas, are interested in the topic of sustainable energy.

2.2.1.4 Geography

The geographical analysis is carried out based on the case organization's geographical location or the primary author's country. This review includes publications from 26 different countries, with Turkey having the most articles (27), followed by China (13), and Iran (11). The number of publications published in each country is depicted on the world map (Fig. 2.4). After reviewing the overall scenario, it is clear that the current topic is gaining traction around the world, and the entire global community is working to ensure the sustainable development of humanity.

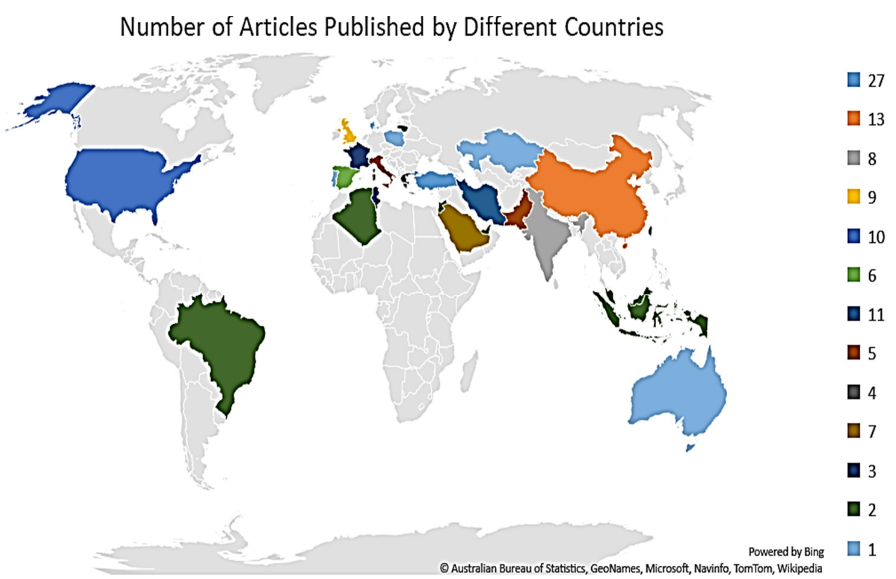


Fig. 2.4: Number of articles published by different countries

2.2.1.5 Citations and keywords

Finally, citations and keywords are examined using the VosViewer software, which determines the number of citations received by an article or the frequency with which a keyword appears in published articles. Prof. T. Satty has the highest number of citations in the gathered literature, followed by Prof. Zavadskas and Prof. Kahraman. The details of the citations can be found in Fig. 2.5. Whereas in terms of keywords, decision-making is the most frequently used criterion (76 times), followed by energy policy (53), and renewable energy sources (46). The frequency of employing the keywords is depicted in Fig. 2.6, along with the size of the keywords based on their use. This would assist researchers in determining the precise required material based on the author's details or keywords.

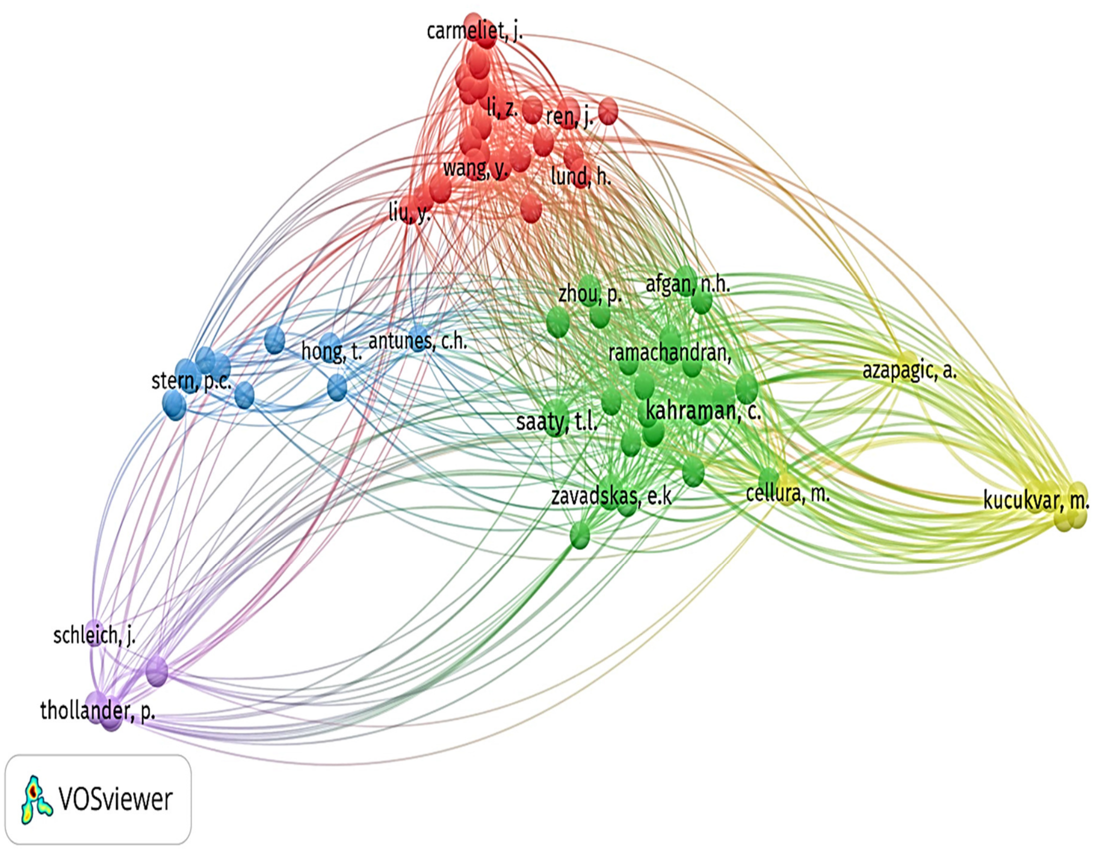


Fig. 2.5: Citation analysis of Phase – I collected literature

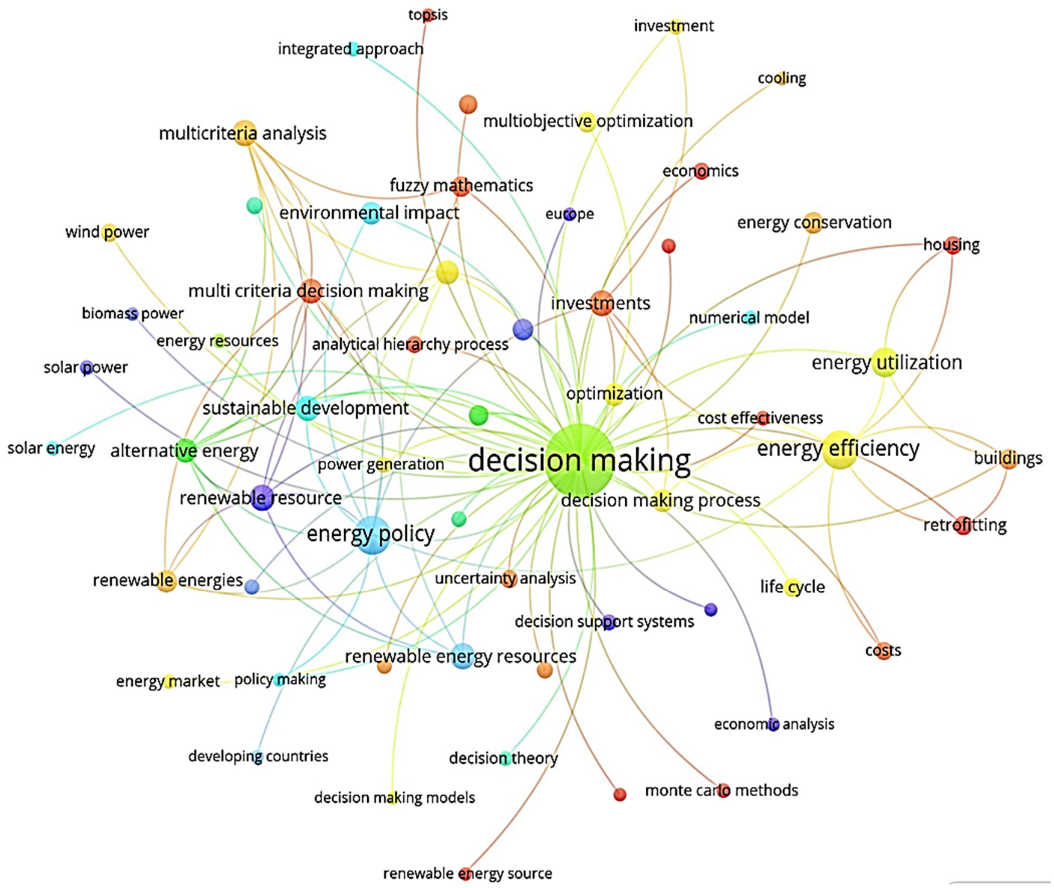


Fig. 2.6: Frequency of keywords in the collected literature

2.2.2 Comprehensive Analysis

This section discussed the collected literature in-depth and comprehensively, encompassing the study fields, used methodology, employed research approach, expected objectives, and so on. The accessible literature is as follows.

Kaya and Kahraman [35] used an integrated fuzzy AHP-fuzzy TOPSIS technique to establish a system for selecting a suitable energy source in Turkey. They used the four criteria and nine sub-criteria to evaluate seven energy alternatives: conventional, nuclear, solar, wind, biomass, CHP, and hydraulic energy sources. Wind energy was ranked as the most appropriate energy technology, followed by biomass, solar, CHP, hydraulic, nuclear, and conventional energy sources. They also ran a sensitivity analysis with differently weighted criteria. The limitation of the study is the consideration of limiting factors due to which the weights of the factors cannot be properly allocated.

To rank the renewable energy sources in Turkey, Colak and Kaya [52] employed a fuzzy sets-based MCDM technique. They used six criteria and their corresponding twenty-nine sub-criteria to evaluate the seven energy alternatives: solar energy, wind energy, hydraulic energy, geothermal energy, biomass energy, hydrogen, and wave energy. The authors also employed interval type-2 fuzzy AHP and hesitant fuzzy TOPSIS techniques for a pairwise evaluation of the criteria and ranking of the options. In their study, wind energy came out on top, followed by solar, hydraulic, biomass, geothermal, wave, and hydrogen energy. Finally, it is concluded that a major limitation is to consider only renewable energy sources, some of which are not yet maturely available in the market.

Haddad et al. [37] ranked renewable energy alternatives for the Algerian electrical system using a multi-criteria methodology. For the evaluation of five alternatives: solar, wind, biomass, geothermal, and hydro power, they used four criteria: technical, economic, environmental, and sociopolitical, as well as their 13 sub-criteria. They also recruited eleven experts from the energy policy, industrial, and academic sectors to apply weighting to the criteria and alternatives. They emphasized solar and wind energy as highly sustainable energy sources for the Algerian electricity sector's development. Their main conclusions are that solar and wind energy are the most potential options for long-term energy development and that social and environmental factors are crucial for the establishment of renewable energy sources in the country. Finally, In terms of limitations, the study is the only application of a single AHP approach.

Sengul et al. [53] developed a multi-criteria decision support framework for ranking renewable energy supply systems in Turkey. They looked at four major criteria: technical, economic, social, and environmental, as well as the nine sub-criteria that go with them, to rank four alternatives: regulator, geothermal, hydro, and wind power stations. To assign weights to the criterion, they used interval Shannon's Entropy approach, and fuzzy TOPSIS was used to rank the possibilities. They discovered that hydropower is the best renewable energy source for Turkey, followed by geothermal, regulator, and wind power. They also ran sensitivity analyses for the Alpha cutting values of 0.1, 0.5, and 0.9, and found the same pattern of ranking renewable energy sources in all three scenarios. The study has a limitation of evaluation of only four possibilities of regulator, hydro power, wind power, and geothermal power.

Lee and Chang [36] used four distinct MCDM approaches (WSM, VIKOR, ELECTRE, and TOPSIS) to compare the ranking of renewable energy sources for power generation in Taiwan. They evaluated five different energy alternatives using four criteria (economic, technological, environmental, and social) and their ten sub-criteria: solar PV, wind, hydro, biomass, and geothermal. Further, to determine the weights of the criterion, they used Shannon's entropy methodology, and to rank the energy alternatives, they used four different MCDM approaches (WSM, TOPSIS, VIKOR, and ELECTRE). Finally, they discovered that all the four methods produce similar results, with hydro at the top and biomass and geothermal at the bottom. The only limitation of the study is to consideration of renewable energy sources rather than conventional and renewable both.

In order to find the optimal energy generation source in Lithuania, Streimikiene et al. [54] used a multi-criteria decision-making approach. For the examination of six possibilities, they used five criteria and their twenty sub-criteria: nuclear, gas, biomass, hydro, geothermal, and wind. They calculated the weightage of criteria and the ranking of the options using the AHP and ARAS (additive ratio assessment) MCDM approaches, respectively. Furthermore, twenty-five energy experts agreed that economic criteria were the most important, followed by environmental and technological criteria. As a consequence, they determined that nuclear energy is the best alternative energy source, followed by bio, hydro, gas, wind, and geothermal energy. In addition, they also conducted a sensitivity analysis for five distinct scenarios, concluding that nuclear power is the preferred option in all of the situations evaluated. The results should be validated with other MCDM approaches.

Kabak and Dagdeviren [55] employed a BOCR (Benefits, Opportunities, Costs, and Risks) and ANP (Analytic Network Process) hybrid MCDM technique for the analysis and ranking of renewable energy sources in Turkey. They organized a panel of eight specialists to gather opinions; these opinions were then processed in "Super Decision" software, and the following priority order was obtained: hydro, geothermal, solar, wind, and biomass. The study has the limitation of sensitivity analysis.

Further, using the TOPSIS MCDM technique, Brand and Missaoui [56] looked for an appropriate mix of five distinct energy sources to meet Tunisia's projected energy needs. They created five different energy source combinations: Business as usual (95% gas, 5% wind), DivCoal (60% coal, 35% gas, and 5% wind), DivNuc (75% gas, nuclear 25%, and wind 5%), DivCoalRes (50% coal, 10% wind, 5% solar, gas 35%), and DivRes (70% gas, 15% solar, and 15% wind). In addition, a panel of 70 experts was constituted to assess the produced combinations and collect the results. They discovered that diversification of renewable energy (DivRes), followed by BAU and DivCoalRes, is the best combination for future energy supply. The limitation of the study is that the study explored only a limited number of alternatives.

In Lithuania, Streimikiene et al. [39] developed a multi-criteria decision-making approach for selecting the most environmentally friendly energy generation technology. They looked at three distinct economic, environmental, and social parameters, as well as their thirteen-sustainability indicator. They used two MCDM approaches, MULTIMOORA and TOPSIS, to prioritize the thirty-three energy alternatives, which include nuclear power, fossil-fueled power plants, solar PV, solar thermal, wind, hydro power, and certain electricity and heating production techniques. Renewable energy sources (medium and large hydropower, solar thermal) were identified to be the most preferable sources using a comprehensive criterion weightage approach. The selected indicators pertaining to economic, social, and environmental categories while other important categories such as technical, and political are not considered in the analysis. The study should have used the MCDM approach for the allocation of the appropriate weighting of the criteria.

To identify or choose the most appropriate renewable energy source for Turkey, Buyukozkan and Guleryuz [57] developed an integrated DEMATEL-ANP strategy. They looked at solar, wind, biomass, geothermal, and hydraulic energy as well as five technical, economic, social, political, and environmental criteria and their twenty-one sub-criteria. They investigated and discovered that wind energy is the most suitable energy source, followed by solar, biomass, geothermal, and hydraulic energy. The study approach is very limited only to five renewable energy alternatives.

F E Boran [58] proposed a novel method (fuzzy VIKOR) for evaluating the most sustainable renewable energy sources in Turkey, taking into account technical, economic, environmental, and social factors. They looked at solar, wind, biomass, hydro, and geothermal energy as alternatives for renewable energy sources. They ranked wind energy as the most sustainable energy source, followed by hydro, solar, geothermal, and biomass, based on their analysis. They also undertook a sensitivity analysis on twenty-four other situations and found that the sensitivity results were identical to the initial results. The study is the only application of a single MCDM approach.

Wang et al. [59] developed a hierarchical multi-criteria decision model to determine China's preferred energy option. Coal, natural gas, petroleum, nuclear energy, and renewable energy were all explored as energy sources or alternatives. They used availability, affordability, safety, present energy infrastructure, environmental and social implications as criteria, and their related seventeen sub-criteria to perform a pair-wise comparison. They ranked coal as the most preferred energy alternative based on its easy availability, better current energy infrastructure, low price, and better social support, according the analysis. The study evaluates the opinions of experts only from different industries, rather than combining the opinions of academics, researchers, policymakers, and decision-makers.

Abdullah and Najib [60] suggested a new Intuitionistic Fuzzy – AHP (IF-AHP) approach to cope with the challenge of sustainable energy planning. They addressed the challenge of sustainable energy planning by taking into account the technical, economic, environmental, and social criteria, as well as the nine sub-criteria that go with them. For the sustainability analysis, they looked at biomass, CHP, conventional, hydraulic, nuclear, solar, and wind energy sources. Nuclear energy was determined to be the most sustainable energy source, followed by solar, hydraulic, wind, biomass, CHP power, and conventional energy sources, according to experts. The study only analyses qualitative weights, which may reflect expert consensus.

Ahmad and Tahar [61] looked at the potential of renewable energy sources and developed a methodology for prioritizing them. As a source of renewable energy, they regarded solar energy (particularly solar PV), wind, hydro power (small or micro), and biomass (biomass, biogas, and municipal solid waste). They used the AHP approach of the MCDM technique to examine renewable energy alternatives from technical, economic, social, and environmental perspectives. Using a pairwise comparison, they discovered that economic criterion is the most important, followed by technical, environmental, and social factors. As a consequence, they discovered that solar PV is the most viable option, followed by biomass, hydro, and wind energy. The study explored a single MCDM approach (AHP), although the results could be further robust with an integrated or hybrid MCDM approach.

Tasri and Susilawati [38] also used the AHP integrated WSM approach to evaluate the five renewable energy alternatives: solar, wind, biomass, geothermal, and hydro. The study determined that hydro energy is the most appropriate renewable energy source for power generation in Indonesia based on economic, technical, socio-political, energy source quality, and environmental factors. The study takes into account the views of only four experts, which is a very small number for selecting the optimal renewable energy sources.

E. W. Stein [62] created a model allowing decision-makers to use a multi-criteria decision-making technique to rank various renewable and non-renewable electricity-generating technologies. They looked at four long-term criteria: four economic ones, two technical ones, two environmental ones, and three social-economic-political ones. They looked at nine distinct renewables (wind, solar PV, hydro, biomass, and geothermal) and non-renewable (coal, oil, gas, and nuclear) power generation methods. They employed Super Decision software, which is a generalized AHP-based software. As a result, the study selected wind energy as the best suitable power generation technology, followed by solar-PV, while hydro energy, biomass, and coal are the least suitable electricity generation technologies. The results could have been made more robust by employing multiple decision-making techniques.

In Jilin, Yuan et al. [63] created a linguistic hesitant fuzzy set (LHFS) to choose the best renewable energy source. They evaluated four renewable energy sources (solar, wind, biomass, and hydro energy) using four core and ten supplementary criteria. For weightage collecting, they employed an LHFS and a cloud model to convert LHFS to quantitative data. Biomass energy is obtained as the most desired renewable energy source in Jilin, according to the calculations, followed by wind energy, hydro energy, and solar energy. They also did a sensitivity analysis of their findings, which revealed that biomass and wind energy are the most common energy sources in Jilin. Furthermore, the study only includes the views of three experts, and those views have been assessed from a single decision-making approach, which has a significant impact on the veracity of the conclusions.

Sliogeriene et al. [64] investigated numerous energy sources in order to determine the best alternative energy source for Lithuania. They considered economic, technical, environmental, social, and political factors before selecting the best alternative source from biomass, gas CHPP, geothermal, wind, hydro, and nuclear energy. In the weights assigned by the various 30 energy specialists, they used the AHP (Analytic Hierarchy Process) and ARAS (Additive Ratio Assessment) approaches. As a result, they rank nuclear energy as the best alternative energy source, ahead of biomass, hydro, gas CHPP, wind, and geothermal energy. The authors did not conduct a sensitivity analysis or validate their findings.

In the Iranian province of Yazd, Sadeghi et al. [65] suggested a fuzzy MCDM approach to evaluate four renewable energy sources. To identify the best renewable energy source among solar, wind, geothermal, and hydro energy, they used four criteria (technical, economic, environmental, and socio-political) and their corresponding thirteen sub-criteria. In addition, they used a fuzzy AHP approach to assign relative weightage to criteria, as well as a fuzzy TOPSIS approach to rank the energy alternatives. After conducting research, they determined that solar energy is the most appealing energy source, followed by wind, hydro, and geothermal energy. The study is extremely limited in terms of criteria, alternatives, and experts.

Zhang and Tao [66] used AHP and DEA (data envelopment analysis) to create a comprehensive evaluation index for Chinese renewable energy sources that included economic, technical, social, and environmental benefits. They assessed six renewable energy sources: solar PV, wind, biomass, ocean, hydro, and geothermal, using four criteria with their twelve sub-criteria. Wind energy is the best alternative for China, followed by solar PV, biomass, hydro, ocean, and geothermal energy, according to the total research. A condensed article with scant details.

Yazdani-Chamzini et al. [67] employed numerous AHP integrated MCDM approaches such as COPRAS, TOPSIS, SAW, VIKOR, ARAS, and MOORA, to choose the best renewable source among the different 13 renewable energy sources. The results of COPRAS and ARAS approaches are identical, indicating that the ranking order is valid. The case study just prioritized the alternatives rather than discussing the ideal energy mix scenario.

Ishfaq et al. [68] looked for the best renewable energy source for investment in order to meet Pakistan's escalating energy demand. They used three different MCDM methodologies, AHP, TOPSIS, and VIKOR, to examine the four energy sources of solar, wind, biomass, and hydel from the economic, technical, and social perspectives. As a consequence, all three MCDM approaches identified hydel energy as the most appropriate option for investment in Pakistan. The article did not address the potential scenarios and availability of renewable energy resources.

Doukas et al. [69] used a multi-criteria approach to evaluate ten energy alternatives in Greece, including pressurized fluidized bed combustion, pressurized pulverized coal combustion, natural gas combined cycle, molten carbonate fuel cell, fuel cell, biomass gasification, biomass co-firing, large scale wind farms, off-shore wind farms, and building integrated photovoltaic. They looked at four scenarios: basic (greater priority for technology), pessimistic (technical and financial), optimistic (environmental), and unstable (oil substitute) covering economic, technical, social, and environmental criteria. They analyzed with the PROMETHEE II MCDM tool because of its simplicity and low complexity. As a consequence, they discovered that pressured fluidized bed combustion technology, followed by biomass gasification and large-scale wind farms, is the best option for promoting sustainable electricity technology. The current study's limitation is that it only looks at the results of a specific MCDM technique.

Kaya and Kahraman [70] proposed a hybrid AHP-VIKOR approach for selecting the optimal renewable energy source and its production site in Istanbul, Turkey. They evaluated five energy sources, including solar, wind, geothermal, biomass, and hydraulic energy, using the four primary criteria (economic, technical, social, and environmental) and their related nine sub-criteria. As a result, in the locations of Catalca, Sile, and GOP in Istanbul, they obtained wind energy as the best renewable energy generation technology with the most potential. The study's findings are based on qualitative judgments, which represent the average opinion of the experts that were chosen.

Mourmouris and Potolias [71] conducted research to determine the best renewable energy source and energy mix for the Greek island of Thassos. They used the REGIME multiple-criteria evaluation method to find the best renewable energy source from solar PV, wind, and biomass, as well as their combinations of wind-biomass, wind-PV, and wind-biomass-PV. As a consequence, they chose wind as the best energy source, as well as wind-biomass as the best energy mixing source. The study's findings are limited to only three renewable energy sources and their combinations.

Boran et al. [72] used a fuzzy TOSIS multi-criteria approach to determine the best renewable energy source for electricity generation in Turkey. Their study evaluates four energy sources: wind, solar PV, geothermal, and hydro energy, using five evaluation criteria (price, efficiency, GHG emissions, negative social impact, and resource availability). In Turkey, they determined that hydro energy is the most suited energy generation source, followed by wind, geothermal, and solar PV. The study contributes relatively little to the application of the anticipated output.

Ren and Sovacool [73] proposed a systematic MCDM approach for prioritizing five low-carbon energy sources. They created a model that prioritized five energy sources: solar, wind, biomass, nuclear, and hydro energy, based on four criteria: availability, affordability, acceptability, and accessibility. To offer weightage and rank the energy sources, they used AHP and TOPSIS, two MCDM approaches. Hydro energy is the best energy source in China, according to their proposed model, followed by wind, biomass, nuclear, and solar energy. The article has a lot of room regarding the consideration and selection of renewable energy sources and their availability.

Buyukozkan and Guleryuz [74] created an evaluation technique to help Turkey identify the best renewable energy source. With the ANP, DEMATEL, and TOPSIS techniques, they used linguistic interval fuzzy preference. They looked examined the economic, technical, environmental, social, and political implications of five renewable energy sources: solar, wind, biogas, hydro, and geothermal energy. For the pairwise comparison, they used the DEMATEL and ANP techniques, as well as TOPSIS to rank the alternatives. As a result, geothermal energy is picked as the best renewable energy source, followed by biogas, hydro, solar, and wind. The analysis is also supported by a crisp methodology, with the following energy sources ranked from best to worst: hydro, geothermal, wind, solar, and biogas. They also conducted a sensitivity analysis for five distinct scenarios, with the results indicating that geothermal is the most appropriate energy source in all of them. The limitation of work is to consider of the judgment of only three experts.

Barros et al. [75] developed a model to evaluate the long-term viability of various power plants based on economic, social, and environmental criteria. They evaluated 10 total renewable (PV, onshore wind farm, biomass, solar thermal, and mini-hydroelectric power plant) and conventional (lignite thermal, coal burned, oil-fired, natural gas-fired, and nuclear) energy sources using 16 sustainability indicators. They used a multicriteria decision-making approach called MIVES (Integrated Value Model for Sustainability Assessment). Their research identified high-temperature solar thermal power plants as the most environmentally friendly energy source. Wind energy, photovoltaics, and a mini hydroelectric power plant are in second, third, and fourth place, respectively. The study needs to consider more pillars in terms of criteria.

Atabaki and Aryanpur [76] created a multi-objective optimization model for long-term power generation planning in Iran, taking into account economic, environmental, and social factors.

They conducted research with three goals in mind: (i) cost reduction, (ii) CO_2 emission reduction, and (iii) employment creation. To apply weights to objectives and solve multi-objective models, they used AHP and a fuzzy membership-based weighted technique. They believe that for long-term power generation in Iran, combined cycle power generation and solar PV will be the most viable options. The study should investigate the uncertainty of factors, particularly cost factors.

Chatzimouratidis and Pilavachi [77] assessed the optimal energy source for future energy generation, taking into account economic, environmental, and technological factors. To analyze the different ten energy alternatives, they used an AHP MCDM technique using two criteria and nine end nodes sub-criteria. They got the reserve-to-production ratio criterion as the most weighted criterion by doing a pair-wise comparison. Hydro, geothermal, wind, biomass, solar, nuclear, coal-lignite, natural gas combined cycle, oil, and natural gas turbine are the best to worst energy alternatives, in that order. They also conducted a sensitivity [78] analysis for five scenarios and concluded that renewable energy sources may be the greatest option for future energy needs. The study's approach is limited to the categories of economic, technology, and sustainability, which should be expanded.

To choose renewable energy from the perspective of public investors, Wu et al. [79] develop a fuzzy MCDM approach based on cumulative prospect theory. They looked at five different alternative energy sources: solar PV, solar thermal, biomass, wind, and hydropower, and compared the economic, technological, environmental, and social aspects of each. They used AHP to weight criteria and sub-criteria, as well as cumulative prospect theory to rank renewable energy sources. As a consequence, they discovered that solar PV, followed by hydro, solar thermal, wind, and biomass power, is the best alternative. The alternatives were assessed as a single source of energy rather than hybrid or integrated sources in the study.

Katal and Fazelpour [80] use multi-criteria decision analysis to assess appropriate alternatives among five established power plants in various climatic circumstances. They looked at the economic, technical, and environmental elements of the Rajaei combined cycle power plant, Binalood wind farm, Siah Bishe hydropower plant, Qeshm CHP power plant, and Chabahaar gas power plant. For the weights of criteria, they used Entropy-Shannon, and for the ordering of the alternatives, they used VIKOR. They discovered that the Siah Bishe hydropower project is the best appropriate solution in Iran.

Mirjat et al. [81] used an AHP methodology to examine energy modeling for long-term electricity supply in Pakistan. They looked at seventeen sub-criteria that covered economic, technological, environmental, and socio-political criteria. Clean Coal Maximum, Renewable Energy Technology, Energy Efficiency and Conversion, and Reference were the four options they chose. They used the Expert Choice Comparison tool software to conduct their research. Energy Efficiency and Conversion, according to their findings, are the best options for future energy supply. The authors developed different scenarios as an alternative by considering only energy sources rather than considering the contribution of energy sources to the landscape.

Ghenai et al. [1] used extended step-wise weight assessment ratio analysis (SWARA) and additive ratio assessment (ARAS) to examine the poly silicon solar energy, solid oxide fuel cells, phosphoric oxide fuel cells, and land-based wind energy sources. They put together a team of three energy specialists to assess the four renewable energy sources using five criteria and fourteen sub-criteria. For the evaluation criteria weights, the extended SWARA approach was used, and for the evaluation of renewable energy options, the ARAS approach was used. Based on the sustainability criteria and sub-criteria, land-based wind energy was selected as the top priority, followed by solid oxide fuel cells, phosphoric oxide fuel cells, and poly silicon solar energy.

A few other studies on the evaluation and prioritization of various renewable and non-renewable energy sources in various nations are also available, which are briefly described in Table 2.1.

Table 2.1: The ranking results of energy alternatives based on country and method

Authors	**Method**	**Sensitivity analysis**	**Results**	**Limitations of the Study**
Colak and Kaya [52]	interval type-2 fuzzy AHP and hesitant fuzzy TOPSIS	Yes	Wind > Solar > Hydraulic > Biomass > Geothermal > Wave > Hydrogen Energy	Only renewable energy sources are taken into consideration.
Kaya & Kahraman [70]	Fuzzy AHP and Fuzzy TOPSIS	Yes	Wind > Biomass > Solar > CHP > Hydraulic > Nuclear > Conventional	The outcome is based only on qualitative factors.
Haddad et al., [37]	AHP		Solar > Wind > Geothermal > Biomass > Hydro Power	A limited number of experts are involved in the decision-making process.
Şengül et al., [53]	Fuzzy Shannon's and Fuzzy	Yes	Hydro power station > Geothermal power station > Regulator > Wind	A limited number of alternatives are explored and analyzed.

Authors	Method	Sensitivity analysis	Results	Limitations of the Study
	TOPSIS		power stations	
Lee and Chang, [36]	Fuzzy Shannon's for weights of each criterion and WSM, TOPSIS, VIKOR, ELECTRE to rank the alternatives.	Yes	Ranking of **WSM** Hydro > Solar PV > Wind > Biomass, **TOPSIS,** Hydro > Solar PV > Wind > Geothermal > Biomass, **VIKOR,** Hydro > Wind > Solar PV > Biomass > Geothermal, **ELECTRE,** Hydro > Solar PV > Wind > Geothermal,	The study has not discussed the implications of the research outcome.
Štreimikiene et al., [54]	AHP and ARAS (additive ratio assessment)	Yes	Nuclear PP > Biomass > Hydro > Gas CHPP > Wind > Geothermal.	The results are very limited in terms of decision-making approaches.
Daniel et al., [82]	AHP	No	Wind > biomass > solar	Only three alternatives are explored.
Kabak & Dağdeviren, [55]	BOCR and ANP	No	Hydro > Geothermal > Solar > Wind > Biomass	The study has limitation of sensitivity analysis.
Brand & Missaoui, [56]	TOPSIS	No	Diversification of Renewable energy > Business as usual > Div CoalRes > Div Nuclear > Div Coal	The study explored only a limited number of alternatives.
Büyüközkan & Güleryüz, [57]	ANP, Integrated DEMATEL and ANP	Yes	**Integrated DEMATEL and ANP**, Wind > Solar > Biomass > Hydraulic > Geothermal, **ANP** Wind > Solar > Geothermal > Biomass > Hydraulic	The study approach is very limited only to five renewable energy alternatives.
Fatih Emre Boran, [58]	Fuzzy VIKOR	Yes	Wind > Hydro > Solar > Geothermal > Biomass	The study is the only application of a single MCDM approach.
Wang et al., [59]	A developed Hierarchical decision model	Yes	Coal > Renewable Energy > Petroleum > Natural Gas > Nuclear Energy	Only industry experts are considered.
Al Garni et al., [40]	AHP	Yes	Solar PV > Solar Thermal > Wind > Biomass > Geothermal	Less local data is used in the analysis.
Abdullah & Najib, [60]	Intuitionistic Fuzzy - AHP (IF-AHP)	No	Nuclear > Solar > Hydraulic > Wind > Biomass > CHP Power > Conventional	The study only analyses qualitative weights
Ahmad & Tahar, [61]	AHP	Yes	Solar > Biomass > Hydro > Wind	The study explored a single MCDM approach (AHP)
Tasri & Susilawati, [38]	Fuzzy AHP and WSM	No	Hydro > Geothermal > Solar > Wind > Biomass	The study takes into account the views of only four experts.
Stein, [62]	AHP	No	Wind > Solar > Hydro > Geothermal > Gas > Oil	The result outcome is less robust.

Authors	Method	Sensitivity analysis	Results	Limitations of the Study
			> Nuclear > Coal > Biomass	
Yuan et al., [63]	Linguistic hesitant fuzzy set and cloud model	Yes	Biomass > Wind > hydro > Solar	The study only includes the views of three experts.
Sliogeriene et al., [64]	AHP and ARAS (additive ratio assessment)	Yes	Nuclear > Biomass > Hydro > Gas CHPP > Wind > Geothermal	The authors did not conduct a sensitivity analysis or validate their findings.
Sadeghi et al., [65]	Fuzzy AHP and Fuzzy TOPSIS	Yes	Solar > Wind > Hydro > Geothermal	The study is extremely limited in terms of criteria, alternatives, and experts.
Zhang & Tao, [66]	AHP and DEA (data envelopment analysis)	No	Wind > Solar PV > Biomass > Hydro > Ocean > Geothermal Energy	A condensed article with scant details.
Ishfaq et al., [68]	VIKOR, AHP, TOPSIS	No	Hydel > Wind > Biomass > Solar	The article did not address the potential scenarios and availability of renewable energy resources.
Jha & Puppala, [83]	Fuzzy AHP	No	Geothermal > hydro > wind > biomass > solar	The article ranked geothermal energy as the best energy alternative without any evidence.
Doukas et al., [69]	PROMETHEE II	No	Pressurized Fluidized Bed Combustion > Biomass Gasification > Large Scale Wind Farms > Natural Gas Combined Cycle > Biomass Co-Firing > Pressurized Pulverized Coal Combustion > Building Integrated Photovoltaics > Off-Shore Wind Farms > Fuel Cell/Turbine Hybrids > Molten Carbonate Fuel Cell.	The current study's limitation is that it only looks at the results of a specific MCDM technique.
Kahraman et al., [84]	Fuzzy AHP and Fuzzy AD (axiomatic design)	No	Wind > Solar > Biomass > Geothermal > Hydro Power	The robust analysis with only qualitative factors.
Kulkarni et al., [85]	AHP and Fuzzy Logic	No	Smart micro grid > grid extension > solar home systems	The study did not discuss the implications of the research findings and how they would be beneficial.
Kaya & Kahraman, [35]	Integrated fuzzy AHP and fuzzy VIKOR	No	Wind > Solar > Biomass > Geothermal > Hydro Power	The limitation of the study is the consideration of limiting factors due to which the weights of the factors cannot be properly allocated.
Kahraman &	Fuzzy AHP	Yes	Wind > Solar > Biomass	Only qualitative weights

Authors	Method	Sensitivity analysis	Results	Limitations of the Study
Kaya, [86]			> Geothermal > Hydro Power > Natural Gas > Coal and Lignite > Nuclear > Oil	from four experts.
Kumar and Samuel [87]	AHP -VIKOR	Yes	Wind turbines and solar photovoltaics are preferred.	The result findings are not justified or validated.
Mourmouris & Potolias, [71]	REGIME	No	Wind > Biomass > PV, W/Bio > W/Bio/PV > W/PV	The study's findings are limited to only three renewable energy sources and their combinations.
Boran et al., [72]	fuzzy TOPSIS	Yes	Hydro > Wind > Geothermal > Photovoltaic	The study contributes relatively little to the application of the anticipated output.
Ren & Sovacool, [73]	AHP and TOPSIS	No	Hydro > Wind > Biomass > Nuclear > Solar	The article has a lot of room regarding the consideration and selection of renewable energy sources and their availability.
Büyüközkan & Güleryüz, [57]	linguistic interval fuzzy preferences with ANP, DEMATEL, TOPSIS.	No	Linguistic, Geothermal > Biogas > Hydro > Solar > Wind, Crisp, Hydro > Geothermal > Wind > Solar > Biogas.	The study approach is very limited only to five renewable energy alternatives.
Ghose et al. [88]	Fuzzy TOPSIS	Yes	Hydro > geothermal > solar > wind > tidal > biomass > nuclear	The study area is very specific.
Demirtas, [89]	AHP	Yes	Wind > Biomass > Geothermal > Solar > Hydro Power	Application of single MCDM approach.
Cartelle Barros et al., [75]	MIVES (integrated value model for sustainability assessment)	No	Solar Thermal > Onshore Wind Farm > PV > Mini-Hydroelectric Plants > Natural Gas Fired > Nuclear > Biomass > Oil Fired > Coal Fired > Lignite Thermal	The study needs to consider more pillars in terms of criteria.
Atabaki & Aryanpur, [76]	AHP	Yes	Solar PV and a Combined cycle power plant are the best option.	The study should investigate the uncertainty of factors, particularly cost factors.
Chatzimouratidis & Pilavachi, [78]	AHP	No	Hydro > Geothermal > Wind > Biomass > Photovoltaic > Nuclear > Coal-lignite > Natural gas combined cycle > Oil > Natural gas turbine.	The study's approach is limited to the categories of economics, technology, and sustainability, which should be expanded.
Wu et al., [79]	fuzzy AHP with cumulative prospect theory	Yes	Solar PV > Hydro Power > Solar Thermal Power > Wind Power > Biomass Power	The alternatives were assessed as a single source of energy rather than hybrid or integrated sources in the study.
Katal &	Entropy-	No	Hydro > Wind > CHP power > Combined cycle	The result findings are not validated by the sensitivity

Authors	Method	Sensitivity analysis	Results	Limitations of the Study
Fazelpour, [80]	Shannon and VIKOR		> Gas power plant	analysis.
Ghose et al. [90]	Fuzzy logic with COPRAS	No	Wind > biomass > hydel > solar > geothermal > tidal	The study area is very specific.
Yang et al., [91]	TOPSIS	No	Solar Heating > Heat Pumps > Wood Pellet Boilers	The work did not deal with vagueness.
Mirjat et al., [81]	AHP	Yes	Energy Efficiency and Conversion > Reference > Renewable Energy Technologies > Clean Coal Maximum	The authors developed the scenarios without considering the share of a particular energy source.

After a thorough and in-depth examination of the collected literature, it is discovered that the collected research evaluates either renewable or conventional energy sources with the specific goal of meeting current needs. It also addresses a limited number of aspects that are unable to effectively define the sustainability path or even accomplish sustainable growth. Further, in the case of India, the country is trailing behind on the international stage, with only a few studies in the area of evaluating diverse energy sources and prioritizing energy alternatives. As a result, there is a pressing need to identify sustainability indicators and determine the most sustainable energy source among the various energy sources that may address the current challenges from the Indian perspective.

2.2.3 Content Analysis

This section briefly discusses supporting or essential information such as criteria used in prior research, frequency of various methodologies utilized, and so on. Firstly, the study determined the indicators employed in prior studies and their associated categories after thoroughly examining the literature review. Table 2.2 lists the categories that have been evaluated in prior studies, whereas section 3.1 of the next chapter lists the indicators that have been utilized in past studies.

Table 2.2: Significant categories of indicators that used in previous studies

S. No.	Authors	Year	Criteria											
			Economic	Environmental	Technical	Social	Political	Quality of Energy Sources	Risk	Supply Security	Availability of Resources	Natural Conditions	Flexibility	Emission in Air, Water and Soil
1.	Colak and Kaya [52]	2017	√	√	√	√	√	√						
2.	Kaya and Kahraman [35]	2011	√	√	√	√								
3.	Haddad et al. [37]	2017	√	√	√	√	√							
4.	Sengul et al. [53]	2015	√	√	√	√								
5.	Lee and Chang [36]	2018	√	√	√	√								
6.	Streimikiene et al. [54]	2016	√	√	√	√	√							
7.	Vafaeipour et al. [42]	2014	√	√		√			√					
8.	Brand and Missaoui [56]	2014	√	√		√				√				
9.	Streimikiene et al. [39]	2012	√	√		√								
10.	Buyukozkan and Guleryuz [57]	2016	√	√	√	√	√							
11.	F. E. Boran [58]	2018	√	√	√	√								
12.	Wang et al. [59]	2010	√	√		√					√			
13.	Jha and Puppala [83]	2017	√	√	√									
14.	Garni et al. [40]	2016	√	√	√	√	√							
15.	Abdullah and Najib [60]	2016	√	√	√	√								
16.	Ahmad and Tahar [61]	2014	√	√	√	√								
17.	Tasri and Susilawati [38]	2014	√	√	√	√		√						
18.	E. W. Stein [62]	2013	√	√	√	√	√							
19.	Arce et al. [92]	2015	√	√	√	√								
20.	Yuan et al. [63]	2017	√	√	√	√								
21.	Sliogerience et al. [64]	2013	√	√	√	√	√							
22.	Sadeghi et al. [65]	2012	√	√	√	√	√							
23.	Zhang and Yang [66]	2014	√	√	√	√								
24.	Ishfaq et al. [68]	2018	√	√	√									
25.	Doukas et al. [69]	2006	√	√	√	√								
26.	Kahraman et al. [84]	2009	√	√	√	√	√		√					
27.	Kaya and Kahraman [70]	2010	√	√	√	√								
28.	Kahraman and Kaya [86]	2010	√	√	√	√	√							
29.	Mourmouris and	2013	√	√	√	√								

S. No.	Authors	Year	Criteria											
			Economic	Environmental	Technical	Social	Political	Quality of Energy Sources	Risk	Supply Security	Availability of Resources	Natural Conditions	Flexibility	Emission in Air, Water and Soil
	Potolias [71]													
30.	Kulkarni et al. [85]	2017	√	√										
31.	Buyukozkan and Guleryuz [74]	2017	√	√	√	√	√							
32.	Ozgur Demirtas [89]	2013	√	√	√	√								
33.	Erdogan and Kaya [93]	2016	√		√							√		
34.	Barros et al. [75]	2015	√	√		√								
35.	Atabaki and Aryanpur [76]	2018	√	√		√								
36.	Karger and Hennings [94]	2009	√	√						√			√	
37.	Chatzimouratidis and Pilavachi [77]	2009	√		√									
38.	Wu et al. [79]	2018	√	√	√	√								
39.	Katal and Fazelpour [80]	2018	√	√	√									
40.	Yang et al. [91]	2018	√	√	√									
41.	Mirjat et al. [81]	2018	√	√	√	√	√							
42.	Ghenai et al. [1]	2020	√	√	√	√					√			

According to the aforesaid research, the authors evaluated the energy alternatives using three or four aspects, which were either adapted from direct literature or determined based on their needs. There are only a few studies that used indicators tailored to their specific geographical and environmental conditions. As a result, there is a pressing need to establish indicators that take into account one's particular geographical and environmental circumstances in order to attain sustainability.

Further, the study also examined the frequency of application of single or multiple MCDM approaches in previous literature. In the present analysis, the usage of a single approach or fuzzy logic is only considered in a single approach, whereas the remaining combinations are considered in a hybrid MCDM approach. Further, the assessment of the last two decades reveals that the trends of using a single business-as-usual scenario approach are gradually shifting towards the usage of a hybrid MCDM approach as shown in Fig. 2.7.

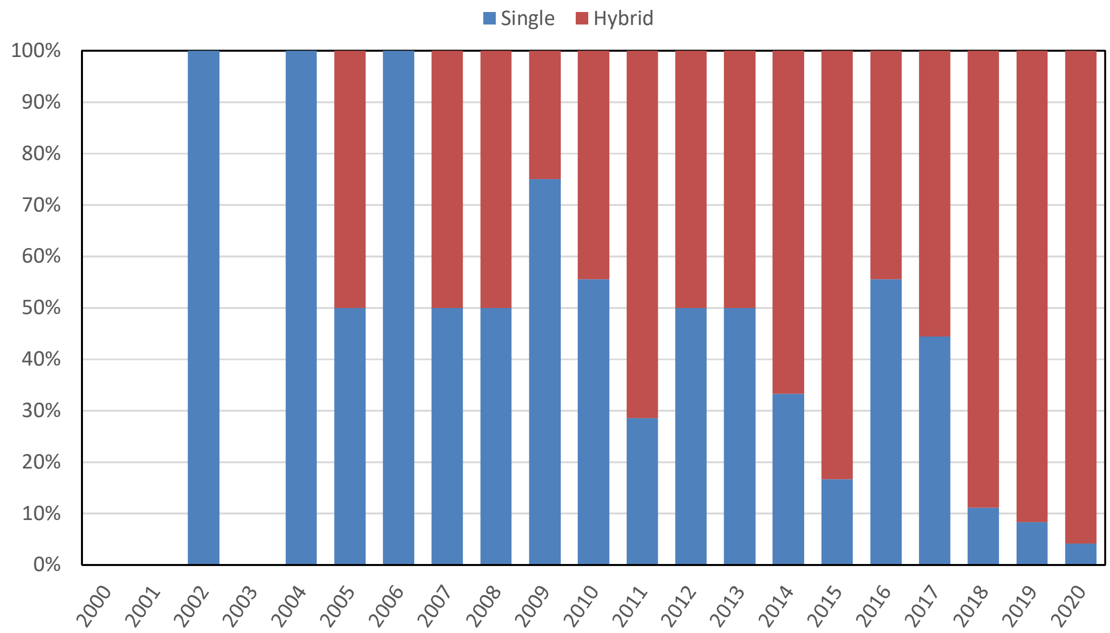


Fig. 2.7: Number of articles published with single or hybrid MCDM approaches

Further, of the single and hybrid approaches, AHP is the most extensively used approach, having been used in 50 articles. Furthermore, TOPSIS is the second most promising approach, with a share of 15.56%. Following that, PROMETHEE and ELECTRE approach to take the lead in the research. Furthermore, the ANP and VIKOR techniques cover 5.43% and 3.26% of the total number of articles considered, respectively. Table 2.3 provides a high-level overview of these approaches.

Table 2.3: MCDM approaches used in the energy sector

MCDM Approach	Integrated approaches	Number of Research Paper	Percentage	Reference with author Name and Year
AHP	TOPSIS, WSM, WASPAS, VIKOR, ELECTRE, ARAS, DEA, Bayesian approach, SWOT	50	54.35%	[37,38,40,54,60–62,64,70,76,78,81–83,85,86,89,95–127]
TOPSIS	AHP, Shannon's, MOORA, MULTIMOORA	14	15.23%	[35,36,39,52,53,65,72,73,91,128–132]
PROMETHEE	AHP	12	13.04%	[132–143]
ELECTRE	AHP	8	8.69%	[36,69,135,144–148]
ANP	DEMATEL, BOCR, TOPSIS	5	5.43%	[55,57,149–151]
VIKOR	AHP, Shannon’s	3	3.26%	[80,152,153]
Total		92	100%	

2.3 SYSTEMATIC LITERATURE REVIEW: PHASE-II

Similar to the preceding section, the literature review is divided into three sections, which are as follows.

2.3.1 Descriptive Analysis

The analysis encompasses journals and conferences, temporal distribution, authorship, geography, citations, and keyword analysis, all of which are similar to the preceding section.

2.3.1.1 Journals and conferences

The second phase of literature includes 167 papers from 27 reputed journals. The journal 'Renewable and Sustainable Energy Reviews' has the most articles (48), followed by Renewable Energy (29), and Energy Policy (19). Here, Fig. 2.8 shows only those journals in which more than 3 such articles have been published. Furthermore, the papers are culled from prestigious journals and are accompanied by brief abbreviations, such as Renewable and Sustainable Energy Reviews – RSER, Renewable Energy – RE, Energy Policy – EP, Energy – EN, Applied Energy – AE, Sustainable Energy Technologies, and Assessment – SETA, Journal of Cleaner Production – JCP, Energy Conversion and Management – ECM, and Energy Procedia – Eproc.

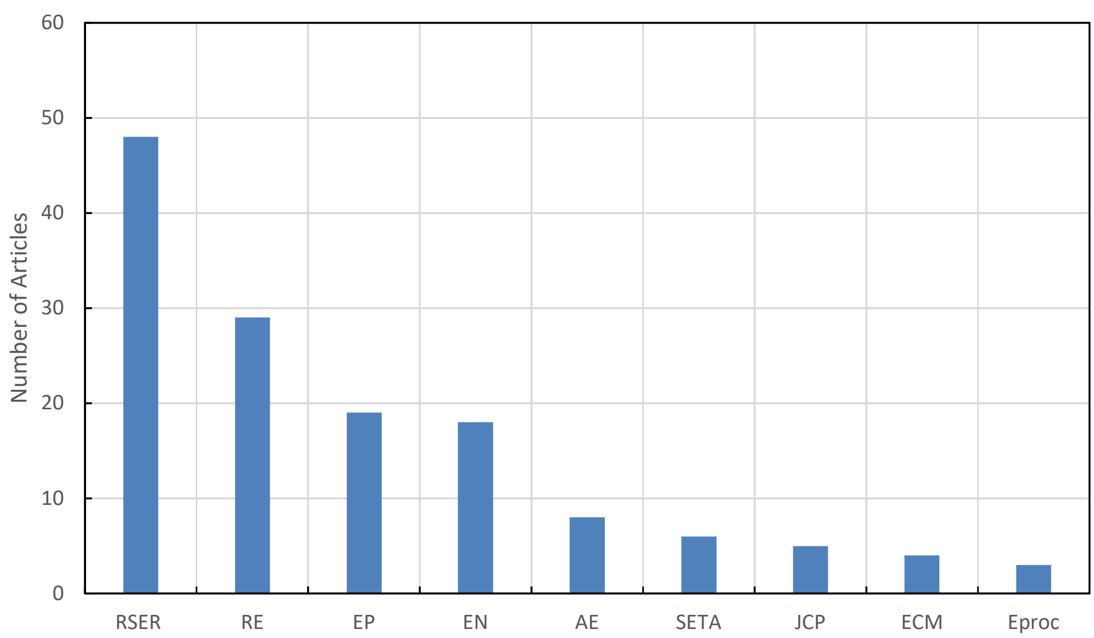


Fig. 2.8: List of journals with the number of published articles among the collected literature (Phase-II)

2.3.1.2 Timeline distribution

The study of temporal distribution reveals that the number of published articles is steadily increasing, with a significant increase after 2012. In addition, there are the most articles available in 2021. The details are depicted visually in Fig. 2.9. A thorough examination reveals that the unique GIS and MCDM combination is constantly attracting academics to study the vast region of renewable energy prospective sites.

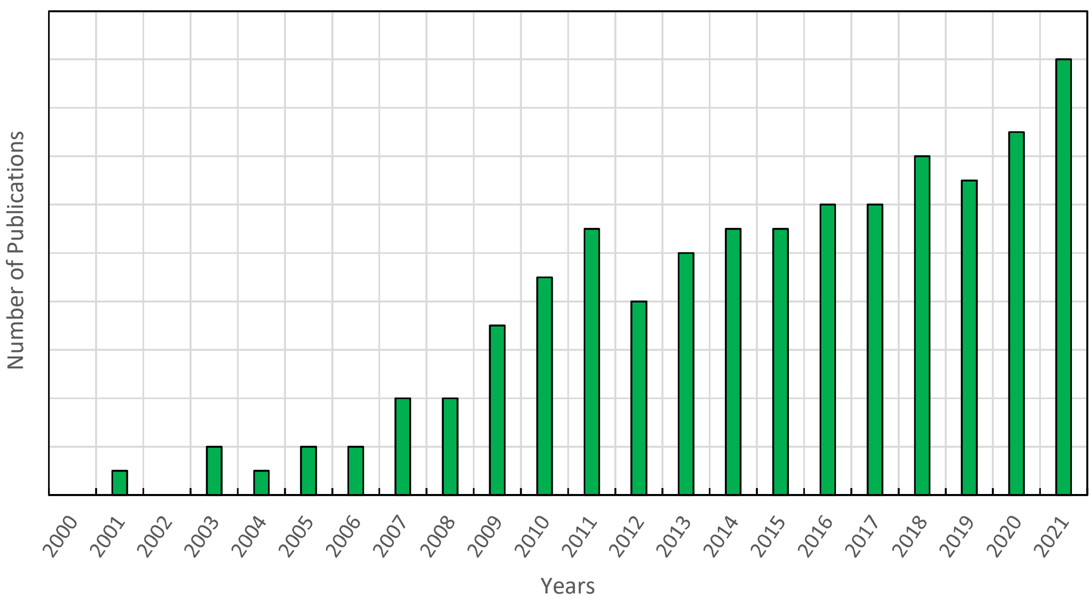


Fig. 2.9: Timeline distribution of selected articles during Phase-II literature survey

2.3.1.3 Authorship

In this section, it is identified that the three authors have authored the most number of papers (47), followed by 39 articles by two authors and 34 articles by four authors. Furthermore, 16 articles have five authors, 12 articles have six authors, and the remaining 13 articles are written individually. Finally, there are seven and ten authors in the least 05 and 01 articles, respectively. In comparison to the previous section, this section has more papers with many authors while collaborating with the fewest international institutes/universities. This signifies that the articles are written by multiple authors from a university or institute. In addition, this research topic is being handled explicitly by their native country researchers to precisely explore the prospective sites for renewable energy sources using the locally available resources and infrastructure.

2.3.1.4 Geography

The collected literature comes from a total of 26 countries, with China publishing the most articles (34), followed by Spain (17), and Turkey (14). Further, the order followed by Malaysia (10), Morocco (09), Greece (08), South Africa (08), Saudi Arab (08), Iran (07), United Kingdom (07), United States (06), and Germany (06). In Fig. 2.10, a world map depicting the number of papers published by different countries is visually depicted. The participation of scholars from around the world demonstrates that the entire community is working to explore available resources in order to maximize renewable energy potential.

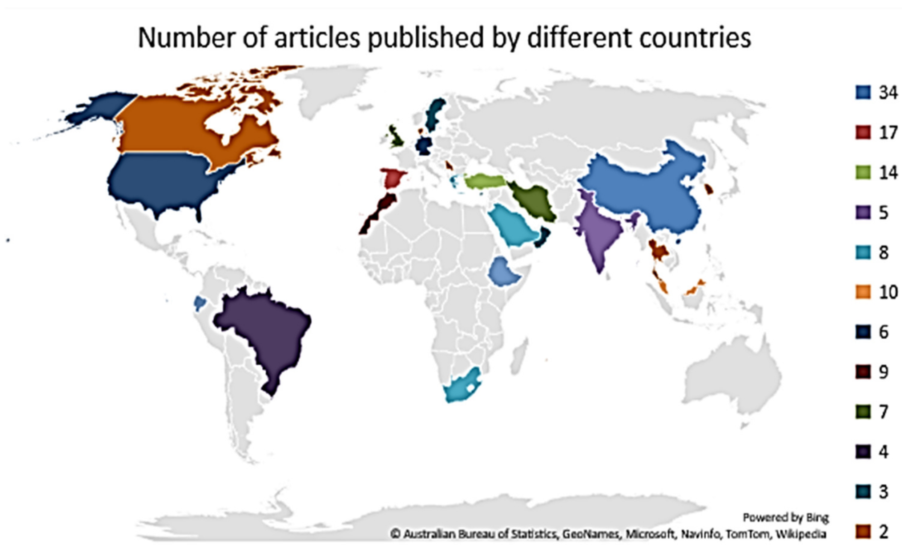


Fig. 2.10: The number of articles published by different countries in the Phase-II literature survey

2.3.1.5 Citations and keywords

Further, in the citation and keyword analysis, the highest citation is provided to Prof. Satty, the creator of the AHP technique. After that, the author J. M. Sanchez-Lozano, who has written many publications on this burgeoning topic, receives the most citations. Several other authors, including Noorollahi, Al Garni, Mostafaeipor, Charabi, Zavadskas, and Ramachandran, are receiving a significant number of citations. Fig. 2.11 depicts the citation details graphically. The most often used keyword in the gathered literature is 'decision making (135),' followed by 'geographical information system (128).' The terms 'analytical hierarchy process', ‘renewable energies,' 'wind power,' and 'solar energy' are also relevant. The main keywords are also graphically depicted in Fig. 2.12. The aforesaid analysis would help researchers find specific literature by using the most often used keywords or by following the researcher with a large number of citations.

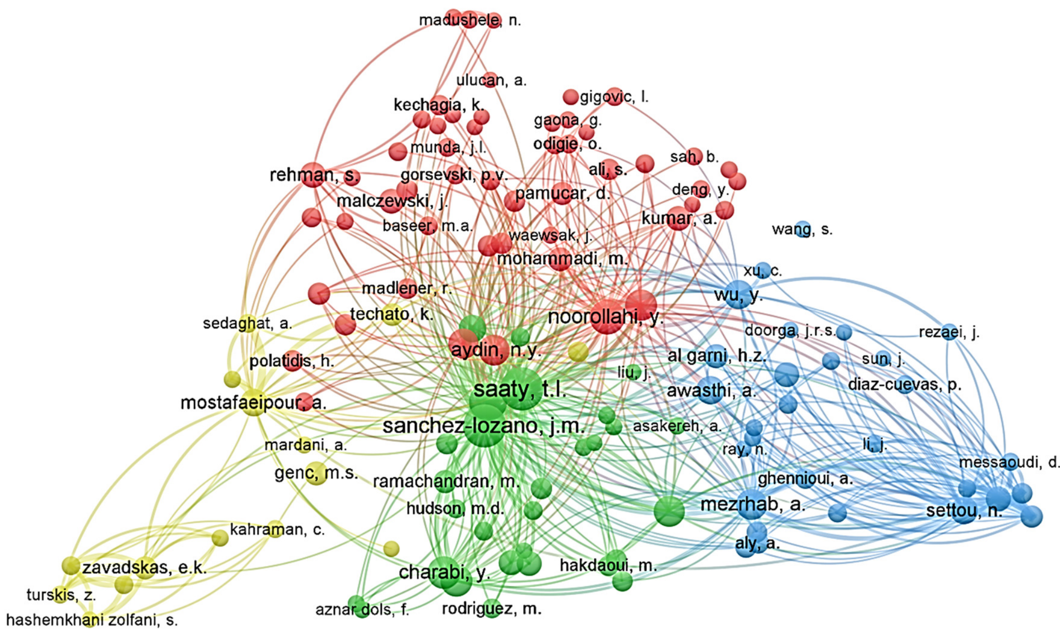


Fig. 2.11: Citation's analysis of phase-II literature

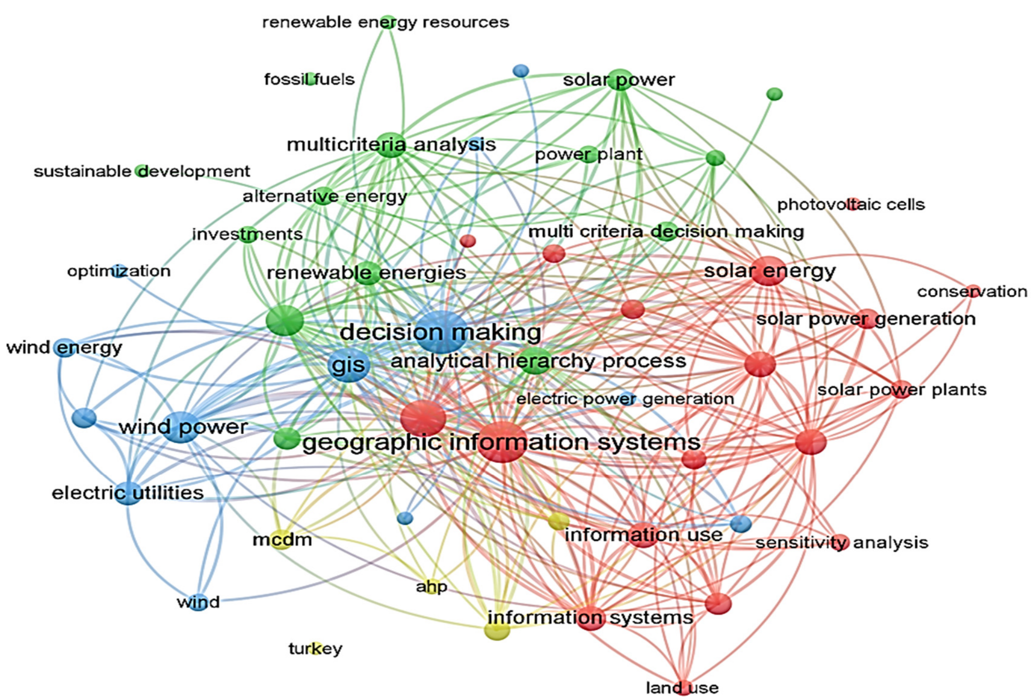


Fig. 2.12: Frequency of keywords in the collected phase-II literature

2.3.2 Comprehensive Analysis

The section discusses the literature on evaluating potential sites, determining available potential, and calculating achievable potential. The following is an extensive review of the literature.

Sanchez-Lozano et al. [154] used fuzzy MCDM techniques combined with a GIS methodology to assess feasible sites for onshore wind farms in the Murcia region of southeast Spain. The eight constraints and ten criteria were used to produce the thematic layer of appropriate land using the gvGIS technique. The fuzzy AHP approach was used to provide weights to the criteria, and the available appropriate alternative lands were rated using the fuzzy TOPSIS approach. They pointed out that just a small portion of the land is suitable for the installation of onshore wind farms. They conducted sensitivity analyses for both scenarios, ensuring that (i) all criteria were given equal weights, and (ii) the top ten best alternatives were assessed and compared to other MCDM methodologies. Rather than one or two positions, the ranking of the alternatives is steady.

Siyal et al. [155] employed the ArcGIS tool to examine the economic and technical feasibility of wind turbines (Veastas-82 and Veastas-112) across Sweden's twenty-one counties. During their analysis, they took into account land-use limits, economic considerations, and wind energy generating losses. They singled out the country's central and southern regions as the most cost-effective areas for wind energy production. For the V-82 and V-112 wind turbines, they predicted a Levelized cost of electricity (LCOE) and payback period of 45-96 USD/MWh or 35-76 USD/MWh and fewer than 12 years of payback period, respectively. They conducted a sensitivity analysis using the economic variables of initial investment cost, interest rate, and power selling price. As a result, they observed that the study's sensitivity analysis findings are extremely sensitive to economic indices.

Sun et al. [156] used the ArcGIS tool to create a regional model for solar PV power generation potential in Fujian province and analyze the geographical, technical, and economic power potential. For solar PV power potential estimation, they looked at the built-up area (roof top) and outside the built-up area (big scale). Non-built-up areas and built-up areas have geographical power potentials of 14.46 PWh/year and 157 TWh/year, respectively. Furthermore, Fujian province has a technological potential of 592.37 TWh, which is almost 4 to 5 times the province's total energy consumption. They demonstrated that Fujian's coastal region, as well as the Zhangzhou and inner west regions, are appropriate for decentralized roof-top and large-scale grid-connected solar PV power generation. They also ran sensitivity analyses for the PV system's performance ratio, the roof-top area to total built-up area ratio, and the popularizing ratio with technical potential. They concluded that the technical potential and the sensitivity factors had a linear connection.

Yushchenko et al. [157] calculated the geographical and technical potential of large-scale grid-connected solar PV, solar CSP, and off-grid solar PV systems for energy generation in rural South Africa (ECOWAS region). For the analysis, they used GIS and an MCDM (AHP) technique. The restricted criteria were urban settlements, land cover, risk areas, protected areas, land slope, and population density. In addition, solar irradiance, distance to power grid lines, distance to highways, population density, and distance from communities were selected as the evaluation characteristics. Finally, On the available most appropriate areas, they calculated technological potentials of 700 – 1800 TWh/yr, 900 – 3200 TWh/yr, and 81 TWh/yr for grid-connected solar CSP, grid-connected Solar PV, and off-grid solar PV electricity, respectively.

Doljak and Stanojevic [158] used an integrated GIS and MCDM technique to determine the best spatial layout for ground-mounted PV power plants and quantify the amount of electricity generated in Serbia. They looked at climate (global solar radiation, sunshine length, air temperature, and relative humidity), orography (slope, and aspect), and vegetation (NDVI). The highest prospective locations were found in the northern portion of Serbia, specifically in the cities of Zrenjanin, Novi Becej, and Coka. The best generation locations have a potential of between 129.55 and 135.21 Wh/m2/year.

Charabi and Gastli [159] used the ArcMap tool incorporated in the ArcGIS tool to create a geographical solar radiation map and to find the best locations for a large CSP plant in Wilayat Duqum in the Sultanate of Oman. They identified 2.5 km^2 of land area with a slope of less than 1% as an excellent location for a solar power installation. They calculated a 2.3 TWh/year potential for electricity generation. They also assessed the capacity of five established approaches: parabolic trough without storage (1018 GWh/year), parabolic trough with storage (1018 GWh/year), tower (1075 GWh/year), dish (1556 GWh/year), and concentrated PV (2319 GWh/year).

Hofer et al. [160] improved the siting evaluation by adding economic, technical, social, political, and environmental aspects into holistic MCDM techniques. They conducted the siting evaluation in three steps: first, they excluded areas with wind energy potential, urban areas, infrastructure, natural environment, the slope of the terrain, and land cover type; second, they used the AHP approach to create rated area maps; and third, they classified the suitable areas. Wind energy potential, the slope of the terrain, land cover type, landscape architecture, distance from the road network, power grid, urban areas, places of interest, and natural environments were among the variables they utilized in their analysis. The bulk of appropriate locations (high and medium suitable) are found in the Stadteregion Aachen region's northeastern and central regions. High and medium suitable land areas account for 1.74 percent and 7.37 percent of total available land, respectively.

Garni and Awasthi [161] used GIS and MCDM techniques to evaluate and identify the best suitable location for the building of large-scale grid-connected solar PV power plants in Saudi Arabia. They used metropolitan areas, protected land, important road networks, and steeper slope lands (>5 degree) as limiting variables in their analysis. Solar irradiation, air temperature, slope, land aspects, closeness to metropolitan areas, proximity to highways, and proximity to power lines were chosen as decision factors, and the weights of these decision criteria were calculated using the AHP MCDM approach. They identified the north and northwest parts of the study region, as well as the west of Taif city near the west coast, as the best locations for large-scale solar power projects. They ran sensitivity tests for two scenarios: (i) equal weights for technical and economic criteria, and (ii) larger weights for economic criteria. The sensitivity results in the case of the equal weight are very steady and constant, but in the higher weights to economic category case, there is a significant rise in available most suitable land area.

Further, using a GIS tool and the MCDM technique, Tahri et al. [162] examined certain sets of places to carry out renewable energy projects in Ouarzazate, Morocco. They used the AHP approach to assign weights to the four categories of climate, orography, location, and land use, as well as the seven sub-categories of solar radiation, land surface temperature, slope, slope orientation, distance to road, distance to urban regions, and land use. Agricultural land, lakes, protected and urban areas, and land utilized to develop infrastructure and utilities were all excluded from the study. As a result, the solar power projects are extremely suited for installation on 23% of the total land.

In continental Ecuador, Villacreses et al. [43] used a combination of GIS and MCDM techniques to locate the most practicable sites for wind generating projects. For the criteria weights, they used the AHP approach, and for alternate ranking, they used Ordered Weighted Averaging (OWA), VIKOR, Occupational Repetitive Actions (OCRA), and TOPSIS. The most appropriate land covers a surface area of 0.4% to 1.1% of Ecuador's total land area. The location with the highest score is in the Andean region, while the area with the lowest score is in the country's east.

Merrouni et al. [163] used GIS-based software to identify appropriate places for the installation of CSPP in Morocco's eastern region. They excluded places with yearly direct solar radiation less than 1750 kWh/m^2, land buffered from roads and trains by 500 meters, land buffered from waterways by 500 meters, slopes larger than 2%, and land covered by towns, dams, power grids, and vegetation. They believe that more than 65% of the total surface area of Morocco's eastern region is suitable for the building of CSP power plants. They also used existing solar power facilities to corroborate their land suitability findings.

Merrouni et al. [164] used GIS software to locate potential places in Morocco's Eastern region for the development of large-scale solar PV installations. They studied meteorological data collected from ten meteorological stations located throughout eastern Morocco. On the basis of hydrology, infrastructure, and land occupation, they created the exclusion mask. They discovered that 74.9 percent (44863 km^2) of Eastern Morocco's total territory is extremely favorable for the installation of large-scale solar PV power facilities. They also used Greenius software developed by the German Aerospace Center to simulate a large-scale 15 MW electrical power plant in Morocco's eastern area.

Merrouni et al. [118] used a combination of MCDM and GIS techniques to find the most appropriate sites for large-scale solar PV power projects in Morocco's eastern area. Their research was based on four main criteria: climate, orography, location, and water resource, as well as eight sub-criteria. They used the AHP technique to weight criteria and sub-criteria and discovered that global solar radiation (climate) received the most weight, followed by the slope (orography). According to their findings, only 19% of the area is highly suitable for solar power installation, while the remaining 20% is marginally suitable.

On the Greek island of Lesvos, Tegou et al. [116] used a combination of GIS and MCDM to assess the potential areas for wind farm installation. They assessed the suitable land using the eight sub-factors of environmental, technological, economic, and social categories. They used the AHP method for weighing criteria and GIS software to eliminate constraint layers and create the final suitability map. As a result, they were only able to attain the optimal suitability index for wind farm installation on 1.4% of the island's territory.

Using multi-criteria decision support and a GIS-based approach, Noorollahi et al. [165] found the most suitable sites for wind farm installation in western Iran. During their analysis, they took into account environmental (residential areas, highways and roads, railways, airports, electric power lines, ancient and cultural monuments, rivers, coast lines, and wetlands, environmental protected areas, lakes and water bodies, and faults) as well as physiographic (slope and digital elevation model) restrictions. They discovered that the northern portion of Arak nation, the majority of Ashtian country, and the provinces in the south of Tafresh and Komijan countries are the finest places to build wind farms. They discovered that 28 percent of the land is suitable for large-scale wind turbines or wind farms in three different classes. They took into account technical, environmental, economic, and geographical factors, and all of the criteria were given equal weighting.

Diaz-Cuevas et al. [119] used a combined GIS and MCDM technique to find the best locations for wind turbine installation in the province of Cadiz, Andalusia (Southern Spain). They looked at two types of regions: minor restrictions and major constraints. They discovered that extremely suitable sites in the minor restriction region can accommodate 416 wind turbines with a capacity of 832 MW, whereas highly suitable sites in the major constraint region can accommodate 30 wind turbines with a capacity of 60 MW. The minor and major limitations regions covered an area of 2731 km^2 and 656 km^2, respectively.

Using geographic and remote sensing research, Wang et al. [166] identified the most promising areas in Tibet, China for the development of photovoltaic power producing plants. The slope was calculated using the GIS overlay and a combination of satellite-measured solar radiation data, land cover factor, and a digital elevation model. Further, the GIS overlay showed the prospective places by merging all of the assessed resources. Furthermore, the most viable sites were discovered using electric infrastructure data and other considerations. They found 4005 most appropriate sites in Tibet's Shigatse and Ngari areas.

Aydin et al. [41] developed a system for selecting the most feasible sites for wind turbine installation based on a GIS-based MCDM approach. Their research was limited to the Turkish regions of Aydin, Burdur, Denizli, Mugla, and Usak. They conducted the research in two phases: (i) meeting environmental objectives, and (ii) determining wind energy potential.

As a result, if the degree of satisfaction in both phases is greater than 0.5, the location is declared suitable for wind turbine installation. They compared the selected sites to the location of existing or already erected plants to corroborate their findings. Further, the authors [167] expanded on their previous study by identifying potential places for hybrid wind-solar-power generation. They gathered several criteria from literature, interviews, and existing Turkish legislation and laws. As a result, they believe that integrating solar PV with these wind farms will boost energy generation.

Grassi et al. [168] used a GIS tool to analyze the technical and economic potential of wind energy in the state of Lowa (United States). After taking into account multiple factors, they came up with the best places for wind power project installation. The most suitable area, maximum cumulative installed capacity, and maximum average annual wind energy production were calculated to be 59,807 km2, 302 GW, and 914 TWh, respectively. They also ran a sensitivity analysis for the power purchase agreement (PPA) and the plant-able land. They came to the conclusion that as PPA rises, so would the percentage of land accessible for wind power plant construction.

In the regional unit of Rethymno, Giamalaki and Tsoutsos [169] presented and tested an approach for defining and selecting the most ideal places to site and install solar power plants. In their analysis, they used a combined GIS and MCDM (AHP) strategy. They chose six experts (one policymaker, one electricity supplier, one academic, one environmental specialist, and two engineers) to provide their input and weightings to the criteria under consideration. According to their research, 2.88% of solar PV land and 0.17% of CSP land are covered in the highest priority sustainable siting area. The highest priority sustainable siting area has the capacity to produce 530 MW of PV and 30 MW of CSP power.

Ozdemir and Sahin [170] determined the best azimuth angle for three sites: Igdir University, Kulluk, and Melekli, in order to choose the best location for solar power plant installation. First, they determined the best azimuth angle for each of the three locations based on daily and monthly solar radiation data acquired by pyranometer and photovoltaic geographic information system. Second, using real-time data analysis and multi-criteria analysis, they chose the most suitable position out of three options. They discovered Kulluk to be the ideal alternative for installing solar PV power plants in both ways.

Palmer et al. [171] identified places in the United Kingdom that are feasible for large-scale solar power installation while meeting physical, technical, environmental, and geographical requirements, as well as being economically viable and implementing government regulations. To create suitability maps, they employed a GIS tool and Boolean logic.

Firozjaei et al. [172] used the OWA approach in conjunction with a GIS tool to assess the risk of solar power installation and determine the best places for solar power plant installation in Iran. They looked at solar radiation, NDVI (Normalized Difference Vegetation Index), distance from the road, distance from the city, and slope as five evaluation factors. Fars, Kerman, Khuzestan, Yazd, Baluchistan, Sistan, South Khorasan, and Isfahan provinces were chosen because they have abundant solar energy.

Gorsevski et al. [173] used GIS-MCDM techniques to assess wind farm site suitability in Northwest Ohio, based on many participants' perspectives. Environmental (wind speed, distance to significant bird regions, and land use), as well as economic (people density, soils, proximity to transit and transmission lines) aspects, were considered as the decision criteria. They organized a panel of 30 experts, all of whom were undergraduate and graduate students, to assign weights to the criteria. Further, to examine the assigned weights to these criteria, the study developed an SDSS (Spatial Decision Support System) tool. As a result, they identified 2.4% of the land as extremely suitable for wind farm installation and 78.3% of the land as suitable for wind farm development.

Azizkhani et al. [174] used combined GIS-MCDM techniques to examine the most advantageous areas in Iran for installing solar power plants. Lakes, bogs, and embayment's were used as restrictions, while global horizontal irradiance, economic, technological, and geographical factors were used as evaluative criteria. For GHI, economic, technical, and land use criteria, they used the AHP technique and got 0.6078, 0.0614, 0.2084, and 0.1223 weights, respectively. They chose Sistan, Baluchistan, and parts of Hormozgan, Fars, Kerman, and Yazd provinces as the best places to build solar power plants.

Doljak et al. [175] assessed the potential of solar energy in the city of Poarevac, Serbia, along with an explanation of the importance of degraded areas in the city's new energy mix. They used open-source geospatial technology to prepare a solar radiation map with a spatial resolution of 90 m over Serbia, using GHI and DHI data from the Meteonorm software. They discovered a 2778.18 ha available area with a 2428.90 MW installed capacity and a 2569.12

GWh yearly energy production. They predicted that over the course of 25 years, 30 million tons of CO_2 emissions will be avoided.

Sanchez-Lozano et al. [176] compared the TOPSIS and ELECTRE TRI MCDM approaches for determining the best locations for photovoltaic solar farm installation in Spain. In their analysis, they used GIS, AHP, TOPSIS, and ELECTRE TRI technologies. As a consequence, a high percentage of the acceptable surface area of 21.25 percent was highlighted. The findings of both procedures are radically different, although the best option (A2147) picked in both approaches was the same.

Using a GIS-MCDM technique, Omitaomu et al. [177] assessed potential sites for the installation of new power plants. They created the OR-SAGE (Oak Ridge Analysis for Power Generation Expansion) methodology to evaluate advanced coal, nuclear, CSP, and compressed air energy storage as energy sources. For the siting of new power plants, they take into account environmental indicators, population expansion, tectonic dangers, water availability, and geological hazards. The technology quickly and effectively-identified suitable sites for the building of new power plants while also examining their long-term environmental consequences.

Aly et al. [113] used GIS and MCDM approaches to examine possible sites for large-scale solar power (PV and CSP) installation in the Republic of Tanzania (South Africa). In the study, they looked at six exclusion criteria (poor solar radiation, protected area, land cover, geography, water bodies, and urban expansion) as well as four decision criteria (solar resources, water availability, accessibility, and demand). They employed the AHP method to assign weight and rank to the decision criterion. They displayed the results as land suitability in the four classes, namely, most appropriate, suitable, moderately suitable, and least suitable. Finally, they obtained 3584 km^2 and 20,801 km^2 as the most suitable land for CSP and PV power plant installation, respectively.

Jangid et al., [122] identified the potential zones for harvesting wind energy through multi-criteria analysis and GIS for the Jodhpur district of Rajasthan, India. The study used five decision criteria of wind speed, slope, distance from residential areas, distance to roads, and land use. Finally, the study identified the most suitable potential sites in the northwestern (along Osian, Shergargh, Dechu, and Shaitrawa, Phalodi) part of Jodhpur district, India.

Ayodele et al. [178] used interval type-2 fuzzy AHP and GIS techniques to determine the best locations for wind farm installation in Nigeria. They examined using two types of criteria: weighted criteria (wind speed, slope, proximity to roads and gridlines) and limitations criteria (wind speed, slope, proximity to roads and gridlines) (protected areas, water bodies and rivers, land cover, airport, urban areas, and bird areas). They gathered wind data from ground stations and interpolated it over the areas under consideration. They came up with 377959 km^2 of appropriate land and 530380 km^2 of unsuitable land, respectively. They further analyzed and divided the suitable land into four groups: less suitable (0.42%), suitable (74.77%), very suitable (22.71%), and extremely suitable (2.11%).

Ali et al. [45] explored hybrid MCDM and GIS-based methodologies to investigate the best locations for solar and wind farm installation in Thailand's Songkhla province. To assign weights to the selected twelve sub-factors, they used the AHP technique. Further, they gathered wind speed and GHI data from Thaksin University's wind and solar research units, as well as solargis, with spatial resolutions of 200 m and 1000 m, respectively. They divided the available land area into four categories: highly suitable, moderately suitable, low suitable, and not suitable. Finally, in the province of Songkhla, they got 38.749 km^2 and 69.50 km^2 of highly suitable land area for wind and solar energy installations, respectively.

Sabo et al. [179] identified suitable sites for the installation of solar photovoltaic power plants in Peninsular Malaysia and estimated their technical potential and carbon emission reduction potential. They gathered information from federal organizations, NASA, and Diva GIS firms. They discovered that Johor state has the most ideal sites, accounting for 24.11 percent (601201.63 acres) of the total optimum area. Both Johor and Perak have the capacity to generate power and reduce emissions by 300,000 GWh/yr. and 200,000 kt-CO2/yr., respectively.

In Turkey, Mevlut Uyan [110,180] assessed the most favorable sites for solar farm installation in the provinces of Konya and Karaman. They used the GIS and MCDM techniques to look at economic (distance from transmission lines, distance from highways, and slope) and environmental (land usage, and distance from residential area) considerations. The results were divided into four groups: best suited, suitable, moderate, and low suitable. In the Karaman province, 67598 hectares of land have been recognized as the most appropriate for solar power installation. Similarly, the province of Konya picked 840.07 km^2 as the best suitable land area.

Charabi and Gastli [181] created a terrain suitability index for solar PV and CSP power generation in Oman. They employed a combination of FLOWA (Fuzzy Logic Ordered Weight Averaging), AHP, and GIS. They determined that 0.5 percent of the accessible land is highly appropriate. They also looked into the analysis by evaluating available solar panel technologies and calculating generation potential in terms of (GWh/year) on suitable terrain. They also calculated that CSP technology has a 45.5-fold greater potential than currently present PV technology.

Zoghi et al. [182] optimized the site selection for solar panel installation in the arid and semi-arid areas of Iran's Isfahan province. In their analysis, they used Boolean logic, WLC, MCDM, and GIS technologies. They looked at four criteria: climatic, location, environmental, and geomorphological, as well as their thirteen sub-criteria. They divided the land into four groups: not suitable, good suitability, very good suitability, and excellent suitability, with 11.9%, 8.18%, 76.8%, and 3.12% of the total accessible land falling into each of these categories. The province's eastern, south-eastern, and central regions include the majority of suitable areas.

Tucho et al. [183] assessed Ethiopia's potential for large-scale or grid-connected renewable energy sources. They calculated solar, wind, and hydro energy sources' theoretical, geographical, and final appropriate potential. They calculated the final appropriate potential of solar, wind, and hydro energy to be 7.1, 4, and 143 PWh per year, respectively, using analytical methods.

Castillo et al. [184] suggested a GIS and MCDM strategy to develop a European Union (EU) suitability map for solar PV power systems. Solar radiation, topography, grid electricity network, distance to urban areas, and proximity to highways were used as suitability criteria, while natural and artificial regions were used as limits. They came to the conclusion that there is still a lot of untapped solar energy potential. They also conducted a validation experiment of the European suitability map using existing solar electricity in Europe. They discovered a good match between the European suitability map and current solar farms in their findings.

Christoforaki and Tsoutsos [185] provided an approach for locating offshore wind power installations in a sustainable manner. The researchers devised a three-step process for removing unsuitable locations, assessing environmental concerns, and determining wind energy potential. They gathered information from several federal and international institutions, including wind speed data from the National Observatory of Athens at a 50-meter hub height above sea level. They pinpointed the areas with the strongest winds as well as those with the most carrying capacity. They used the VESTAS V80 – 2.0 MW wind turbine model to calculate a total potential of 490 MW, which is 22.3% greater than previous estimates.

Cevallos-Sierra and Ramos-Martin [186] used a GIS program to identify prospective locations for renewable energy sources in Ecuador. In their analysis, they looked at wind, CSP, and SPV energy sources. They divided the components into evaluation and constraint factors and used the AHP technique to calculate the weights of these variables. Solar energy was discovered to be the most dominant energy source in Ecuador. They chose the Andes Cordillera and Insular parts of the country as the country's solar center.

Dhunny et al. [46] created an analytical methodology for locating economically viable and sustainable sites for the development of solar, wind, and hybrid solar-wind energy facilities. Solar radiation, wind velocity, slope, site elevation, proximity to grid lines, and the existence of settlement areas were all included in the analysis. The maximum site potential for the Le Morne and La Laura-Malenga sites was calculated as 161.58 GWh/year and 281.28 GWh/year, respectively.

Bina et al. [187] proposed a novel comprehensive strategy to evaluate the wind energy potential of three regions in northern Iran, taking into account environmental, economic, and technical factors. Geographic constraints forced the elimination of 36% of the overall area. Further, 9116 km^2 of the total suitable area is occupied by class III large-scale wind farms. The Vestas V47 wind turbine model was used to conduct an economic and exploitable power potential analysis. The System Advisor Model (SAM) software was used to calculate the decrease in CO_2 emissions (M tons) and the levelized energy cost ($/kWh). A total of 11180.17 GWh of yearly energy output capacity has been projected for highly suitable sites. They also projected a 0.15 $/kWh energy cost for eligible sites, which is cheaper than the government's 0.18 $/kWh energy tariff.

In the southeast of Spain, Sanchez-Lozano et al. [142,188] developed a GIS integrated decision support system for selecting suitable sites for solar photovoltaic power plant installation. The criteria weights were calculated using the AHP and ELECTRE-TRI methods. The study considered the environmental (agrological capacity), geomorphological (slope, orientation, and area), location (distance to highways, power lines, settlements, and substations), and climatic factors (solar radiation, temperature) for further analysis purposes. As a result, they categorized the available land area into four categories: poor, good, excellent, and very good.

Using a GIS and MCDM technique, Doorga et al. [189] studied appropriate land for solar photovoltaic power plant installation. They included economic, technical, social, environmental, and legal considerations. The study used Google Earth, GIS, and AHP as well as other approaches and tools. They stated that the northwestern part of the island of Mauritius has the most promise. Cottage, Poudre d'Or, and Roche Terre had the highest potential of 202.9, 202.4, and 201.9 kWh/m2.year, respectively.

Further, on the island of Mauritius, Doorga et al. [190] identified appropriate territory for the installation of solar photovoltaic power plants. They looked at available data (road network, meteorological data, grid network, settlement area, and digital elevation model), derived data (slope, aspect, and shadow zone), and developed data (slope, aspect, and shadow zone) (wildlife, world heritage sites, nature reserves). Here also, the northern region was chosen as a viable possibility. At last, the results were also compared and validated against the PVGIS and Solargis agencies' results.

Previous research has concentrated on both site selection and potential estimation. Aside from that, the current study also addresses the many sorts of potential evaluated by various authors. The following are the highlights.

Zhang et al. [47] calculated China's solar energy potential in terms of geography, technology, and economics. As a result, they found that solar power is extremely suited for 25.19% of the total usable land area. Further, at these suitable sites, the accessible geographical potential ranged from 5400 to 8245.05 Mj/m2. The technical potential was found to be between 0.90 and 479.49 MJ, in addition, the economic potential was found to be between 0.12 and 6.20 $/MJ. Tibet, Xinjiang, Shanxi, Sichuan, Gansu, Fujian, Inner Mongolia, Qinghai, Hebei, Ningxia, Shandong, and Shanxi all have suitable sites for large-scale solar power. Finally, Xinjiang has the most suitable land areas of all these provinces.

Sun et al. [156] developed a comprehensive framework for estimating the solar energy potential of Fujian province in China at the regional level. In the non-built-up area, the study assessed 6511 km2 of the appropriate area and 72 km2 in the built-up area. The study predicted 586 TWh and 6.37 TWh potential in the suitable area for non-built-up and built-up areas, respectively. In the built-up area, the economic potential is 0.17 to 0.27 $/kWh, whereas in the non-built-up area, it is 0.16 to 0.27 $/kWh. In non-built-up areas and built-up areas, solar PV generation power has the potential to reduce CO2 emissions by 3500 million tons per year and 3.8 million tons per year, respectively.

Sun et al. [49] created a multi-phase framework for evaluating suitable sites and estimating the technical power potential for SPV and CSP generation in these suitable locations. The study identified areas of 1940 and 1281 km^2 as being particularly favorable for SPV and CSP power generation, respectively. On these extremely suitable sites, they assessed a technological potential of 443 TWh/year for solar PV and 308 TWh/year for CSP electricity, respectively.

Ermolenko et al. [191] devised a novel method for calculating the renewable energy (solar PV, wind energy) potential across Russia and its 85 regions in relation to oil, coal, and natural gas power resources. The republics of Sakha, Orenburg, Krasnoyarsk, Rostov, Yamalo-Nenets, Volgograd, Chukotka, Sarastov, Krasnodar, Nenets, and Altai have the largest wind energy potential. Certain northern locales, on the other hand, have a larger technical solar energy potential.

Using the GIS tool, Hong and Möller [192] estimated the technical, spatial, and economic potential of China's exclusive economic zone. The provinces of Fujian, Jiangsu, Zhejiang, Shanghai, and northern Guangdong were rated as highly suitable for offshore wind power development in the study. For the years 2010, 2020, and 2030, the study predicted a technological potential of 1715 TWh, 2405 TWh, and 2758 TWh offshore wind electricity, respectively. At an economic potential of 140 €/MWh, 60 to 70% of this technical potential will be available.

For the assessment of Canary Island's techno-economic potential, Schallenberg-Rodrguez and Pino [193] devised a GIS integrated approach. The study took into account a variety of criteria while evaluating potentials, including wind speed, altitude, slope, and protected areas. For the potential assessment, a 2 MW Gamesa G87 wind turbine model with a 12D x 4D array arrangement was chosen. While 12.5% of the overall regional area was designated as very suitable land capable of producing 15,208 GWh of electricity. In addition, the study concluded that the highly suitable sites for onshore wind power generation have an economic potential of 2.6 to 4 c€/kWh.

Kulkarni et al. [194] evaluated the best performing wind farm cluster in Belagavi district of Karnatak state in India based on the MCDM approach. They employed the AHP approach to deal with the decision criteria. The results of the analysis suggested that Chikkodi wind farm cluster was the best performing wind farm, followed by Saundatti, Raibag, and then Belagavi wind farm.

Liu et al. [195] calculated the economic potential of onshore wind generation. For the years 1995 to 2014, they gathered data from the national climate center. The assessment of potentials was done using this data and a 1.5 MW turbine model (GW82-1500). With a feed-in-tariff price of 0.60 yuan per kilowatt-hour, they calculated an annual economic potential of 8.13 PWh. In comparison to a thermal power plant, it can save 6.27 Gt of CO2 per year in terms of environmental potential. The results were tested for robustness using a capacity factor, turbine configuration, and economic parameters.

Polo et al. [196] used ground-measured data, satellite data, and reanalysis data to create solar radiation (direct and global) intensity maps. These solar radiation intensity maps were also used to calculate Vietnam's theoretical and technical solar power potential. For CSP electricity, the study focused on two regions in South Vietnam: the central highlands and the southeast. Whereas, solar PV potential is present throughout the country, including the Mekong River delta, the central highlands, all coastal locations, and the southeast and northeast regions. Finally, the study estimated that CSP and PV power system technologies have potentials of 60-100 GWh/year and 0.8-1.2 GWh/year, respectively.

McKenna et al. [197] calculated Germany's onshore technical wind power potential as well as associated wind power generation costs. According to the research, the 'suitable area' for wind power project installation was 41,623 km^2. Bavaria and Lower Saxony dominated the overall suitable land with a combined share of 38%. The total technological potential of 855 TWh/a has been estimated based on an average LCOE (€/kWh) of 0.081. Lower Saxony and Bavaria, with 167 and 146 TWh/a, respectively, have the largest potential.

Nagababu et al. [198] created a GIS-based methodology for estimating the technical and economic potential of offshore wind power along India's eastern and western coasts. The coastlines of Tamil Nadu and Gujarat, notably on India's eastern and western coasts, were high-potential zones. The study evaluated offshore wind technological power potential in India's eastern and western coasts at 38.7 TWh and 58.4 TWh, respectively. Approximately 40% of these potentials will be available at a cost of 200 €/MWh (feed-in-tariff).

Feng et al. [50] used GIS, wind speed distribution, and wind turbine performance tools and techniques to calculate the technical and net energy onshore potential in China. The research looked at two scenarios: (i) existing agricultural land is not suitable, and (ii) 70% of agricultural land is suitable. After eliminating the restricted lands, the study predicted 4.75 million km^2 and 6.49 million km^2 of appropriate land for scenarios 1 and 2. The study calculated the 2560 TWh and 3501 TWh power potentials for scenarios 1 and 2, respectively, as the technological potential.

Resch et al. [199] calculated the global renewable energy potential while taking into account physical constraints, energy system boundaries, resource limitations, and the corresponding energy policy framework. The study examined the potential for application in the mid-term (2020) and long-term (2030 & 2050). According to the study findings, geothermal energy (140,000,000 EJ) has the highest theoretical potential, followed by solar energy (3,900,000 EJ), ocean energy (7400 EJ), wind energy (6000 EJ), biomass energy (2900 EJ), and hydropower (150 EJ). As a result, the study concluded that the world's theoretical renewable energy potential is 3000 times greater than the global primary energy demand. Even with certain technical constraints or limits, the technical potential is 16 times more than the present global electricity demand.

Dupont et al. [200] evaluated the worldwide wind power potential using a new methodology that included land constraints, kinetic energy limits, wind regimes, and energy return on investment considerations. According to the study, North America, Canada, Argentina and Chile, and Europe have 19.75%, 15.07%, 15.92%, and 15.53% of the global available potential, respectively.

A thorough examination of the above-mentioned literature reveals that only a few authors conducted analyses for their specific regions or provinces. However, there are only a few studies that focus on major countries like India. In addition, there are several opportunities to work for huge countries as well as to further study research for their states and union territories. Furthermore, rather than checking the theoretical potential, it is necessary to verify the economic feasibility and environmental sustainability of the technical potential.

2.3.3 Content Analysis

The following part gathers information on the decision criteria, restrictive criteria, and various potentials calculated in prior studies. In the sections that follow, these factors are briefly explained.

The significant categories and their indicators are important elements for the analysis, as seen in the preceding study. As a result, the current study (Table 2.4) gathered the major categories that had been evaluated in prior investigations.

Table 2.4: Significant categories used in previous studies

S. No.	Authors	Year	Criteria					
			Economic	Technical	Geographical	Enviro	Social	Political
1.	Siyal et al. [155]	2016	√	√	√			
2.	Sun et al. [156]	2013	√	√	√			
3.	Yushchenko et al. [157]	2017	√	√	√			
4.	Hofer et al. [160]	2016	√	√		√	√	√
5.	Garni and Awasthi [161]	2017	√	√				
6.	Tegou et al. [116]	2010	√	√		√	√	
7.	Aydin et al. [41]	2010		√		√		
8.	Aydin et al. [167]	2013	√			√		
9.	Grassi et al. [168]	2012	√	√				
10.	Giamalaki and Tsoutsos [169]	2019	√	√		√	√	
11.	Palmer et al. [171]	2019	√	√	√	√		
12.	Gorsevski et al. [173]	2013	√			√		
13.	Azizkhani et al. [174]	2017	√	√	√			
14.	Sanchez-Lozano et al. [201]	2015						
15.	Ayodele et al. [178]	2018	√	√		√	√	
16.	Mevlut Uyan [110,180]	2013 &2017	√			√		
17.	Tavana et al. [202]	2017	√			√		

Further, the study individually identified the decision criteria, and the MCDM technique utilized in previous studies. In addition, the weights assigned by the authors in prior investigations were also noted in the study. This key information is contained in Table 2.5, which is displayed below.

Table 2.5: Details of criteria and MCDM used in the previous studies

S. No.	Author	Year	MCDM Approach	Criteria and their weights
1	Yushchenko et al. [157]	2017	AHP	Solar irradiance – 46.9% Distance to electricity grid lines – 24.9 % Distance to roads – 14 % Population density – 9.5 % Distance from settlements – 4.7%
2.	Doljak and Stanojevic [158]	2017	AHP	**Climate – 0.648** Global solar radiation (kWh/m2/year) – 0.471 Duration of sunshine (h) – 0.284 Air temperature (degree centigrade) – 0.171 Relative humidity (%) – 0.074 **Orography – 0.230** Slope (%) – 0.667 Aspect – 0.333 **Vegetation – 0.122** NDVI (normalized difference vegetation index) -1.0
3.	Hofer et al. [160]	2016	AHP	Wind energy potential – 21.6 % Distance from natural environments – 20.4 % Distance from urban areas – 18.5 % Distance from electricity grid – 8.0 % Distance from road network – 7.4 % Distance from places of interest – 7.2 % Landscape architecture – 6.2 % Land cover type – 6.0 % Slope of terrain – 4.6 %
4.	Garni and Awasthi [161]	2017	AHP	**Technical** Solar irradiation – 0.350 Air temperature – 0.237 **Economic** Slope – 0.159 Land aspects – 0.106 Proximity to urban areas – 0.032 Proximity to roads – 0.046 Proximity to power lines - 0.070
5.	Tahri et al. [162]	2015	AHP	**Climate** Potential solar radiation – 42% Land surface temperature – 22% **Orography** Slope – 11% Slope orientation – 7% **Location** Distance to road – 6%

S. No.	Author	Year	MCDM Approach	Criteria and their weights
				Distance to urban area – 7% **Land use** Land use – 5%
6.	Villacreses et al. [43]	2017	AHP	**Meteorological – 0.5309** Wind speed – 0.3982 Air density – 0.1327 **Relief – 0.2151** Slope – 0.2151 **Location – 0.2150** Distance to electrical substations – 0.1009 Distance to road network – 0.0432 Distance to transmission lines – 0.0185 Distance to charging ports – 0.0092 **Environmental – 0.0390** Vegetation coverage and land use – 0.0390
7.	Merrouni et al. [118]	2018	AHP	**Climate – 0.590** Global horizontal irradiation(kWh/m2/a) - 0.590 **Orography – 0.235** Slope (%) – 0.235 **Water resources – 0.118** Distance from waterways (km) – 0.0767 Distance from dams (km) – 0.0307 Distance from ground water (km) – 0.0106 **Location – 0.057** Distance from residential (km) – 0.0262 Distance from road and railway network (km) – 0.0182 Distance from electricity grid (km) – 0.0125
8.	Tegou et al. [116]	2010	AHP	**Economic** Land value – 0.025 Distance from electricity grid – 0.145 Distance from road network - 0.145 **Technical** Slope – 0.039 Wind potential – 0.276 **Environmental** Land cover – 0.210 Electricity demand – 0.095 **Social** Visual impact – 0.065
9.	Noorollahi et al. [203]	2016	Weighted Index Overlay (WIO)	Wind speed – 45% Distance to electric power lines – 25% Distances to highways and roads – 30%
10.	Diaz-Cuevas et al. [119]	2018	AHP	Population facilities – 0.07 Electrical network – 0.36 Road network – 0.07 Forest area – 0.17 Slope – 0.30
11.	Giamalaki and	2019	AHP	**Techno-economic scenario**

S. No.	Author	Year	MCDM Approach	Criteria and their weights
	Tsoutsos [169]			Distance from electricity transmission lines – 7% Distance from road network – 8% Slope directions – 10% Slope – 8% Elevation – 9% Solar potential – 7% **Socio-environment scenario** Distance from coastlines – 16% Distance from water bodies – 12% Land cover – 12% Visibility from most visited sites – 9%
12.	Firozjaei et al. [172]	2019	OWA	Slope – 0.14, Distance from city – 0.10, Distance from road – 0.08, NDVI – 0.18, Solar radiation – 0.5
13.	Gorsevski et al. [173]	2013	Borda Count	**Environmental – 0.47** Wind speed – 0.55 Distance to important bird area – 0.19 Land use – 0.26 **Economic – 0.53** Proximity to transportation – 0.29 Proximity to transmission lines – 0.35 Soils – 0.17 Population density – 0.19
14.	Azizkhani et al. [174]	2017	AHP	**Global horizontal irradiation – 0.6078** Diffuse horizontal irradiation (DHI) Direct normal irradiance (DNI) **Economic – 0.0614** Distance to roads Distance to electricity infrastructure **Technical – 0.2084** Geographical (slope, aspect) Wind Temperature **Land use – 0.1223**
15.	Sanchez-Lozano et al. [176]	2016	AHP	Agrological capacity (classes) – 0.0419 Slope (%) – 0.0586 Area (m2) – 0.1271 Field Orientation (classes) – 0.0513 Distance to main roads – 0.0493 Distance to power lines (m) – 0.1449 Distance to cities (m) – 0.1855 Distance to electricity transformer substations (m) – 0.1680 Potential solar radiation (kJ.m2/day) – 0.1195 Average temperature (℃) – 0.05384
16.	Sanchez-Lozano et al. [154]	2017	AHP	Distance to game preserves (m) – 5.25 % Distance to towns or villages (m) – 15.12 % Distance to main roads (m) – 10.11 %

S. No.	Author	Year	MCDM Approach	Criteria and their weights
				Plot area (m2) – 8.73 % Slope (%) – 5.72 % Distance to ecological corridors (m) – 11.49 % Distance to areas contaminated by nitrates (m) – 5.72 % Distance to crops (m) – 10.11 % Desertification risk (Classes) – 10.56 % Level of Protection (Classes) – 17.18 %
17.	Ayodele et al. [178]	2018		Wind Speed (m/s) – 0.4974 (50%) Slope (%) – 0.1681 (17%) Proximity to gridlines (m) - 0.2449 (24%) Proximity to roads (m) – 0.0378 (4%) Proximity to towns (m) – 0.0519 (5%)
18.	Mevlut Uyan [180]	2013	AHP	**Environmental – 0.550** Distance from residential area – 0.250 Land use – 0.750 **Economic factors – 0.450** Distance from roads – 0.071 Slope – 0.180 Distance from transmission lines – 0.748
19.	Mevlut Uyan [110]	2017	AHP	**Environmental – 0.600** Distance from residential area – 0.150 Land use – 0.850 **Economic factors – 0.400** Distance from roads – 0.261 Slope – 0.106 Distance from transmission lines – 0.633
20.	Tavana et al. [202]	2017	Fuzzy AHP	**Economic** Distance from power transmission lines – 0.110 Distance from roads – 0.080 **Environment** Intensity of solar radiation – 0.315 Distance from residential area – 0.185 Access to land – 0.309
21.	Charabi and Gastli [44]	2011	AHP	Solar radiation – 0.545 Constraint layer – 0.287 Distance to major roads – 0.168
22.	Noorollahi et al. [203]	2016	FAHP (super decisions)	**Climatology - 0.346** Solar radiation – 0.275 Average annual temperature – 0.071 **Location – 0.2812** Distance from power transmission lines – 0.112 Distance from residential area – 0.0882 Distance from major roads – 0.081 **Environmental – 0.231** Elevation – 0.081 Slope – 0.08 Land use – 0.07 **Meteorology – 0.1472** Average annual cloudy days – 0.058

S. No.	Author	Year	MCDM Approach	Criteria and their weights
				Average annual humidity - 0.041 Average annual dusty days – 0.0482
23.	Zoghi et al. [182]	2015	AHP	Potential solar radiation – 0.250 Dusty days – 0.053 Total hours of sunshine – 0.19 Total days of snow and rain – 0.091 Humidity – 0.043 Total days of cloud cover – 0.11 Slop – 0.042 Distance from transport network – 0.032 Aspect – 0.066 Distance from power lines – 0.050 Elevation – 0.059 Distance from city – 0.014
24.	Azizi et al. [204]	2014	ANP, ANP-DEMATEL	Wind speed – 0.228 Elevation – 0.021 Wind power density – 0.153 Distance from protected areas – 0.030 Percentage of windy days – 0.144 Distance from main roads – 0.032 Distance from airport – 0.088 Land cover/land use – 0.036 Distance from urban areas – 0.080 Distance from rural areas – 0.038 Distance from fault lines – 0.059 Distance from rivers – 0.039 Slope - 0.052
25.	Aly et al. [113]	2017	AHP	**Solar resources – 69.6** Solar resources – 69.6 **Accessibility – 22.9** Proximity to utility grids – 15.3 Proximity to roads – 7.6 **Demand – 7.5** Proximity to cities 1,00,000 to 2,50,000 – 0.8 Over 2,50,000 – 1.6 Proximity to mines – 5.1
26.	Georgiou and Skarlatos [115]	2016	AHP	Viewshed from primary roads – 0.037 Distance from road network – 0.105 Land value – 0.078 Elevation – 0.052 Distance from electricity grid – 0.133 Solar – 0.545 Slope – 0.051
27.	Baseer et al. [111]	2017	AHP	Wind resource - 60 Buffer from airports – 5.5 Proximity to roads and highways – 7.5 Proximity to settlements – 13.5 Proximity to national electricity grids – 13.5

S. No.	Author	Year	MCDM Approach	Criteria and their weights
28.	Castillo et al. [184]	2016	Based on the literature and experts' opinions	Solar radiation – double weights (2), Proximity to electricity grid – equal weights (1) Proximity to roads – equal weights (1) Topographic parameters (slope elevation, and aspect) – equal weights (1) Population potentially affected – equal weights (1)
29.	Dawod and Mandoer [205]	2016	AHP	**Technical – 60%** Solar radiation – 0.30 Slope – 0.15 Distance from electrical network – 0.15 **Economic – 40%** Distance from roads – 0.10 Distance from coastlines – 0.10 Distance from cities – 0.10 Distance from airports – 0.10
30.	Cevallos-Sierra and Ramos-Martin [186]	2018	AHP	**Wind** Resource potential – 30.57 Visual impact – 4.63 Resource frequency - 25.68 Distance to roads – 9.89 Terrain slope - 4.22 Distance to transmission lines – 8.30 Land cover – 16.71 **Solar PV** Resource potential – 31.48 Resource frequency – 26.51 Distance to roads – 5.16 Terrain slope – 19.88 Distance to transmission lines – 4.94 Land cover – 12.01
31.	Ozdemir and Sahin [170]	2018	AHP	Potential energy production Environmental factors Safety Distance from existing transmission line Topographical properties
32.	Dhunny et al. [46]	2019	Fuzzy logic	Wind speed Solar radiation Slope Settlement areas Proximity to grid lines
33.	Ziuku et al. [206]	2014	AHP	Solar radiation – 50% Land use – 6% Water bodies – 20% Power lines – 4% Land slope – 20%
34.	Sanchez-Lozano et al. [188]	2013	AHP	**Environmental – 5.553%** Agrological capacity – 5.553 **Orographical – 17.259** Land slope – 11.203 Plot areas – 1.241

S. No.	Author	Year	MCDM Approach	Criteria and their weights
				Land orientation – 4.815 **Location – 48.625** distance to power lines – 32.539 distance to villages – 2.849 distance to sub-stations – 8.946 distance to main roads – 4.291 **climate – 28.562** solar irradiation potential – 23.802 average temperature – 4.7604
35.	Sanchez-Lozano et al. [142]	2014	ELECTRE-TRI method using IRIS software	**Climatology** Solar irradiation (kJ/m2day) Average temperature (degree centigrade) **Environment** Agrological capacity (classes) **Location** Distance to electricity transformers (m) Distance to town or villages (m) Distance to main roads (m) Distance to power lines (m) **Orography** Plot area (m2) Slope (%) Orientation (Cardinal points)
36.	Doorga et al. [190]	2019	AHP	**Climatology – 0.581** Global solar radiation – 0.401 Sunshine duration – 0.131 Temperature – 0.033 Relative humidity – 0.016 **Topography – 0.261** Elevation – 0.021 Slope – 0.194 Aspect – 0.046 **Location – 0.158** Proximity to grid – 0.093 Proximity to grid – 0.065
37.	Doorga et al. [189]	2019	AHP	**Climatic – 0.626** PV output – 0.433 Sunshine duration – 0.193 **Topography – 0.255** Slope – 0.166 Aspect – 0.089 **Location – 0.119** Proximity to settlements area – 0.052 Proximity to grid – 0.039 Proximity to road – 0.028
38.	Marques-perez et al. [207]	2020	AHP	Solar radiation – 0.205% Temperature – 0.301% Grid connection – 0.145% Land cover – 0.046% Altitude – 0.102%

S. No.	Author	Year	MCDM Approach	Criteria and their weights
				Accessibility – 0.059% Slope – 0.143%
39.	Ghose et al. [208]	2020	AHP	Global solar radiation – 0.401% Proximity to roads – 0.065% Air temperature – 0.033% Slope – 0.065% Sunshine duration – 0.131% Humidity – 0.194% Proximity to grid – 0.093%
40.	Rediske et al. [209]	2020	AHP	**Climate** Solar radiation – 23% **Environmental** Land use – 13% Agrological capacity - 16% **Geomorphological** Slope – 10% **Localization** Distance from urban area – 4% Distance from substations – 27% Distance from roads – 7%
41.	Potic et al. [210]	2021	AHP	Wind power density – 20% Annual energy output – 30% Wind power output – 30% Grade (degree) – 3% Distance to the road – 4% Distance to an urban areas – 7% Pasture – 6%
42.	Haddad et al. [211]	2021	AHP	Direct normal irradiance – 27.05% Distance to electricity grid network – 23% Distance to high population density – 22.95% Distance from waterbodies – 12.51% Slope – 5.48% Distance to roads and railways – 5.31% Slope orientation – 3.70%
43.	Adedeji et al. [212]	2021	AHP	Wind speed – 22.70% Distance to urban area – 9.60% Distance to power lines – 15.40% Distance to aerodromes and airports - 13.70% Distance to waterbodies – 10.10% Distance to wet lands – 8.20% Distance to major roads – 8.10% Distane to the railway – 8% Elevation – 4.20%

From the in-depth analysis of the above literature, it is concluded that the potential site should be selected by considering the technical factors on priority while striking a balance between the remaining factors of environmental, economic, and social. Afterward, discussing the decision criteria used in previous studies, it is also essential to discuss the restrictive and decision criteria with their classification scale. Therefore, all these essential details are summarized in Table 2.6.

Table 2.6: Details regarding the restrictive and decision criteria and its classification scale

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
1.	Yushchenko et al. [157], 2017, Solar PV and CSP	Urban Settlements, Land cover (built-up area, agricultural zones, forests, wetlands, and water bodies) Risk areas (flood zones) Protected areas Land slope (5.71 for PV, 1.15 for CSP) Population density (> 500 inhabitants/km^2)	**Solar irradiance** GHI Less suitable - < 1800 kWh/m2/year Moderately – 1800-2100 Suitable- 2100-2300 Best suitable- >2300 DNI Less suitable - < 1800 kWh/m2/year Moderately – 1800-2300 Suitable – 2300-2700 Best suitable- > 2700 **Distance to electricity grid** Less suitable - > 30 km Moderately – 5-30 Suitable- 1-5 Best suitable- < 1 km **Distance to roads** Less suitable - > 5 km Moderately – 3-5 km Suitable- 1-3 km Best suitable- < 1 km **Population density** Less suitable - > 500 inhabitants/km2 Moderately – 100-500 Suitable- 1-100 Best suitable- 0 inhabitants/km2 **Distance from settlements** Optimize distance from urban settlements (> 10,000 inhabitants/km2) Less suitable - < 1 km Moderately – 1-2 km Suitable- 2-5 km Best suitable- > 5
2.	Hofer et al. [160], 2016, Wind turbines		**Wind energy potential** (< 6 m/s) **Urban areas (residential area** – 550 m, mixed-use area – 400 m) **Infrastructure** – roads, highways (20 m from rotor tip blade), railroads (at least 100 m away), transmission lines (100 m) **Natural environmental** – natural resource area, national parks, FFH areas, a bird reserve, protected biotopes, natural monuments, water bodies **The slope of terrain (> 30 %)** **Land cover type** – deciduous wood,

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
			experimental woodland, natural forest cells, seed area in forests
3.	Tahri et al. [162], 2015, Solar energy	Agricultural land, urban and protected areas, lakes, and land used to build infrastructure and facilities	**Climate** Potential solar radiation – 741-1414, 1414-1563, 1563-1640, 1640-1717, 1717-1967 kWh/m2/year Land surface temperature – 0-15, 15-30, 30-45, >45 ° **Orography** Slope – 0-4, 4-8, 8-12, 12-24, >24% Slope orientation – south, south-east, south-west, west, north-east, north-west, north **Location** Distance to road – 1.4-3, 3-5, 5-10, >10 km Distance to urban area – 0-1.5, 1.5-3, 3-5, 5-10, >10 km **Land use** Land use – area without vegetation
4.	Villacreses et al. [43], 2017, Wind farms	Urban areas Flood areas Volcanic hazard Airports National system of protected areas Mangroves Archeology	Urban areas – 3000 m of the security area Flood areas – completely restricted area Volcanic hazard – completely restricted area Airports - 2500 m away from the airport National system of protected areas – 250 m from an ecological sensitive area Mangroves – 4000 m from water bodies Archeology – completely restricted area Wind velocity – exclude ≤ 5 m/s at 80 m height Slope - exclude > 15%
5.	Merrouni et al. [163], 2014, CSP	All vegetation, watersheds, roads network, the power grid, and the delimitations of the cities	Annual direct solar radiation – exclude < 1750 kWh/m^2 Roads – exclude with a buffer of 500 m Railways - exclude with a buffer of 500 m Power grid – exclude Cities – exclude Vegetation – exclude Dams – exclude Waterways – exclude with a buffer of 500 m Slopes – exclude > 2%
6.	Merrouni et al. [164], 2016, Solar PV		**Infrastructure Layer - completely exclude** National roads, regional roads, provincial roads, high way, railways, power grid **Vegetation layer – completely exclude** Natural forests, protected areas, reforestation **Slopes – excluded > 5%** Land

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
			Hydrology layer - completely exclude Permanent waterways, non-permanent waterways, and Dams
7.	Merrouni et al. [118], 2018, Solar PV	Mountains, Forest, City, Waterways,	Completely excluded Mountains, Forest, City, Waterways, 100 m from the road and railways network, A buffer of 500 m from vegetation and protected areas, A buffer of 500 m from hydrology (dams and waterways), A buffer of 5 km and 2 km from a residential area in big and small cities respectively. Slope (%) – exclude > 5% GHI – exclude < 1816 kWh/m2/a Distance from electricity grid – exclude > 10 km
8.	Merrouni et al. [117], 2018, CSP		Buffer of rail and road network – 100 m Completely excluded Mountains, Forest, City, Waterways, A buffer of 500 m from vegetation and protected areas, A buffer of 500 m from hydrology (dams and waterways), A buffer of 5 km and 2 km from residential area in big and small cities respectively. DNI – excluded < 1800 kWh/m2/a Slope – excluded > 2.1%
9.	Tegou et al. [116], 2010, Wind Energy		Petrified forest Wetlands NATURA 2000 Land of high productivity Slope angles – excludes > 30% Settlements Distance from settlements, traditional < 1500 m, significant < 1000 m, other < 500 m Archaeological sites Distance from archaeological sites < 500 m Distance from monasteries < 500 m Distance from road network > 10,000 m Airports Wind potential < 4 m/s **A buffer of 100 m from electricity grid and road networks**
10.	Noorollahi et al. [165], 2016, Wind Energy		**Environmental** Residential area – cities excludes < 2000 m, Villages < 500 m Highway and roads – area in distance < 500

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
			m Railway - < 300 m Airports – military airport < 15,000 m - Commercial airport < 2500 m Electric power line - < 250 m Ancient and cultural monuments - < 700 m River - < 500 m Coast lines and wetlands - < 500 m Environmental protected areas - < 2000 m Lakes and water bodies - < 1000 m Faults - < 500 m **Physiographic** Digital elevation model – area with elevation > 2000 m Slope – area with slope of > 15%
11.	Wang et al. [166], 2016, Solar PV	Solar radiation Distance from the electricity grid	The slope should be less than 5 degrees. The altitude should be less than 5000 m. Land cover to be grassland or desert.
12.	Aydin et al. [41], 2010, Wind Energy		**Acceptable in terms of natural reserves** Distance to natural reserves – exclude < 300 m from the ecologically sensitive area, water bodies, and area of ecological value **Acceptable in terms of safety and aesthetics** Large city center - < 1000 m Town center - < 2000 m Airport - < 3000 m **Acceptable in terms of noise** Nearest settlement - < 400 m **Acceptable in terms of bird habitat** Nearest lake and wetlands - < 2500 m **Sufficient potential for wind energy generation** Wind power values at a height of 50 m – exclude < 200 W/m2
13.	Phadke et al. [213], 2011, Wind turbines	Wind power density – exclude < 200 W/m2	Terrain slope - exclude > 20% Elevation - > 1500 m Protected areas – 100% Water bodies - 100% Urban areas - 100% Forests - 100% Snow/ice - 100% Grassland - 100% **Baren land – 0 %** **Grassland/cultivated land – 0 %** Farmland – sensitivity
14.	Grassi et al. [168], 2012, Wind energy		Forests – 300 m Governmental lands – 600 m Native American reserves – 300 m Major roads – 240 m

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
			Minor roads – 60 m Protected areas – 300 m Railroads – 150 m Airports – 2000 m Settlements and farms – 240 m Slope > 20% - 100% exclusion Water bodies – 240 m
15.	Palmer et al. [171], 2019, Solar Energy	Solar energy resources, Distance to grid connection points, Slopes	Exclude Solar yield > 210Wh/m^2, national parks, urban areas, woods areas, moors, mountains, land in flood zones over 40 km^2, and agriculture land grades 1, 2, and 3.
16.	Azizkhani et al. [174], 2017, Solar Energy	The lakes, embayment, and bog	Slopes (tilt angle) degree 1-9 = score 8 9-18 = 9, 18-27 = 10, 27-36 = 10, 36-45 = 10, 45-54 = 9, 54-63 = 8, 63-72 = 7, 72-81 = 5, 81-90 = 5 Slope directions (aspect) Flat – 10, north – 0, northeast – 3, northwest – 3, west – 5, east – 5, southeast – 7, southwest – 7, south – 10
17.	Sabo et al. [179], 2016, SPV		Elevation - < = 60 m Slope - < 5 degree water bodies, environmentally sensitive areas, developed urban areas, vulnerable areas like flood plains, landslides areas – completely excluded roads and highways - > 500m and < 10,000 m grid lines - > 500m and < 10,000 m land requirement - >= 165 acre for 50 MW SPV
18.	Charabi and Gastli [44], 2011, Solar Energy (PV & CSP)	Dams, rivers, flood area, land use, sand dunes, roads, village boundary, slope (> 5 degrees), tourist monuments, and historical places.	
19.	Tsoutsos et al. [214], 2015, Wind farms		**Buffer land** Special protection area of bird habitat – 1500 m From areas of cultural heritage – at least 500 m **From urban activities** Towns and settlements with population more than 2000 inhabitants – 1000 m Traditional settlements – 1500 m Rest settlements – 500 m Monasteries – 500 m Main roads and transport network – 120 m

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
			High voltage lines, antennas, radars – 120 m Rural lands – 120 m Aquaculture – 120 m livestock plants – 120 m mining zones and activities – 500 m tourist and productive areas – 1000 m
20.	Noorollahi et al. [203], 2016, Solar farms	**Exclusion limits** Solar radiation - ≤ 1300 kWh/m2/year Distance from power transmission lines - ≥ 50 km Distance from the residential area – 45 ≤ city ≤ 2 km 45 ≤ village ≤ 0.5 km Distance from major roads – 0.1 ≤ roads ≤ 50 **Environmental** Elevation - ≥ 2200 m Slope - > 11% Land use – forest and agriculture land **Restricted Criteria** Protected area - ≤ 2 km Lake and water bodies - ≤ 1 km Fault unsuitable - ≤0.5 km	**Solar radiation** 1300-1700, 1700-1900, 1900-2000, 2000-2100, >2100 **Temperature** 24-25, 25-26, 26-27, 27-28, >28 **Power transmission lines** 20-50, 15-20, 10-15, 5-10, 0-5 **Roads** 30-50, 20-30, 10-20, 5-10, 0-5 **Residential area** 30-45, 20-30, 15-20, 10-15, 3-10 **Elevation** 0-200, 200-450, 450-750, 750-1200, 1200-2200 **Slope** <1, 1-2, 2-3, 3-4, 4-11 **Land use** Barren, rangeland, Shrub, rainfed land, irrigated land, **Cloudy days** 170-120, 120-80, 80-50, 50-30, 30-12, **Humidity** 83-60, 60-50, 42-50, 42-35, 35-26 **Dusty days** >120, 120-70, 70-50, 50-30, <30
21.	Zoghi et al. [182], 2015, Solar panels	Buffer areas Urban – 500 m Transport network – 250 m Protected areas – 1000 m Wetlands – 500 m Water resources and dense forest – complete exclude	Potential solar radiation $8x10^5$ to $1.5x10^6$ wh/m2/year Dusty days - 20 to 50 days Total hours of sunshine - 2500 to 3500 Total days of snow and rain - 40 to 60 days Humidity - 30 to 50% Total days of cloud cover - 20 to 50 days Slop - 3, 10, 20, and 100% Distance from transport network - 20 to 200 km Aspect - N,NE S,F SE,SW,W E,NE Distance from power lines - 500 m, 10, 15, 60 km Elevation - 500, 1500, 2000, 4500 Distance from city - 15 to 350 km
22.	Azizi et al. [204], 2014, Wind power plants	Buffer zones Main roads – 0.5 km River – 0.4 km	

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
		Urban areas – 2 km Rural areas – 0.5 km Airport – 3 km Reservation areas – complete exclude	
23.	Aly et al. [113], 2017, PV & CSP		**Annual GHI (kWh/m^2)** 2250-2300 value-100, 2200-2250 = 95, 2150-2200 = 90, 2100-2150 = 85, 2050-2100 = 80, 2000-2050 = 75, 1950-2000 = 70, 1900-1950 = 65, 1850-1900 = 60, 1800-1850 = 40, 1750-1800 = 30, 1700-1750 = 20 **Proximity to water resources** 0-3 = 100, 3-5 = 80, 5-7 = 70, 7-9 = 60, More than 9 km = 0 **Proximity to roads** 0-5 = 100, 5-10 = 80, 10-15 = 60, 15-20 = 40, More than 20 km = 0 **Proximity to utility grid** 0-5 = 100, 5-10 = 90, 10-15 = 80, 15-20 = 70, 20-25 = 60, 25-30 = 50, 30-40 = 40, 40-50 = 30, More than 50 km = 0 **Proximity to cities with over 2,50,000 inhabitants** 8-15 = 100, 15-25 = 70, 25-35 = 60, 35-45 = 40, More than 45 km = 0 **Proximity to cities with 1,00,000 to 2,50,000 inhabitants** 6-10 = 100, 10-15 = 80, 15-20 = 70, 20-25 = 50, 25-30 = 40, More than 30 km = 0 **Proximity to mines** 0-5 = 100, 5-10 = 80, 10-15 = 40, more than 15 km = 0
24.	Georgiou and Skarlatos [115], 2016, Solar photovoltaics		**Buffer zones** Primary and secondary roads – 50 m Urban zones, national forest, and natura 2000 – 200 m Airport – 2000 m Shoreline – 200 m Surface waters – 100 m Archaeological sites – 200 m Areas with aspect – north, west, east, northwest, and northeast High vegetation – complete exclude Slope > 45 degree Road >2500 m Electricity grid > 2000 m
25.	Castillo et al. [184], 2016, Solar PV	Water bodies, wetlands, forest, built-up areas, natural areas, protected areas, and	Excluded Solar radiation < 900 kWh/m2 Slope – 16 to 30 degree poor, > 30 –

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
		sensitive areas	unviable, Population - > 500m from cities and residential area are more suitable Transportation network - > 5000 m unfeasible locations
26.	Siyal et al. [215], 2015, Wind Turbines	National roads Railroads Electricity grids Airports Military zones Lakes, watercourses and shorelines Urban areas Single residential houses and churches Protected areas Areas of national interest for nature, culture and recreation values	Excluded High elevation areas > 2000 m Steep slope areas > 15 degree Buffer zones National roads – 200 m Railroads - 200 m Electricity grids – 200 m Airports – 2500 Lakes, watercourses and shorelines - 100 m Urban areas – 1000 m Single residential houses and churches – 500 m
27.	Argin et al. [216], 2019, Wind Energy	Mean wind speed at height of 50 m/s and 150 m/s	Territorial waters Military zone Civil aviation Shipping routes Pipelines Social concerns Environmental concerns
28.	Cevallos-Sierra and Ramos-Martin [186], 2018, Wind, CSP, and SPV	Resource potential and frequency National parks Wetlands Distance to urban settlements Altitude Distance to roads Terrain slope Distance to transmission lines	CSP Resources < 3.5 = 0, 3.5-4 = 3, 4-4.5 = 6, 4.5-5 = 8, > 5 = 10 SPV Resources < 3.8 = 0, 3.8-4 = 4, 4-4.5 = 6, 4.5-5 = 8, > 5 = 10 Wind speed ≤2 = 0, 3=1, 4=2, 5=3, 6=4, 7=5, 8=6, 9=7, 10=8, 11=9, 12=10, >13=10
29.	Ziuku et al. [206], 2014, CSP	Exclusion based on the Direct normal irradiance Proximity to transmission lines, Water bodies, Flatness of the area, Vulnerability of vegetation and wildlife	
30.	Sanchez-Lozano et al. [188], 2013, Solar photovoltaic	Mountains, Community interest sites, Areas of bird special protection Watercourses and streams, Archeological sites, Paleontological sites,	

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
		Cultural heritage, Cattle trails, Military zones Infrastructure	
31.	Sanchez-Lozano et al. [142], 2014, Solar photovoltaics	Urban lands, Community interest sites Protected and undeveloped land, Roads and railroad network, Areas of high landscape areas, Cultural heritage, Water infrastructure, Military zones, Paleontological sites, Watercourses and streams, Archaeological sites	
32.	Deng et al. [217], 2015, Solar PV, CSP, Wind		**Exclusion of Antarctica** Elevation wind > 2000 m Land cover – urban areas, forests, ice, water, coast, cliffs, dune, rock Protected areas Slope – PV and wind – 15 degree (27%) CSP – 2 degree (4%) Resource intensity – solar CSP < 1900 kWh/m2/a PV – 800 kWh/m2/a Wind - < 6 m/s **Sea based** Ocean floor depth - > 50 m ocean depth Distance from shore - > 200 km Maritime use Cut off wind speed - < 8 m/s
33.	Doorga et al. [190], 2019, Solar photovoltaic	World heritage sites, Major settlement areas Native vegetation and wildlife Permanent water bodies Religious and tourist sites Airports	
34.	Doorga et al. [189], 2019, Solar photovoltaic	World heritage sites Natural reserves Wildlife	
35.	Shao et al. [218], 2020, Renewable sources	Water bodies, archaeological sites, urban areas, railroads, vegetation, paleontological sites, military zones, forests, cultural heritage, and watercourses	
36.	Karipoglu et al. [219], 2021, Wind Energy	Spatial constraint and Agriculture regions are completely excluded.	Higher than 3 km from bird migration paths Higher than 5 km from military regions Higher than 3 km airports Higher than 5 km from designated areas

S. No.	Authors, Year, Source	Restriction or exclusion criteria	Classification scale of criteria and considered buffers
			Higher than 0.1 km roads Higher than 3 km from urban areas Higher than 0 to 5 km from energy transmission lines

The thorough examination of the table above will aid in the definition of decision and restrictive criteria, as well as their classification ranges. The variety of restricted criteria and buffer zones will be useful in future investigations.

Until far, the study had only covered the most important aspect in determining suitable sites for the development of solar and wind power projects. The research will now evaluate the different types of potentials calculated on these highly suitable sites. Table 2.7 summarizes the key points concerning the various potentials. In addition, a brief explanation of these potentials is summarized in Appendix-II.

Table 2.7: Potential investigated in various studies

Authors	Year	Country	Energy sources	Potentials									
				Theoretical or total	Geographical	Technical	Techno-economic	Practical	Realizable	Economic	Market	Net potential	Environmental
J.P. Painuly [220]	2001	Denmark	RES			√	√			√			
Harald Winkler [221]	2005	South Africa	RES	√						√			
Yue and Wang [222]	2006	Taiwan	RES (Wind, photovoltaic, biomass)			√							
Dudhani et al. [223]	2006	India	Small hydro power			√							
Šúri et al. [48]	2007	European Union	Solar Energy	√									
Vries et al. [224]	2007	Global level	Wind, solar, biomass		√	√				√			
Ozturk et al. [225]	2007	Turkey	RES (solar, wind, hydro, geothermal, biomass)			√				√			
A. Stangeland [226]	2007	Global	RES	√		√		√	√				
Hoogwijk and Graus [227]	2008	Global	RES	√	√	√				√	√		

Authors	Year	Country	Energy sources	Potentials									
				Theoretical or total	Geographical	Technical	Techno-economic	Practical	Realizable	Economic	Market	Net potential	Environmental
Nouni et al. [228]	2008	India	SPV, wind, and hydro power		√								
Thompson and Duggirala [229]	2009	Canada	Solar, wind, and biomass	√									
Fthenakis et al. [230]	2009	US	Solar energy		√	√				√			
Chen et al. [231]	2010	Taiwan	RES (solar, wind, hydro, biomass, geothermal, ocean)	√		√							
Mondal and Denich [232]	2010	Banglades h	Solar, wind, biomass, hydro	√		√				√			
Liu et al. [233]	2011	China	RES (solar, wind, hydro, biomass etc.)	√									
Angelis-Dimakis et al. [234]	2011	EU and US	RES (solar, wind, biomass, geothermal, biomass)	√		√				√			
Castro et al. [235]	2011	Global	Wind power	√	√	√				√		√	
Hong and Möller [192]	2011	China	Offshore wind energy			√				√			
Hubert and Vidalenca [236]	2012	France	RES (solar, wind, biomass, hydro, geothermal)		√	√							
Rumbayan et al. [237]	2012	Indonesia	Solar energy							√	√		
Sun et al. [156]	2013	China	Solar PV (roof top and utility scale)		√	√				√			
Farooq and Kumar [238]	2013	Pakistan	RES (solar, wind, biomass, small hydro)	√	√	√	√			√	√		
Diaf et al. [239]	2013	Adrar in Southern Algeria	Wind power	√		√				√			
Purohit et al. [240]	2013	Northwest ern India	CSP	√		√				√			
Chandel et	2014	India	Wind power	√									

Authors	Year	Country	Energy sources	Potentials									
				Theoretical or total	Geographical	Technical	Techno-economic	Practical	Realizable	Economic	Market	Net potential	Environmental
al. [241]		(western Himalayan region)											
McKenna et al. [197]	2014	Germany	Onshore wind energy		√	√				√			
Polo et al. [196]	2015	Vietnam	Solar power (SPV and CSP)	√		√							
Grigoras and Scarlatache [242]	2015	Romania	RES (wind, SPV, hydro, biomass, biogas, cogeneration	√		√				√	√		
Liu et al. [195]	2017	China	Onshore wind energy			√				√			√
Nagababu et al. [198]	2017	India	Off-shore wind energy			√				√			
Yushchenko et al. [157]	2018	West African countries	Solar PV and CSP		√	√							
Ghasemi et al. [51]	2019	Iran	Solar energy	√		√				√			
Santos et al. [243]	2020	Brazil	Solar and wind		√	√				√			
Almutairi et al. [244]	2021	Afghanistan	Wind energy			√				√			√

A thorough examination of the preceding literature reveals that the authors calculated the potential of one or two categories without establishing a sequential relationship between them. Therefore, there is a pressing need to organize potential in a logical order, take into account various constraints and limitations, compute various potentials, and analyze their economic viability and environmental sustainability.

2.4 CRITICAL OBSERVATION AND RESEARCH GAPS

Some of the significant observations and research gaps are identified after a systematic review of collected literature:

- Following the previous studies, it is observed that research publications employ indicators depending on existing literature or their own needs; for example, many articles solely consider economic, technical, and environmental factors. On the other hand, the sustainability aspect cannot be fully realized without taking into account factors such as the government's political will and the social acceptance of local people. As a result, there is a pressing need to consider and develop indicators for completely assessing the sustainability of energy sources in the Indian context [36–38,84,86].

- There are very few articles in previous research that analyzed the overall energy sector covering the sustainability aspect, instead only focusing on renewable or conventional energy sources with one or two factors. As a result, in order to fill this research gap, the goal of the present study is to analyse major energy sources (thermal, gas power, solar, wind, hydro, nuclear, and biomass) that contribute to India's overall energy production covering the entire sustainability aspects. Simultaneously, the goal of the study is to develop an optimal energy mix scenario for India using sustainable energy sources for the year 2030 [27,42–44].
- Decisions regarding the evaluation of the most sustainable alternative energy sources in India are crucial and complex due to multi-aspect problems. From the survey of the literature, it is clear that very few studies are available from the Indian context and that the evaluation of various alternatives is based on limited and non-validated criteria [34,223,240,245,246].
- In the previous literature, studies are available on the analysis of a few select sites, regions, or some parts of the state of large countries like India. As a result, there is a need to analyse potential areas in India as a whole country for the installation of sustainable energy projects [45,47,113,180].
- The majority of the previous articles assessed the potential on the entire land area of the region or country, without taking into account geographical constraints or theoretical limitations. In this case, the capacity cannot be calculated as accurately as it should be. As a result, there is a pressing need of present and future to a very precise assessment of the potential with only highly suitable sites being considered, taking into account geographical constraints, theoretical limitations, and technical losses [112,247,248].
- From the aforementioned literature, it appears that just a few papers have validated the available potential while taking economic and environmental factors into account. It is critical that the potential be made available at a low cost without causing harm to the environment. As a result, there is a pressing need to examine the available potential's economic viability and environmental sustainability. In addition, the study conducted a first-of-its-kind case study to evaluate the project's technical viability, economic feasibility, and environmental sustainability [237,242,244].

2.5 SUMMARY

This chapter contains a systematic literature review of 302 articles on energy sustainability and sustainable energy. In addition, the literature's descriptive, comprehensive, and content analysis have been offered. The study followed the evolution of energy source evaluations with needed indicators, potential site evaluations, exploitable power potential, different research approaches used, and study emphasis areas.

CHAPTER – 3

EMPIRICAL INVESTIGATION AND VALIDATION OF SUSTAINABILITY INDICATORS FOR THE ASSESSMENT OF ENERGY SOURCES

The present chapter compiles available sustainability indicators and empirically investigates their significance in the Indian geographical region. Furthermore, the survey's findings are also statistically validated.

3.1 INTRODUCTION

To address and analyse the different issues of various regions of the country, a standard set of national-level sustainability indicators are required. To evaluate sustainable energy sources in the Indian continent, some indicators from the Indian context are required. Few indices in the available literature have attempted to understand the energy sustainability aspect of India. Singh et al. [245] provided an overview of indices for market and economy, investment ratings and asset management, product-based sustainability, environment indices for policies, industries, regions, and nations. Mainali et al. [246] developed a method to assess the energy sustainability of rural households in developing countries. Sustainability was analyzed with thirteen indicators of technical, economic, social, and environmental dimensions. Kwatra et al. [33] measured the sustainability development index for different union territories and states of India. The measurement proceeded with nineteen indicators of the economy, environment, and social group. They observed that smaller administrative areas with higher income have higher sustainability values. Narula et al. [34] assessed the sustainable energy security index for India. They did an analysis using eight energy sources and sixteen sustainability indicators according to acceptability, affordability, availability, and efficiency. Sharma and Balachandra [32] developed a multidimensional framework to evaluate the Indian electricity system using national-level indicators with the best values available from the global world.

Despite various authors who explored the different types of indicators for the analysis of the sustainability concept of the Indian energy and economy sector, however, the available indicators of the above studies were not able to evaluate the sustainability concept of the Indian energy sector because, many of them measured the sustainability through one or more sustainability categories of economic, environmental, and social. Additionally, most of the studies are from out of India and they considered the indicators according to their respective countries. Therefore, there arouse a need to identify and validate the sustainability indicators of India which cover all aspects from cradle to grave, and also provide a baseline to the policy drafters and decision-makers of the country to improve the sustainability of the Indian energy sector. To fill the research gap, the objectives of the present research chapter are as follows: -

- To identify and evaluate the sustainability indicators from an Indian perspective.
- To empirically and statistically validate the results of the survey.

3.2 REVIEW OF EXISTING INDICATORS

An extensive literature review was carried out to identify the indicators required for the assessment of sustainable energy sources. The literature review covers the extensive literature of the last twenty years. A review of the literature shows the indicators used in different countries to analyze renewable and non-renewable energy sources such as Colak and Kaya [52] prioritized the renewable energy sources in Turkey using the factors of sustainability, durability, and distance to the user, affordability, and labor impact. Kaya and Kahraman [35] developed a methodology using efficiency, energy, investment cost, O & M cost, land use, CO_2 emission, NOx emission, job creation, and social acceptability factors for the selection of the best energy technology in Turkey. Haddad et al. [37] included factors of energy production capacity, life service, payback period, and potential for reduction of greenhouse gases, to choose an appropriate energy source for the Algerian electricity system. Sengul et al. [53] developed a multi-dimensional framework using factors of installed capacity, amount of energy produced, payback period, the value of CO_2 emission, etc. to rank different renewable energy supply systems. Lee and Chang [36] carried out the research work based on the criteria of economic (investment cost, O & M cost, electric cost), technical (efficiency, technical maturity, and capacity factor), environmental (greenhouse gases emission, land use), and social (social acceptance, job creation), for the evaluation of renewable energy sources in the country of Taiwan. Streimikience et al. [54] considered both qualitative and quantitative factors of energy viz. price, technology reliability, treat of waste compliances with natural resources, technology autonomy, influence on sustainable development of society, etc. for the selection of the best energy technology in Lithuania. Vafaeipour et al. [42] considered net present values, land availability, transmission grid availability, and risk factors for the selection of suitable locations to install solar power plants in Iran. Kabak and Dagdeviren [55] employed hybrid benefits (preservation of the environment), opportunities (decrease dependency on the imported fuels, decrease energy prices), costs (land cost, ecological damage), risks (social resistance, dependency on the foreign technology), then analytical network process (ANP) approach was adopted to analyze the renewable energy sources in Turkey. Brand and Missaoui [56] selected the suitable energy combination in Tunisia through the factors of local manufacturing share, response to peak load events, average jobs created, and emission of gases and solid waste. Streimikiene et al. [39] did an analysis of the sustainable electricity sector with the sub-criterion of security of supply, peak load response, severe and fatal accidents, pertaining to economic, environmental, and social dimensions. Buyukozkan and Guleryuz [57] proposed an integrated decision making trial and evaluation laboratory (DEMATEL)-ANP approach to evaluate the renewable energy sources in Turkey covering the aspects of reliability, resource availability, technology maturity, research & development cost, return on investment, foreign dependency, and compatibility with national, public, and financial supports. Boran [58] evaluated renewable energy sources for the climatic conditions of Turkey using criteria of sustainability and predictability of sources, environmental impacts, economic potential, incentives and subventions, generation cost per unit, and the reaction of local, non-governmental organizations. Wang et al. [59] made a group of eight experts identify the most preferred energy alternatives in China through fulfilling the aspects of sustaining time by exploitable and proved reserves, industrial added value, and easiness in importing. Jha and Puppala [83] calculated the energy index for the renewable energy sources of India covering environmental and techno-economic aspects. They did an analysis using a criterion of land requirement, turnkey investment, future energy cost, design period, water requirement, and emission of CO_2, SO_2, and NOx emission. Garni et al. [40] considered the criterion of resource availability, ease of decentralization, national economic development, impact on emission level, and maintaining energy leading position for sustainable development of electricity production sector of a developed country of Saudi Arabia. Ahmad and Tahar [61] employed the analytical hierarchy process (AHP), a multi-criteria decision making (MCDM) approach to identify the best renewable energy source for electricity generation in Malaysia through pairwise comparisons among the criteria of lead time, maturity, resource potential, feed-in tariff rate, impact on the environment, and public acceptance. Tasri and susilawati [38] developed a selection methodology using factors of sustainability, durability, distance to the user, economic value, local technical knowledge, government policy, and the requirement for waste disposal, to determine the most appropriate renewable energy source for the Indonesian electricity system. Stein [62] employed the MCDM approach to analyze the renewable and non-renewable energy electricity generation technologies in the United States by employing the factors of production efficiency, fixed and variable O & M cost, loss of life expectancy, fuel reserve years, and net import as percentage of consumption. Ishfaq et al. [68] found the optimum source of renewable energy alternatives to meet the rising energy demand of Pakistan. They included the factors of initial cost, O & M cost, environmental effects, efficiency, expected life, and power production capacity, these factors pertaining to groups of economic, environmental, and technical. Ghenai et al. [1] assessed the sustainability indicators of renewable energy sources using extended step-wise weight assessment ratio analysis (SWARA) and additive ratio assessment (ARAS) MCDM approaches in the United Arab. They considered the factors of the capital intensity of fuel and construction, growth rate, CO_2 emission intensity, and energy intensity. Similarly, Doukas et al. [69] included the factors of economic viability using payback period, continuity and predictability, knowledge of innovative technology, contribution to energy dependency, and climate change, for the country of Greece. Evans et al. [30] and Onat and Bayar [31] reviewed the sustainability indicators of the energy sector. They considered the indicators of unit energy cost, availability, efficiency, CO_2 emission, land use, social impacts, and freshwater consumption. From the above literature studies, it is clear that the majority of studies are from European countries and/or developed countries. Very few studies are reported to avail the effective indicators for the sustainability assessment of the Indian energy sector. Nevertheless, these studies also lack in considering the comprehensive approach for the identification and validation of sustainability indicators, which will be suitable for the assessment of energy sources in India.

To bridge the research gap, in the present study, various indicators were explored from the available literature. A total of 93 sustainability indicators subjected to 15 sustainability dimensions are identified from the literature review and expert discussions. Table 3.1 below shows the details of identified indicators with their classifications. A research methodology has been developed for the empirical validation of proposed indicators. The following section discussed the research methodology followed by the ‘Results and Discussion’ section.

Table 3.1: Sustainability indicators with their nomenclature and citations

Criteria	Sub-Criteria	Nomenclature	References
Economic (EC)	Capital Cost/ Investment Cost	**EC1**	[36–40,42,53,57,60,62,63,65,66,68–70,74–76,78,79,81,84,86,92,249–252]
	Operation & Maintenance Cost	**EC2**	[12–14,16,19,20,24,27,28, 33,35,36,41–46,48–53]
	Research & Development Cost	**EC3**	[57]
	Payback period	**EC4**	[37,42,53,57,69,71,79,91,254]
	Levelized Cost of Electricity (electricity cost per unit)	**EC5**	[5,13–15,18,20,23–25,30–32, 46,48,49,55–57]
	Useful/operational Life	**EC6**	[37,53,61,66–68,71,76,83,250]
	Fuel Cost	**EC7**	[39,53,62,71,75,78,92]
	Market Maturity	**EC8**	[79]
	Site Advantage	**EC9**	[102]
	Availability of Funds/Incentives	**EC10**	[58,74,84,86,250]
	Future Potential Energy Cost	**EC11**	[58,73,83]
	Technology Cost	**EC12**	[32,61,74]
Technical (TE)	Technology Maturity	**TE1**	[36,37,40,53,57,58,61,73,74,79,92]
	Efficiency	**TE2**	[30,31,36,40,53,57,60–63,66,68–71,74,76,79–81,92,255]
	Capacity Factor	**TE3**	[36,62,66,76,83,130,255,257]
	Reliability	**TE4**	[37,53,54,57,71,73,74,79,81,84,86,258]
	Deployment Time	**TE5**	[65,76,81,84,86,251]
	Expert Human Resource	**TE6**	[81,84,86]
	Distribution grid availability	**TE7**	[42]
	Safety of energy system	**TE8**	[37,40,53,71]
	Ease of decentralization	**TE9**	[32,40]
	Safety in covering peak demand	**TE10**	[39]
	Energy input-output ratio	**TE11**	[58,83,259]
	Exergy efficiency	**TE12**	[35,53,60,92,260]
	Technical Feasibility	**TE13**	[65]
	Local technical knowledge	**TE14**	[250]
Social (SO)	Social benefits	**SO1**	[37,53,54,57,64,71,74,79,251]
	Job creation	**SO2**	[13,14,18–22,24,25,27,29, 32,33,36,38,40,42–46,52,57]
	Social acceptance	**SO3**	[36–38,42,54,56,57,60,61,63–66,70,71,73,74,79,81,84,86,92,249,250,255]
	Impact on human health	**SO4**	[92,249,255]
	Local manufacturing share	**SO5**	[56]

	Feasibility	**SO6**	[84,86,250]
	Worker Safety	**SO7**	[84,86,250,252]
Environmental (EN)	Land requirement	**EN1**	[30,36,38,40,42,57,60,61,65,66,70,71, 79–81,83,84,86,249–251,253,255,256,261]
	Pollutant Emission	**EN2**	[12,14,53,54,58,60,61,20, 26,34,35,39,40,44,46]
	Impact on ecosystem	**EN3**	[37,57,58,61,65,74,79,96,255,262]
	Disturbance of ecological balance	**EN4**	[40]
	Need for waste disposal	**EN5**	[38,81,84,86,250]
	Noise	**EN6**	[63,75,249]
	Visual amenity	**EN7**	[62,71,249,263]
	Climate change	**EN8**	[32,54,69,252]
	Severe accidents (Fatalities)	**EN9**	[252,256]
	Legislations	**EN10**	[32,264]
Political (PO)	Political acceptance	**PO1**	[37,40,65,84,86,250]
	Foreign dependency	**PO2**	[57,74,81]
	National energy security	**PO3**	[32]
	National economic benefits	**PO4**	[265,266]
	Compatibility with national energy policy	**PO5**	[57,65,74,81,86,250,267]
	Maintain leading position as a supplier	**PO6**	[265]
	Fuel reserve years	**PO7**	[62]
	Net import as percentage of consumption	**PO8**	[62,252]
Quality (QU)	Sustainability	**QU1**	[32,38,52,58,268]
	Durability	**QU2**	[38,52]
	Distance to user	**QU3**	[38,52]
Natural (NA)	Geological and topological conditions	**NA1**	[93]
	Weather conditions	**NA2**	[93]
	Hydrological conditions	**NA3**	[93]
Risk (RI)	Political risk	**RI1**	[42,269]
	Environmental risk	**RI2**	[42]
	Economic risk	**RI3**	[42,86]
	Social risk	**RI4**	[39]
	Time delay risk	**RI5**	[42,251]
	Food safety risk	**RI6**	[39,62]
Usability (US)	For secondary power generation (Reuse)	**US1**	[266]
	For other applications (Recycle)	**US2**	[266]

	Direct disposable (Disposability)	**US3**	[266]
Decommission (DE)	Salvage value	**DE1**	[266]
	Usability of plant land area	**DE2**	[266]
	Energy required	**DE3**	[270]
	Manpower required	**DE4**	[270]
Flexibility (FL)	In integration with another source	**FL1**	[271,272]
	In running with alternative fuels	**FL2**	[271,272]
	In increasing the installed capacity of the plant	**FL3**	[94]
	In fulfilling the peak load demand	**FL4**	[39,56,255]
	To fulfil the demand variation	**FL5**	[42]
Resource required (RR)	Land	**RR1**	[32,261,273,274]
	Water	**RR2**	[30–32,83,249,261,275]
	Fuel/coal	**RR3**	[261]
	Skilled manpower	**RR4**	[261]
Market (MA)	Existence of stakeholder support	**MA1**	[272,276]
	Stability of sufficient market base	**MA2**	[272,276]
	Influence of stakeholder groups	**MA3**	[272,277]
	Consumer interest about technology	**MA4**	[276,277]
Supply Security (SS)	Aptitude to respond to peak load events	**SS1**	[39,56,255]
	Total fuel consumption	**SS2**	[56,251]
	Contribution to energy independency	**SS3**	[56,94]
	Security of plants/grid	**SS4**	[94]
Emission (EM)	CO_2 emission	**EM1**	[31,53,56,58,60,61,66,70,80,81,83,130]
	SO_2 emission	**EM2**	[53,56,66,83]
	NOx emission	**EM3**	[53,56,60,70,83]
	Fine dust particle emission	**EM4**	[56]
	Particulate matters	**EM5**	[53]
	Radioactive waste	**EM6**	[56]

3.3 RESEARCH METHODOLOGY

To empirically and statistically validate the proposed indicators, initially, a two-step research methodology has been developed which is appended below for reference (refer to Fig. 3.1). The first step discussed the identification of indicators, preparation of survey instrument, the conduct of the survey, and data collection. Whereas, the second step statistically and analytically validates the results of the survey using the SPSS software.

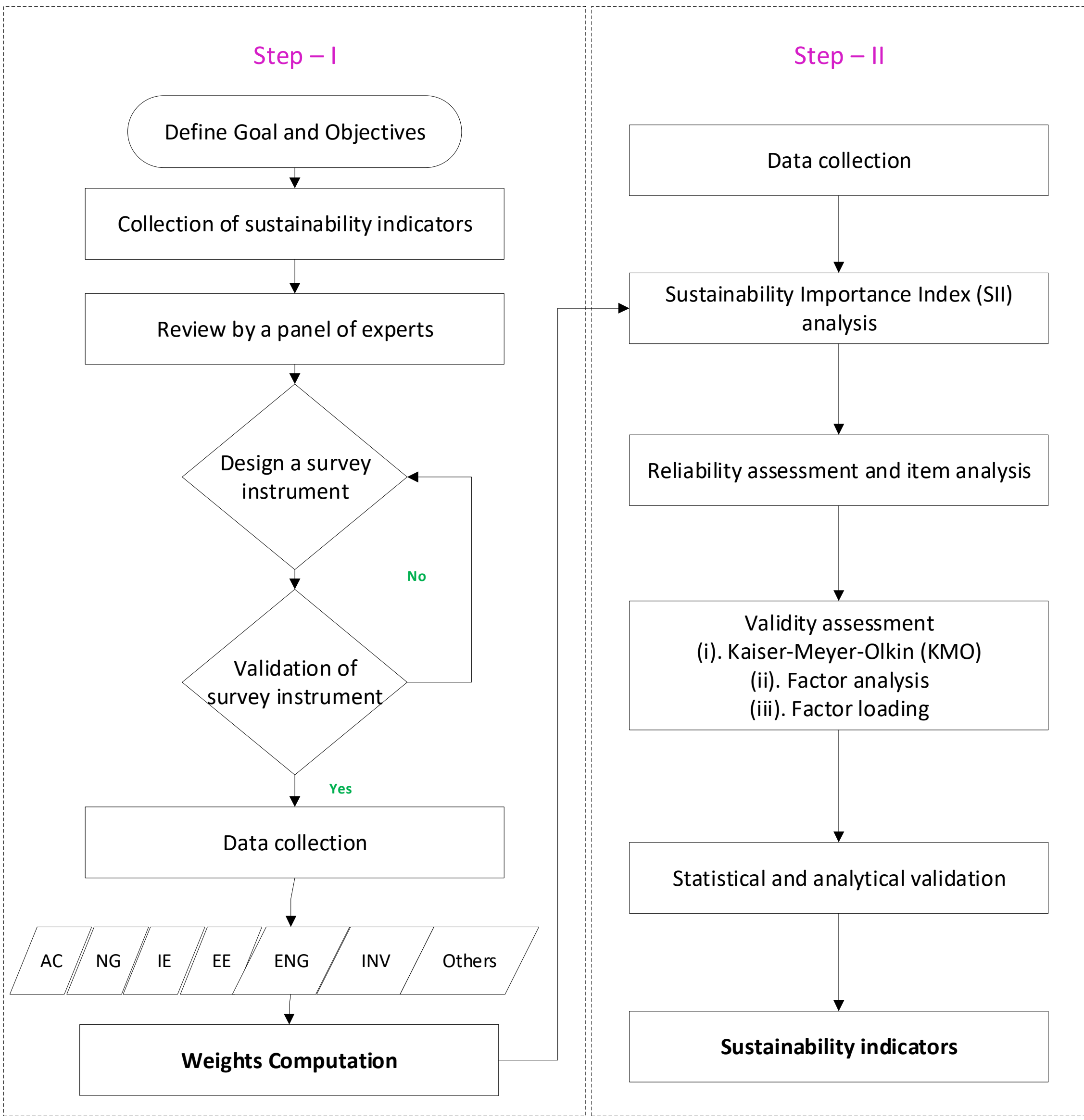


Fig. 3.1: Flow chart of research methodology

Here, AC denotes – Academics, NG - Non-Government Organizations, IE – Industry Experts, EE – Environment Experts, ENG – Engineers, INV – Investors, and Others.

3.3.1 Goal and Objectives of the Study

The goal of the research work is to identify and validate the sustainability indicators for the evaluation of energy sources from an Indian perspective. The evaluation of sustainable energy sources will help the policy and decision-makers to improve the sustainability of the Indian energy sector. It will also be helpful in the calculation of the maximum exploitable power potential through sustainable energy sources.

3.3.2 Identification of Sustainability Indicators

To identify the sustainability indicators, an extensive review of literature has been carried out. The keywords of "sustainability indicators," "sustainable energy indicators," "economic indicators," "environmental indicators," "technical indicators," "social indicators," "Indian energy indicators", etc. were used for the investigation of the available literature. Total of 767 indicators were identified from the extensive literature survey (Appendix III).

Then, the indicators were assessed to avoid repeatability and irrelevancy. The following questionnaire was developed for the filtration process.

1. Is the indicator clear in the objective?
2. Is the indicator coherent and consistent?
3. Is the indicator carry sufficient information?
4. Does the indicator have a proper classification scale?
5. Is the indicator linking energy sources with sustainability?
6. Is the indicator data collection method available?
7. Is the indicator applicable for both national and regional level analysis?

After the filtration process, only 106 indicators remained from the available 767 indicators, hence, these 106 indicators were considered for further analysis.

3.3.3 Selection of Parameters

In the third step, the filtered indicators were reviewed by the panel of experts. The nominal grouping techniques approach was adopted for checking the relevancy of the indicators with their main categories and this technique also avoided the repeatability of the indicators. The experts considered highly repeated indicators such as capital cost, payback period, technology maturity, social acceptance, foreign dependency, etc. They have also given preferences to some more new indicators such as environmental risk, political risk, fuel reserve years, legislations, local manufacturing share, etc., and designated a separate group for these indicators. Finally, a panel of experts grouped the 93 indicators corresponding to the 15 main factors. These indicators with their corresponding categorizes are shown in affinity diagram Fig. 3.2 affinity diagrams. In addition, a brief definition of these selected indicators is also included in Appendix IV.

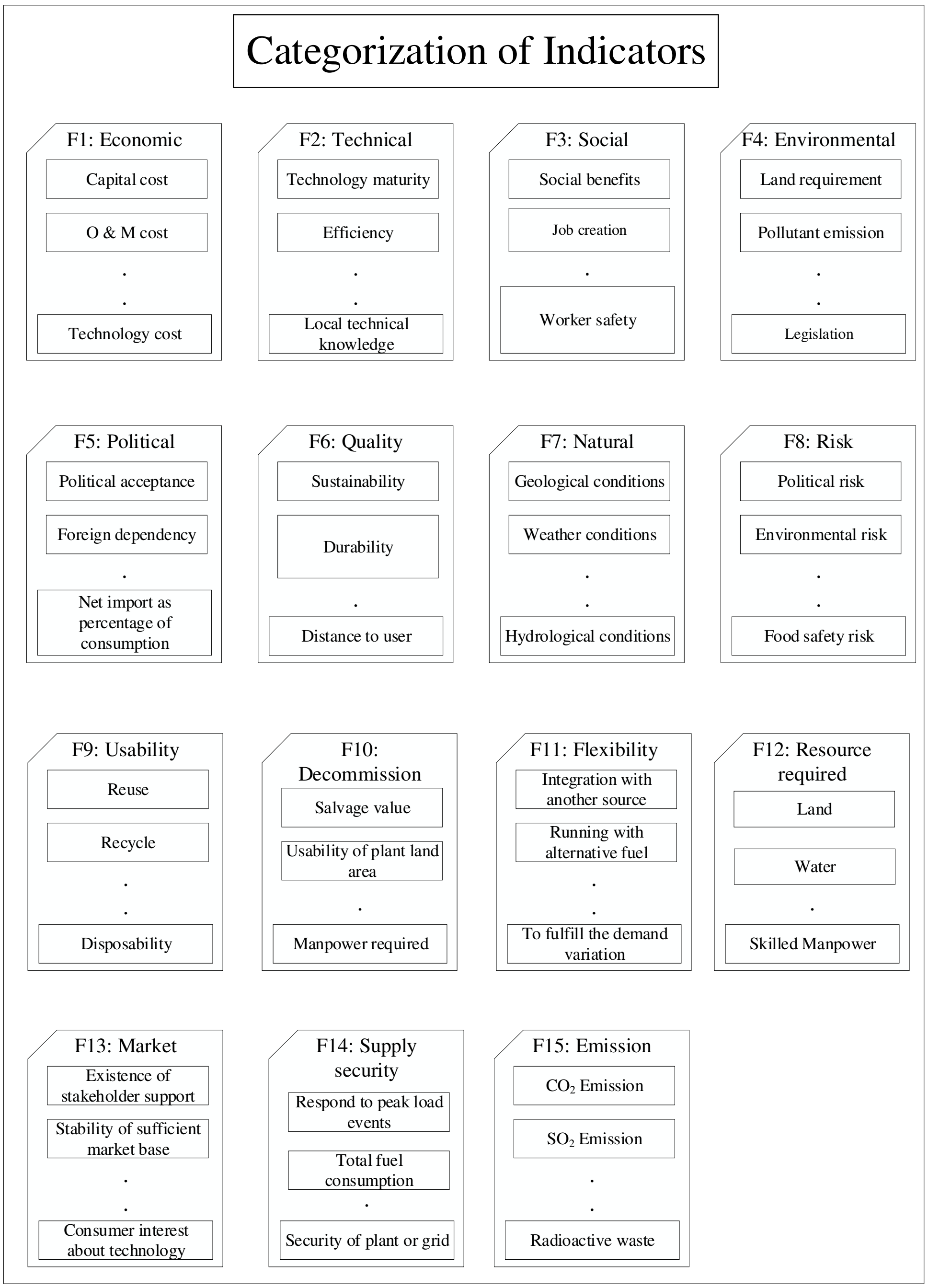


Fig. 3.2: Affinity diagram

3.3.4 Survey Instrument

To analyse the importance and consistency of the selected indicators from the Indian perspective, a survey instrument has been developed. Initially, it was tested for its simplicity and adequacy by academicians and practitioners. The pre-tested survey instrument was then prepared in both online (web-based) and offline (face-to-face) survey mode. The experts were considered from different fields of academics (AC), Non-Government Organizations (NGOs), Engineers (ENG), Industry Experts (IE), Environment Experts (EE), Investors (INV), and Others. The categories of expertise "others" include the politicians, social workers, people from the general public, and government employees. The experts were considered from different fields to cover their perspectives and appropriate evaluation of the sustainability indicators.

The experts were asked to give their judgments using a five-point interval rating scale. The five-point linear scale: 1-Not Suitable, 2-Less Suitable, 3-Moderate Suitable, 4-Suitable, 5-Highly Suitable. A typical questionnaire sample is included in Appendix V.

3.3.5 Computation of Sustainability Importance Index (SII)

The numerical scores from the questionnaire provided a measure of the strength of opinion of the effect of each variable on the success of a project. These are subsequently transformed into relative importance index using the following formula adopted from Digalwar et al. [278].

$$\text{Sustainability Importance Index (SII)} = \frac{\sum_{i=0}^{n} W_i}{k \times n} \quad (3.1)$$

where, n = number of respondents, k = maximum weight given to single criterion ($k = 5$), and W_i = weight given by the respondent to the criterion

The importance indices range from 0 to 100. These indices reflect the relative importance of the variables/items listed in the questionnaire. As would be expected, some items have high leverage, and others do not. The importance indices have been classified into five categories to reflect the respondents' ratings as follows:

1. Very important 80.0% < I ≤ 100%
2. Important: 60.0% < I ≤ 80.0%
3. Preferred: 40.0% < I ≤ 60.0%
4. Less important: 20.0% < I ≤ 40.0%
5. Not important: 0 < I ≤ 20.0%

In the survey, a total of 985 experts were contacted through emails and face-to-face meetings. A total of 467 responses were collected through both online and offline modes, representing a response rate of 47.31%. The response rate was increased by the remainder of phone calls, emails, and verbal meetings. A total of 25 responses were rejected due to incomplete and adequate information. Finally, 442 responses were considered for further analysis, among them 278 were obtained through offline mode and 164 were received through online mode.

3.4 RESULTS AND DISCUSSION

A total of 442 experts responded to the survey operation. These 442 experts were classified according to their field of expertise and geographical locations. The present study has received more than 30 responses from each category, which satisfied the need for further statistical analysis Flynn et al. [279]. Table 3.2 below shows the number of responses received from each category. It is difficult to attribute any specific reason, but high interest is taken by academicians, followed by environmental experts and it is reflected from the responses.

Table 3.2: The number of experts participated in the survey

Total Responses – 442		
Category	Number of responses	Share of total response
Academicians	118	27%
NGO's	42	9%
Engineers	63	14%
Industry experts	56	13%
Environment experts	84	19%
Investors	47	11%
Others	32	7%

The respondents were further classified based on their academic qualifications. There were 42 experts, who had a doctorate (Ph. D.), 94 experts had the Post-Graduation (PG) degree, 243 experts had the Under-Graduation (UG) degree, and 63 experts had less than a UG degree as these are especially the investors, social worker, and politicians. The respondents were further categorized based on gender. There were 309 male respondents and 133 female respondents, as given in Table 3.3. The survey has captured the different qualification levels of the respondents to understand the significance of indicators from research and higher education level to undergraduate level.

A total of 42 experts had Ph. D. degrees among them 25 were male and 17 were female experts. Similarly, 64 male experts and 30 female experts had a post-graduation degree. The 173 male and 70 female respondents had an undergraduate degree. There were 63 experts, who had less than under graduation degree. Among them 47 were male and 16 were female participants.

Table 3.3: Academic qualification of the respondent experts

		PhD	**PG**	**UG**	**<UG**	**Total**
AC	Male	10	24	44	0	78
	Female	5	7	28	0	40
NG	Male	4	9	10	7	30
	Female	2	3	5	2	12
ENG	Male	4	8	36	8	56
	Female	2	3	1	1	7
IE	Male	1	7	43	0	51
	Female	0	2	3	0	5
EE	Male	5	9	30	0	44
	Female	6	11	23	0	40
INV	Male	1	5	6	17	29
	Female	1	3	7	7	18
OTHERS	Male	0	2	4	15	21
	Female	1	1	3	6	11
	Total	42	94	243	63	**442**

In further descriptive classification, the responses are categorized based on the geographical locations of India. Broadly India is classified into five regions i.e., the Eastern region, North-eastern region, Northern region, Southern region, and Western region. The Eastern region has the states of Bihar, Jharkhand, Odisha, Sikkim, and West Bengal. While, Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, and Tripura are located in the northeastern region. Onward, Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Punjab, Rajasthan, Uttar Pradesh, and Uttarakhand are situated in the northern region. Whereas, Chhattisgarh, Dadra & Nagar Haveli, Daman & Diu, Goa, Gujarat, Madhya Pradesh, and Maharashtra are part of the western region. Finally, the southern region carries Andhra Pradesh, Karnataka, Kerala, Lakshadweep, Puducherry, Tamil Nadu, and Telangana in it. A total of 442 responses were received from all the five regions among which the highest number (187) of responses were collected from the northern region, followed by the western region (93 responses), and the eastern region (67). Southern and northeastern regions were the least participating regions with 53 and 42 numbers of significant responses respectively. In addition, the survey responses effectively carry the perception of rural as well as urban communities about sustainable energy. Table 3.4 summarizes the survey responses collected from different states and regions of India. In terms of percentage share, the highest number of responses were received from northern and western regions because the states falling under these categories cover a large part of the country.

Table 3.4: Survey responses from different geographical regions of India

Regions of India	**Corresponding States**	**Participants**	**Percentage Share**
Eastern region	Bihar, Jharkhand, Odisha, Sikkim, and West Bengal	67	15
North-eastern region	Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, and Tripura	42	9.50
Northern region	Chandigarh, Delhi, Haryana, Himachal Pradesh, Jammu & Kashmir, Punjab, Rajasthan, Uttar Pradesh, and Uttarakhand	187	42.50
Western region	Chhattisgarh, Dadra & Nagar Haveli, Daman & Diu, Goa, Gujarat, Madhya Pradesh, and Maharashtra	93	21
Southern region	Andhra Pradesh, Karnataka, Kerala, Lakshadweep, Puducherry, Tamil Nadu, and Telangana	53	12

The expert responses are collected and analysed to obtain the overall SII of the indicators. Further, the responses are sorted out based on the expertise of respondents. SII is also separately calculated for various groups i.e., academicians, NGOs, environment, investors, and engineers' expert category. Table 3.5 shows the category-wise and overall SII of the considered parameters with their mean and standard deviation values.

Table 3.5: Sustainability importance index of all the considered parameters

Parameters	AC	NG	ENG	IE	EE	INV	Others	Overall	Mean	Std. Devi.
EC1	0.892	0.914	0.908	0.933	0.863	0.891	0.967	0.899	4.49	0.624
EC2	0.825	0.943	0.846	0.889	0.874	0.836	0.867	0.858	4.29	0.801
EC3	0.683	0.686	0.785	0.756	0.674	0.691	0.600	0.699	3.49	0.943
EC4	0.917	0.886	0.831	0.844	0.853	0.891	0.900	0.876	4.38	0.683
EC5	0.883	0.829	0.892	0.844	0.832	0.891	0.933	0.870	4.35	0.676
EC6	0.825	0.829	0.831	0.867	0.853	0.873	0.900	0.847	4.24	0.658
EC7	0.842	0.943	0.862	0.800	0.842	0.873	0.933	0.858	4.29	0.710
EC8	0.750	0.743	0.754	0.756	0.705	0.727	0.633	0.730	3.65	0.725
EC9	0.675	0.743	0.754	0.778	0.758	0.709	0.633	0.721	3.61	0.861
EC10	0.842	0.829	0.877	0.889	0.779	0.855	0.800	0.836	4.18	0.732
EC11	0.708	0.743	0.723	0.667	0.758	0.800	0.633	0.726	3.63	0.958
EC12	0.725	0.743	0.769	0.733	0.758	0.709	0.700	0.737	3.69	0.820
TE1	0.875	0.914	0.800	0.889	0.821	0.818	0.933	0.854	4.27	0.780
TE2	0.858	0.943	0.769	0.867	0.863	0.909	0.933	0.865	4.33	0.863
TE3	0.817	0.771	0.846	0.933	0.800	0.818	0.833	0.827	4.13	0.855
TE4	0.758	0.886	0.862	0.822	0.758	0.782	0.867	0.800	4.00	0.853
TE5	0.800	0.914	0.754	0.844	0.758	0.873	0.867	0.811	4.06	0.884
TE6	0.642	0.771	0.677	0.733	0.642	0.727	0.567	0.672	3.36	1.036
TE7	0.625	0.800	0.677	0.578	0.632	0.745	0.500	0.649	3.25	1.199
TE8	0.708	0.686	0.662	0.644	0.705	0.745	0.433	0.679	3.39	1.362
TE9	0.558	0.571	0.631	0.533	0.568	0.745	0.300	0.575	2.88	1.278
TE10	0.742	0.657	0.738	0.689	0.716	0.764	0.633	0.719	3.60	1.074
TE11	0.633	0.571	0.708	0.600	0.695	0.709	0.367	0.640	3.20	1.350
TE12	0.608	0.714	0.538	0.511	0.568	0.655	0.467	0.584	2.92	1.263
TE13	0.733	0.629	0.631	0.689	0.726	0.618	0.367	0.665	3.33	1.175
TE14	0.575	0.514	0.646	0.489	0.663	0.709	0.433	0.598	2.99	1.201
SO1	0.792	0.829	0.846	0.844	0.789	0.800	0.867	0.813	4.07	0.863
SO2	0.825	0.886	0.738	0.800	0.905	0.945	0.900	0.852	4.26	0.846
SO3	0.767	0.829	0.769	0.756	0.874	0.800	0.900	0.807	4.03	0.845
SO4	0.817	0.800	0.892	0.711	0.821	0.836	0.867	0.822	4.11	0.910
SO5	0.533	0.714	0.662	0.600	0.558	0.655	0.567	0.596	2.98	1.066
SO6	0.600	0.657	0.615	0.667	0.663	0.582	0.633	0.627	3.13	1.208
SO7	0.692	0.771	0.646	0.822	0.579	0.618	0.733	0.674	3.37	1.101
EN1	0.775	0.886	0.769	0.756	0.821	0.745	0.967	0.800	4.00	0.989
EN2	0.850	0.943	0.846	0.733	0.842	0.800	0.933	0.843	4.21	1.050
EN3	0.875	0.743	0.800	0.756	0.811	0.818	0.833	0.818	4.09	0.984
EN4	0.625	0.686	0.538	0.511	0.547	0.691	0.600	0.596	2.98	1.288
EN5	0.675	0.543	0.708	0.600	0.705	0.709	0.433	0.656	3.28	1.348

Parameters	AC	NG	ENG	IE	EE	INV	Others	Overall	Mean	Std. Devi.
EN6	0.533	0.486	0.754	0.533	0.537	0.545	0.400	0.555	2.78	1.355
EN7	0.600	0.514	0.600	0.600	0.516	0.600	0.300	0.555	2.78	1.355
EN8	0.917	0.857	0.831	0.756	0.758	0.873	0.833	0.838	4.19	0.877
EN9	0.575	0.600	0.523	0.444	0.632	0.582	0.667	0.575	2.88	1.232
EN10	0.675	0.686	0.800	0.778	0.716	0.727	0.733	0.724	3.62	1.220
PO1	0.808	1.000	0.785	0.800	0.832	0.818	0.900	0.831	4.16	0.878
PO2	0.850	0.943	0.815	0.800	0.800	0.727	0.967	0.829	4.15	0.833
PO3	0.767	0.800	0.723	0.800	0.726	0.800	0.600	0.751	3.75	1.058
PO4	0.817	0.714	0.815	0.867	0.726	0.782	0.633	0.778	3.89	0.970
PO5	0.825	0.886	0.938	0.778	0.832	0.818	0.867	0.845	4.22	0.780
PO6	0.525	0.600	0.662	0.689	0.558	0.600	0.467	0.580	2.90	1.056
PO7	0.792	0.800	0.800	0.844	0.800	0.818	0.800	0.804	4.02	0.892
PO8	0.550	0.629	0.631	0.600	0.663	0.636	0.367	0.596	2.98	1.138
QU1	0.783	0.743	0.785	0.756	0.800	0.891	0.567	0.780	3.91	1.024
QU2	0.642	0.571	0.723	0.556	0.684	0.782	0.600	0.663	3.35	1.145
QU3	0.608	0.600	0.585	0.600	0.674	0.764	0.400	0.622	3.13	1.294
NA1	0.692	0.743	0.662	0.689	0.642	0.691	0.433	0.663	3.31	1.230
NA2	0.708	0.743	0.662	0.667	0.663	0.782	0.400	0.679	3.39	1.267
NA3	0.608	0.657	0.615	0.511	0.505	0.655	0.300	0.566	2.83	1.448
RI1	0.567	0.571	0.600	0.644	0.558	0.545	0.467	0.569	2.84	1.096
RI2	0.725	0.686	0.738	0.644	0.747	0.745	0.600	0.715	3.57	1.167
RI3	0.733	0.629	0.692	0.689	0.705	0.727	0.533	0.694	3.47	1.197
RI4	0.600	0.543	0.662	0.667	0.653	0.655	0.533	0.625	3.12	1.166
RI5	0.525	0.543	0.615	0.578	0.568	0.764	0.267	0.566	2.83	1.350
RI6	0.550	0.543	0.646	0.556	0.589	0.673	0.233	0.566	2.83	1.424
US1	0.650	0.629	0.692	0.667	0.642	0.636	0.433	0.638	3.19	1.214
US2	0.583	0.486	0.662	0.622	0.537	0.545	0.400	0.564	2.82	1.257
US3	0.567	0.571	0.600	0.600	0.537	0.691	0.267	0.564	2.82	1.266
DE1	0.700	0.800	0.677	0.644	0.695	0.782	0.800	0.715	3.57	0.980
DE2	0.642	0.714	0.692	0.556	0.653	0.727	0.500	0.649	3.24	1.145
DE3	0.658	0.629	0.738	0.622	0.632	0.745	0.533	0.661	3.30	1.176
DE4	0.625	0.686	0.692	0.689	0.642	0.636	0.400	0.636	3.22	1.179
FL1	0.858	0.857	0.831	0.867	0.800	0.764	0.767	0.825	4.12	0.795
FL2	0.625	0.686	0.708	0.689	0.674	0.691	0.633	0.667	3.34	1.252
FL3	0.633	0.771	0.677	0.733	0.611	0.600	0.667	0.654	3.27	1.185
FL4	0.825	0.886	0.862	0.756	0.789	0.764	0.833	0.813	4.07	0.902
FL5	0.783	0.800	0.815	0.756	0.821	0.691	0.700	0.778	3.89	0.959
RR1	0.675	0.600	0.692	0.644	0.779	0.709	0.567	0.688	3.44	1.177
RR2	0.733	0.686	0.785	0.778	0.747	0.764	0.600	0.739	3.70	0.958
RR3	0.700	0.686	0.615	0.689	0.768	0.727	0.633	0.699	3.49	1.129
RR4	0.567	0.686	0.754	0.644	0.705	0.782	0.333	0.652	3.26	1.336
MA1	0.650	0.743	0.723	0.644	0.663	0.764	0.467	0.672	3.36	1.047
MA2	0.658	0.686	0.708	0.533	0.705	0.782	0.433	0.665	3.33	1.146
MA3	0.567	0.543	0.569	0.511	0.642	0.673	0.400	0.578	2.89	1.201
MA4	0.667	0.914	0.692	0.622	0.811	0.745	0.467	0.712	3.56	1.252
SS1	0.800	0.886	0.815	0.689	0.779	0.764	0.767	0.787	3.93	0.889
SS2	0.700	0.686	0.754	0.689	0.768	0.709	0.600	0.715	3.57	0.987
SS3	0.625	0.657	0.754	0.489	0.642	0.800	0.567	0.654	3.27	1.277

Parameters	AC	NG	ENG	IE	EE	INV	Others	Overall	Mean	Std. Devi.
SS4	0.667	0.743	0.738	0.578	0.674	0.800	0.467	0.679	3.39	1.193
EM1	0.725	0.800	0.769	0.667	0.726	0.782	0.733	0.739	3.70	1.152
EM2	0.642	0.600	0.723	0.644	0.642	0.764	0.767	0.674	3.37	1.326
EM3	0.633	0.714	0.785	0.600	0.695	0.745	0.667	0.688	3.44	1.224
EM4	0.625	0.571	0.662	0.578	0.653	0.709	0.633	0.638	3.19	1.251
EM5	0.592	0.543	0.738	0.556	0.621	0.709	0.633	0.629	3.15	1.353
EM6	0.583	0.514	0.677	0.600	0.611	0.636	0.400	0.593	2.97	1.563

The economic category included twelve indicators. It is observed that academicians have given the highest importance to the "payback period" (0.917), and "capital cost" (0.892). While the least importance is given to "site advantage" (0.675), and "research & development cost" (0.683). Engineers preferred the "capital cost" (0.908), and "LCOE" (0.892) as the most important consideration for the sustainable energy sector. While "future potential energy cost" (0.723) was considered the least important consideration. Similarly, environment experts gave the highest preference to "O & M cost" (0.874), and "capital cost" (0.863), and the least preference to R & D cost (0.674). Industry experts have chosen the highest and least important indicators as "capital cost" (0.933) and "future potential energy cost" (0.667) respectively. Investors gave the highest and the lowest preference to "capital cost" (0.891) and "R & D cost" (0.691) respectively. NGO experts gave equal and highest weights to "O & M cost" (0.943), and "fuel cost" (0.943) indicators. Similar to others, the "Others" group chose "capital cost" (0.967), and "R & D cost" (0.60) as the highest and lowest weights criterion as shown in Fig. 3.3. Finally, the overall highest and lowest SII is given to "capital cost" (0.899), and "R & D cost" (0.699) indicators.

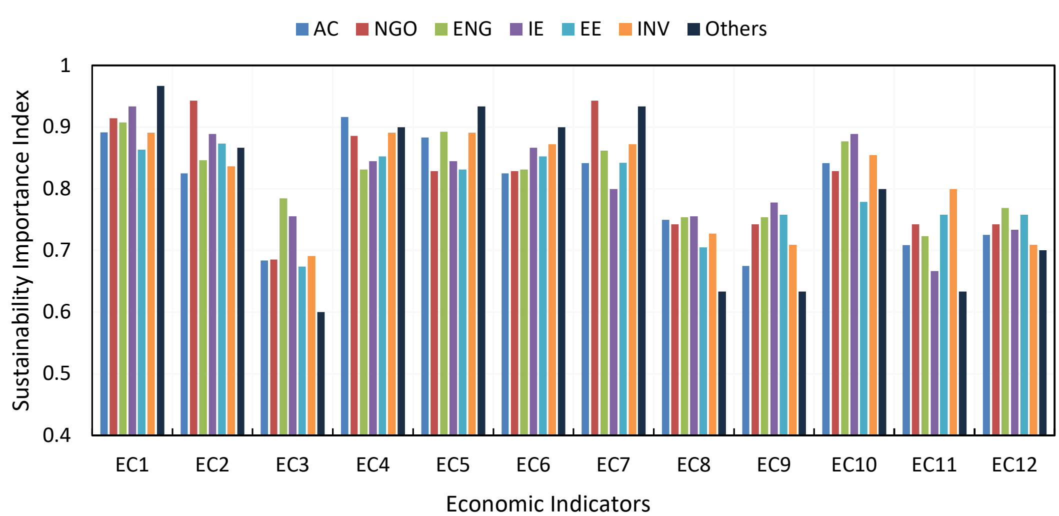


Fig. 3.3: Sustainability importance index of the economic indicators

In the economic category, the highest SII is given to "capital cost" because it may incorporate a large share of overall investment and it is also very crucial for the project development and installation. The second priority is assigned to the "payback period" because of variations in tariff rates in different parts of the country as well as the competitive nature of the market. "Research and development cost" is given the least preferred because of the scarcity of funds and restricted resources in India and other developing countries.

The technical category carries the highest fourteen number of indicators. According to academicians, "technology maturity" (0.875) and "efficiency" (0.858) are the two most important indicators for sustainable energy development. While "ease of decentralization" (0.558) is chosen as the least important indicator. Engineers have highly favored the "reliability" (0.862), and "capacity factor" (0.846) for sustainability. Environment experts considered "efficiency" (0.863), and "technology maturity" as the essential sustainability tools. Investors thought "efficiency" (0.909) and "technical feasibility" (0.618) are the highest and least affecting factors to sustainability. Industry experts gave the highest importance to the "capacity factor" (0.933), and the least weight to "local technical knowledge" (0.489) as shown in Fig. 3.4. NGO experts and Others had chosen "efficiency" (0.943), and "technology maturity" (0.914) as an important consideration for the sustainability assessment. Finally, overall "efficiency" (0.865) has the highest SII, and "ease of decentralization" (0.575) has the least SII for the assessment of the sustainable energy sector.

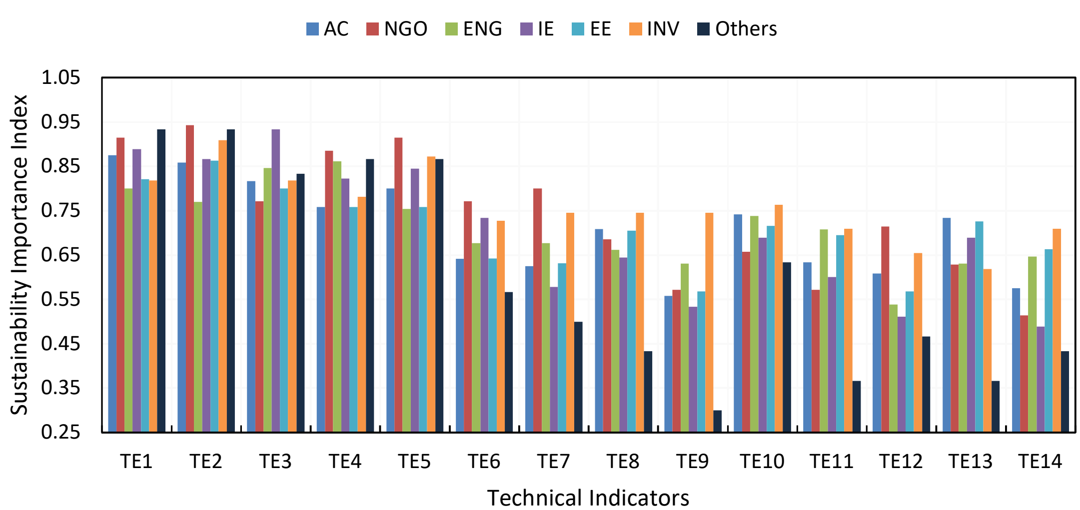


Fig. 3.4: Sustainability importance index of the technical indicators

In technical factors, “efficiency” is preferred unanimously by all the experts because of the reasons such as less fuel consumption, fewer greenhouse gas emission, more energy generation, and high economic benefits of high-efficiency energy systems. “Technology maturity” is chosen as the second most preferable indicator by seeing the importance of the availability of technology at local and national level markets and ease of use without experts. Experts gave the least preference to the “ease of decentralization” indicator probably because of the easy availability of centralized facilities.

The environmental category has ten subfactors. The analysis clearly shows that academicians had a primary concern about “climate change” (0.917), and “impact on eco-system” (0.875). They considered “noise” (0.533), and “severe accidents” (0.575) as the least essential indicators. The environment experts group gave the highest importance to “pollutant emission” (0.842), and “land requirement” (0.821), and the least importance to “visual amenity” (0.516). Similar to academicians, investors are also worried about the “climate change” (0.873), and “impact on the ecosystem” (0.818). Industry experts thought “legislation” (0.778) should be given the highest importance, and “severe accidents” (0.444) the least importance. Engineers and NGO experts favoured “pollutant emission” as an important consideration for sustainability. Others were given preference for “land requirement” (0.967), and “pollutant emission” (0.933) as explained in Fig. 3.5. The overall highest SII is given to “pollutant emission” (0.843) and combined least SII to “noise” and “visual amenity” (0.555).

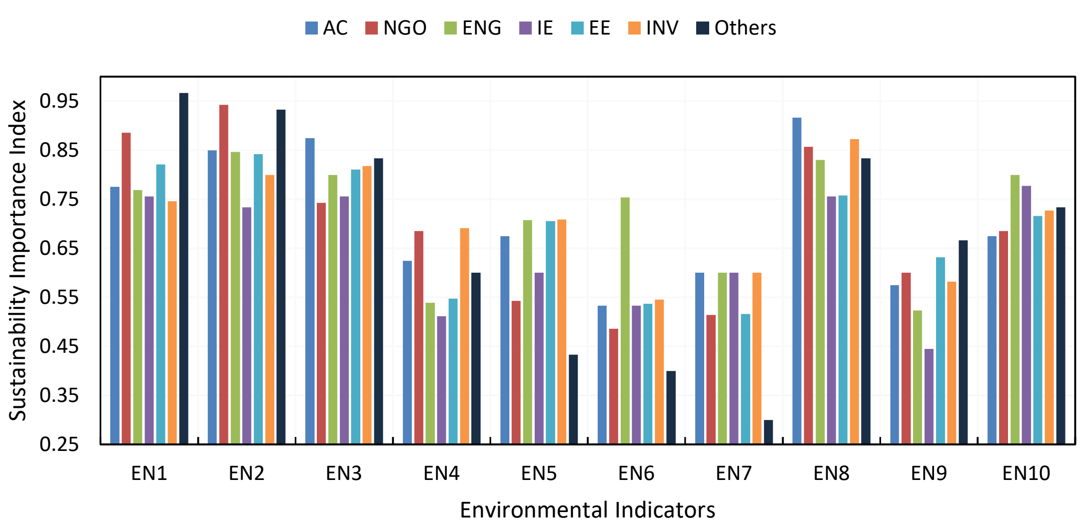


Fig. 3.5: Sustainability importance index of the environmental indicators

In environmental indicators, “pollutant emission” and “climate change” have been given the highest preference because of the concern about global warming. The emission of pollutants such as carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), lead (Pb), and particulate matter (PM) is significantly increasing the effect of global warming and results in increasing tornados, worsening droughts, floods, melting glaciers, and rising sea level. “Noise” and “visual amenity” are given the least importance as the installation of energy sources is planned away from domestic, residential, and densely populated areas.

The social category carries seven indicators. A group of academicians and environment experts had given the highest weight to “job creation” (0.825) and the least weight to the “local manufacturing share” (0.533) indicator. According to the engineer’s perception, “impact on human health” (0.892), and “feasibility” (0.615) are the most and least important indicators for the sustainability assessment. Industry experts gave importance to “social benefits” (0.844), and “worker safety” (0.822). While they gave less importance to “local manufacturing share” (0.600) and “feasibility” (0.667) indicators. NGOs and investors preferred “job creation” and “feasibility” as the most and least important considerations of the sustainability assessment. According to Other's opinion, “job creation” (0.900), and “social acceptance” (0.900) had equal and highest importance as the sustainability indicators as shown in Fig. 3.6. Finally, “job creation” (0.852), and “local manufacturing share” (0.596) had the highest and lowest overall SII.

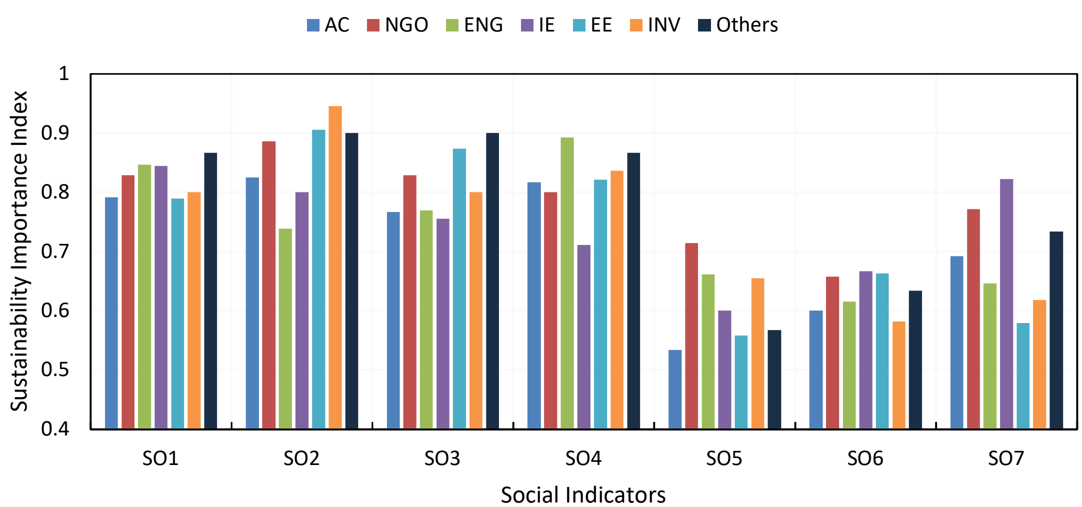


Fig. 3.6: Sustainability importance index of the social indicators

From Table 3.5, it is inferred that the "job creation" indicator holds the highest importance in the overall scenario of social factors. India is a fast-growing large economy with a highly segmented labor market such as a growing number of unemployed educated youth. This also contributes to creating job opportunities for both highly educated and less educated in various sectors right from planning, installation, operation & maintenance, and further decommission of power plants. The second rank is given to "impact on human health" because of some serious issues of chronic cardiovascular & respiratory diseases, preterm delivery, asthma, cardiac arrest, and lung cancer due to emission of harmful fine particulate matter (PM2.5), nitrogen oxides (NOx), Sulphur dioxides (SO2), and mercury. The least preference is given to "local manufacturing share" because of the unavailability of modern invented technology in the local market.

The political category considers the eight sub-criteria. Academicians, gave the highest weight to "foreign dependency" (0.808), followed by the "compatibility with national energy policy" (0.825), and "national economic benefits" (0.817). NGO experts prioritize the sustainability indicators of "political acceptance" (1.00), "foreign dependency" (0.943), and "compatibility with national energy policy" (0.886) in decreasing the order of sustainability. Engineers gave the highest and least importance to "compatibility with national energy policy" (0.938), and "net import as a percentage of consumption" (0.631). Industry experts gave importance to factors of "national economic benefits" (0.867), and "fuel reserve years" (0.844). Environment experts and investors both were given the preference for "compatibility with national energy policy" (0.832, 0.818), and "political acceptance" (0.832, 0.818). Others gave priority to "foreign dependency" (0.967), and "political acceptance" (0.900) as shown in Fig. 3.7. Overall highest and lowest SII is given to "compatibility with national energy policy" (0.845) and "maintain a leading position as a supplier" (0.580) indicators.

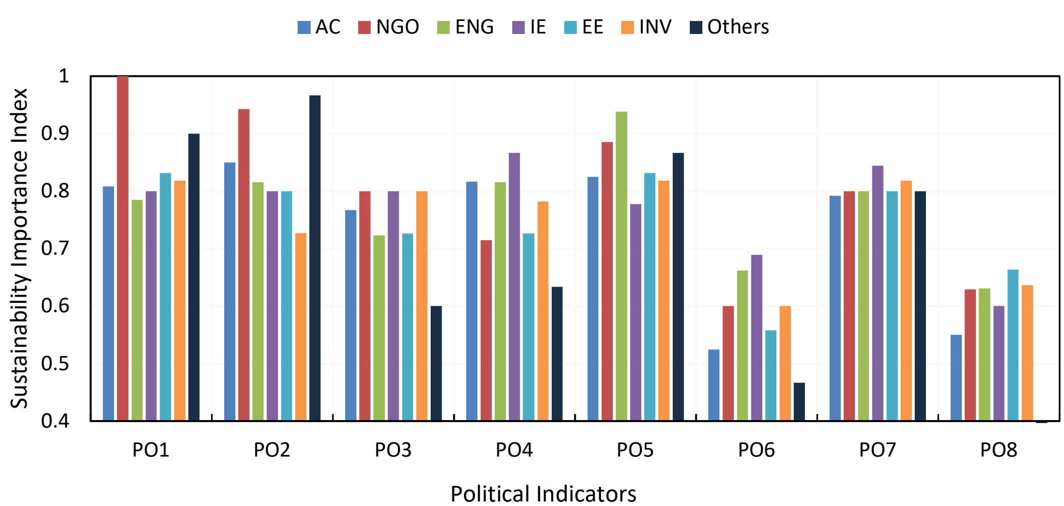


Fig. 3.7: Sustainability importance index of the political indicators

In the political factors, "compatibility with national energy policy" and "political acceptance" are highly preferred as the sustainability indicators. It is easily understood that the government set a target of installation of 100 GW of solar energy by 2022, now someone willing to install solar power plants by following the government rule and regulations will get benefit from the political acceptance as well as government subsidies.

Academicians, NGOs, Engineers, industry experts, environment experts, and investors gave the highest preference to the "sustainability" indicator of the "quality" category as given in Fig. 3.8. In natural conditions, academicians, environment experts, and investors gave the highest importance to "weather conditions" as shown in Fig. 3.9. While industry experts and others gave importance to "geological and topological conditions." NGO and engineers group thought that both the indicators "geological and topological conditions" and "weather conditions" had the same importance level. Risk is an important consideration for the analysis. It complied with political, environmental, economic, social, time delay, and food safety risks. Academicians and industry experts gave importance to "economic risk." While NGOs, engineers, environment experts, and others gave importance to "environment risk" as represented in Fig. 3.10. From the investor's perspective that "time delay risk" is an important consideration. In the category of "usability of waste products," rather than investors, all other experts preferred the "reuse" indicator as shown in Fig. 3.11. That means fuel waste should be used for power generation again.

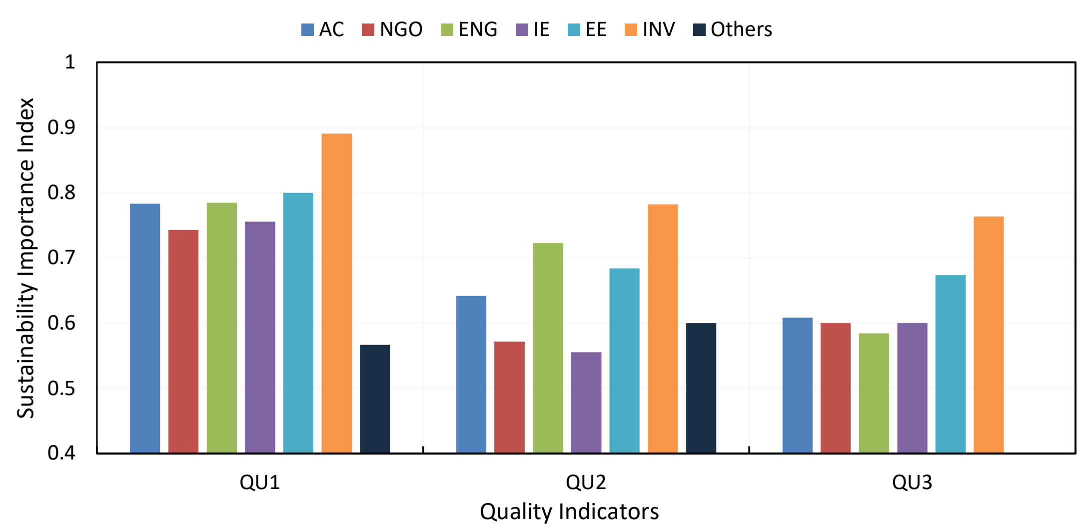


Fig. 3.8: Sustainability importance index of the quality indicators

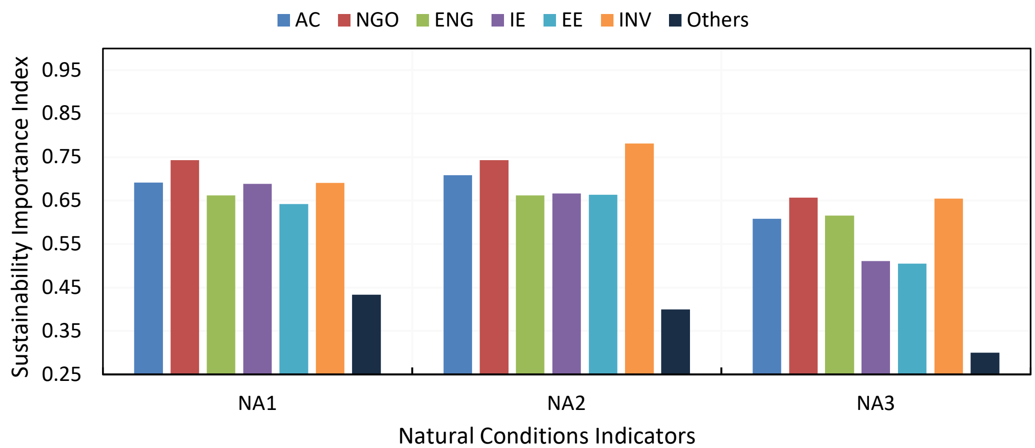


Fig. 3.9: Sustainability importance index of the natural condition indicators

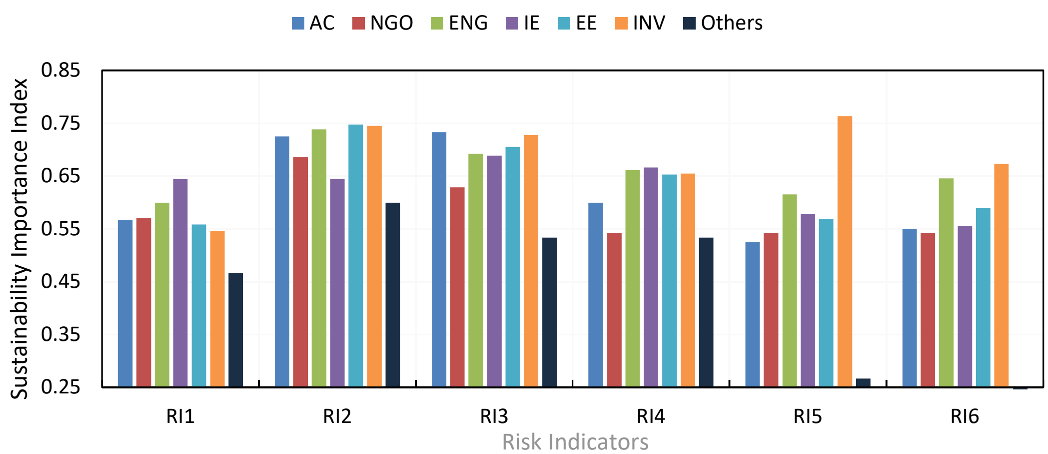


Fig. 3.10: Sustainability importance index of the risk indicators

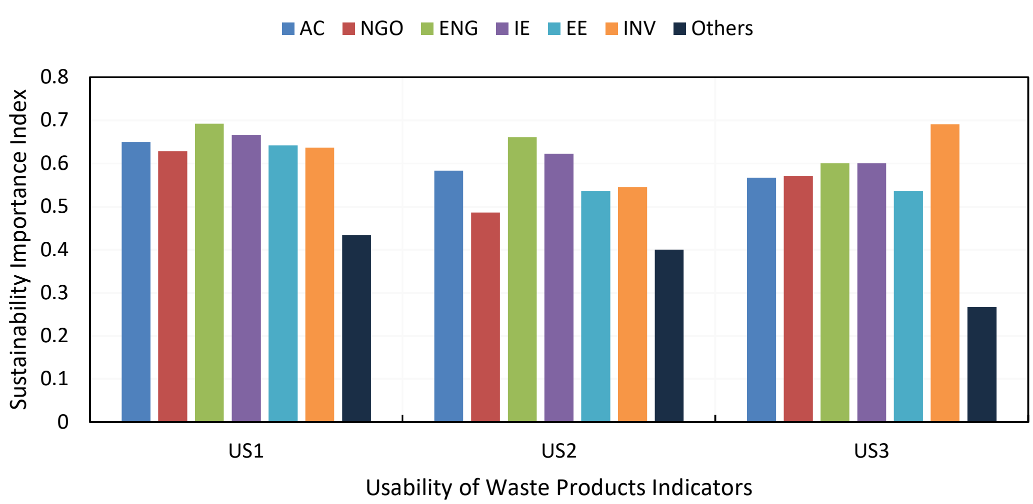


Fig. 3.11: Sustainability importance index of the usability indicators

In the quality factor, “sustainability” as an indicator is given the highest weight. The reason may harmonize, integrate and balance effectively the equity and quality of life, living and non-living natural systems, and financial and non-financial values for the people, planet, and profit respectively. In the factors of the natural condition, “weather conditions” are considered a highly impactful indicator. The reasons may be that weather conditions such as atmosphere temperature, precipitation patterns, wind patterns, average wind speed, and solar resources will highly affect the performance of the thermal plants, bioenergy plants, wave energy plants, wind plants, and solar plants. “Environmental risk” is given the highest importance among the risk factors which might be seeing the risks of habitat depletion, impact on terrestrial and aquatic ecology, atmospheric emissions, natural hazards and risks, and loss of livelihood during the establishment of power plants. In the category of usability of waste products, “fuel reuse for secondary power generation” was given the highest overall importance. The reasons for higher importance may be due to the high feasibility of fuel reuse with a justified sustainability level and fulfills the present need without imposing burdens on future generations.

Fig. 3.12 shows that the academicians, NGOs, environment experts, investors, and others preferred “salvage value” as an important consideration in the category of decommissioning of power plants. While engineers gone with “energy required,” and industry experts gone with “manpower required” as the important factor for decommissioning of power plants. Flexibility is an important criterion for current and future energy perspectives. Flexibility carries five important sub-criterion of “integration with other sources,” “in the running with alternative and mix-fuel,” “increase installed capacity of the power plant,” “fulfill the peak load demand,” and “fulfill the demand variations.” Academicians were given the highest weights performance to “integration with other sources,” and “to fulfill the peak load demand.” They were given the least importance to indicators “running with alternative fuel,” and “to increase the installed capacity of the power plant” as shown in Fig. 3.13. NGO experts, engineers, industry experts, investors, and others have preferred the indicators “integration with other sources,” and “to fulfill the peak load demand” as an important sustainability indicators. Overall highest and least SII is given to “integration with other sources” and “in increasing the installed capacity of the plants.”

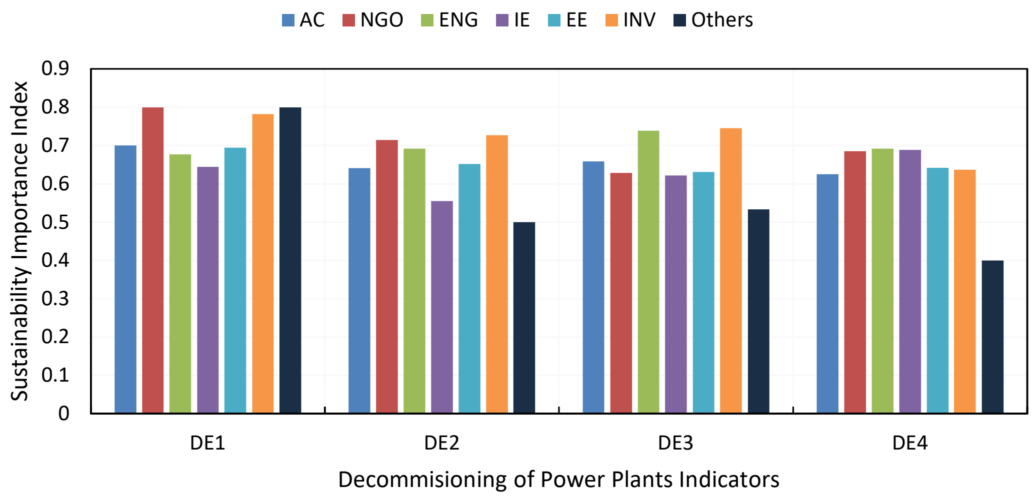


Fig. 3.12: Sustainability importance index of the decommission indicators

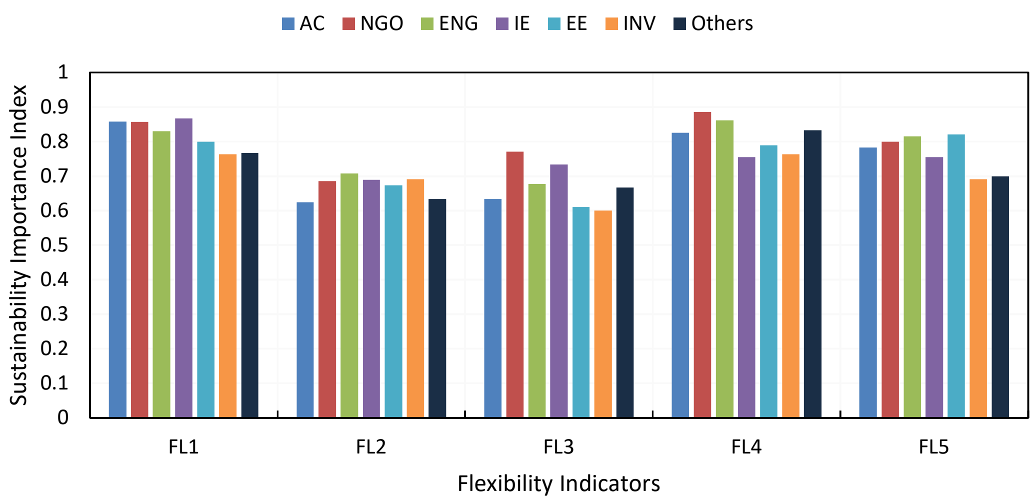


Fig. 3.13: Sustainability importance index of the flexibility indicators

In the decommission category, "salvage value" obtained the highest overall preference score. Salvage value is the estimated resale value of an asset at the end of its useful life. It has high importance because accountants and income tax officers generally consider the salvage value as zero which means depreciation of the total cost of the asset over the life years of the asset. In the flexibility factors, "integration with another source" and "respond to peak-load events" are gaining the highest sustainability importance as the current energy demand shows the fluctuating and irregular behavior, and the available conventional and non-conventional power plants are not able to fulfill that fluctuating and peak load demand. Therefore, to increase the availability and respond to peak-load demand the indicators "integration with another source" and "respond to peak-load demand" are given the highest importance.

In the "resources required" category, academicians, engineers, and industry experts have preferred "water" as an essential resource for the power plant. Similarly, environment experts considered "requirement of the land," investors considered the "skilled manpower," and others considered the "fuel/coal" as an essential consideration for sustainability assessment. NGO experts were given equal weights to "water," "fuel/coal," and "skilled manpower" indicators. In "market maturity," academicians, NGO persons, environment experts, and others have given the preference to "consumer interest about the technology." Engineers, and industry experts chose "the existence of the stakeholder support," and investors chose the "stability of sufficient market base" as an important sustainability indicator. In "supply security," rather than investors, all the experts gave importance to "aptitude to respond to peak-load events" as an important indicator for sustainability assessment. Fig. 3.14 to Fig. 3.17 indicate the importance index of sustainability indicators given by the academicians, environment analysts, industry experts, investors, engineers, NGO persons, and others.

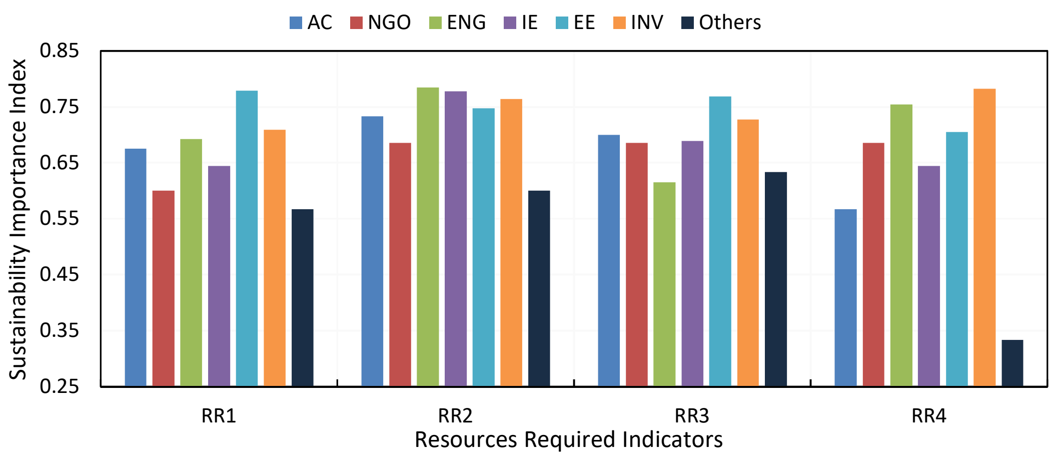


Fig. 3.14: Sustainability importance index of the resources required indicators

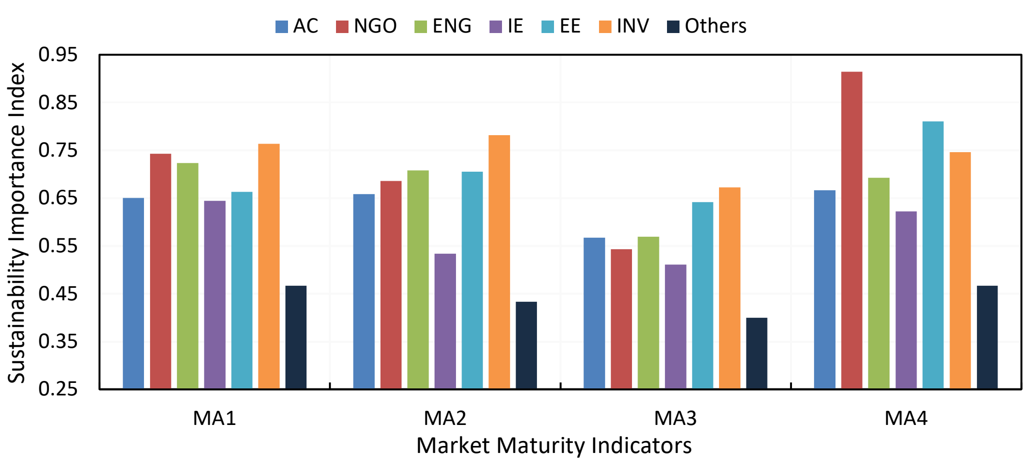


Fig. 3.15: Sustainability importance index of the market maturity indicators

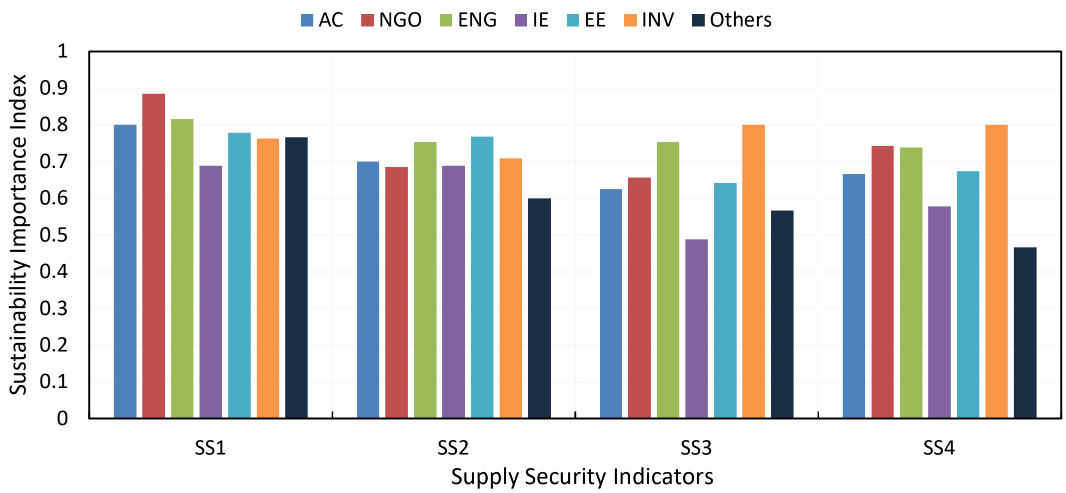


Fig. 3.16: Sustainability importance index of the supply security indicators

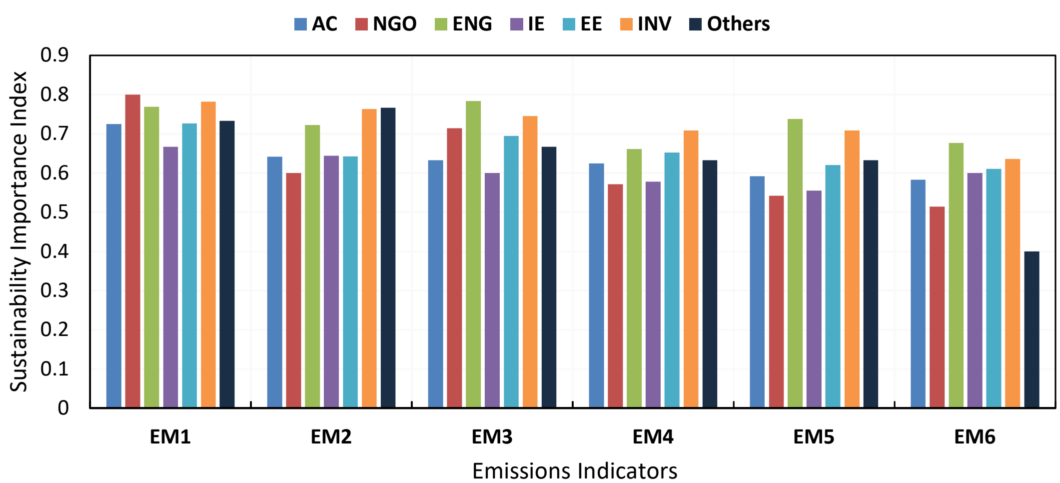


Fig. 3.17: Sustainability importance index of the emission indicators

In resources required factors, "water" is marked as the most essential element, especially in the conventional power plant applications of powering turbines with steam, and high-temperature cooling. In market maturity, "consumer interest about technology" is given the highest importance. It may be the reason if the consumer itself is interested in the technology so that he can make the same reliable, easily available, and cheap. In the supply security category, the preference is given to "aptitude to respond to the peak load events" because of the securely supply or fulfil the energy demand variation of the country to overcome the problems of blackout. In the emission factors, "CO_2 emission" is assigned the highest priority because CO_2 emission is highly responsible for various problems of climate change further leading to global warming.

Along with the SII, the present study also calculated the mean and standard deviation of the 5-point Likert scale (1 to 5). Here, the mean is the ratio of the sum of all collected data (1 to 5) to the total number of survey participants. Standard deviation is a measure that shows how much variation (such as spread, dispersion) from the mean exists. In the survey results, a higher mean value with a minimum standard deviation value is preferred over the minimum mean value with a higher standard deviation. For instance, indicator TE1 has the mean value of 4.27 with a standard deviation of 0.780, and indicator TE14 has the mean value of 2.99 with a standard deviation of 1.201. Here, the values show that the data set of TE14 indicator are having wider dispersion from the mean value compared to the data set of TE1. Therefore, the TE1 indicator is preferred or accepted over the TE14 indicator.

Subsequently assessment of SII, mean and standard deviation, the current study summarizes the Ist preference, IInd preference, and last preference of the indicators given by the experts of academics, NGOs, engineering, environment, industry, investors, and others in Table 3.6.

Table 3.6: Preferences of the experts in each considered category of the indicators

	Preference	**AC**	**NG**	**ENG**	**IE**	**EE**	**INV**	**OTHERS**
EC	Ist Pref.	EC4	EC2/EC7	EC1	EC1	EC2	EC1/EC4/ EC5	EC1
	IInd Pref.	EC1	EC1	EC5	EC2/EC10	EC1	EC6/EC7	EC5/EC7
	Last Pref.	EC9	EC3	EC11	EC11	EC3	EC3	EC3
TE	Ist Pref.	TE1	TE2	TE4	TE3	TE2	TE2	TE1/TE2
	IInd Pref.	TE2	TE1	TE3	TE1	TE1	TE5	TE4/TE5
	Last Pref.	TE9	TE12	TE12	TE14	TE9/TE12	TE13	TE9
SO	Ist Pref.	SO2	SO2	SO4	SO1	SO2	SO2	SO2/SO3
	IInd Pref.	SO4	SO1/SO3	SO1	SO7	SO3	SO4	SO4/SO1
	Last Pref.	SO5	SO6	SO6	SO5	SO5	SO6	SO5
EN	Ist Pref.	EN 8	EN2	EN2	EN10	EN2	EN8	EN1
	IInd Pref.	EN 3	EN1	EN8	EN1/3/8	EN1	EN3	EN2
	Last Pref.	EN 6	EN6	EN9	EN9	EN7	EN6	EN7
PO	Ist Pref.	PO2	PO1	PO5	PO4	PO1/PO5	PO1/PO5/ PO7	PO2
	IInd Pref.	PO5	PO2	PO4/PO2	PO7	PO2/PO7	PO3	PO1
	Last Pref.	PO6	PO6	P8	PO8	PO6	PO6	PO8
QU	Ist Pref.	QU 1	QU1	QU1	QU1	QU1	QU1	QU2
	IInd Pref.	QU 2	QU3	QU2	QU3	QU2	QU2	QU1
	Last Pref.	QU	QU2	QU3	QU2	QU3	QU3	QU3

	Preference	AC	NG	ENG	IE	EE	INV	OTHERS
		3						
NA	Ist Pref.	NA2	NA1/NA2	NA1/NA2	NA1	NA2	NA2	NA1
	IInd Pref.	NA1	-	-	NA2	NA1	NA1	NA2
	Last Pref.	NA3	NA3	NA3	NA3	NA3	NA3	NA3
RI	Ist Pref.	RI3	RI2	RI2	RI3	RI2	RI5	RI2
	IInd Pref.	RI2	RI3	RI3	RI4	RI3	RI2	RI3/RI4
	Last Pref.	RI5	RI4/RI5/RI6	RI1	RI6	RI1	RI1	RI6
US	Ist Pref.	US1	US1	US1	US1	US1	US3	US1
	IInd Pref.	US2	US3	US2	US2	US2/US3	US1	US2
	Last Pref.	US3	US2	US3	US3	-	US2	US3
DE	Ist Pref.	DE1	DE1	DE3	DE4	DE1	DE1	DE1
	IInd Pref.	DE2	DE2	DE2/DE4	DE1	DE2	DE3	DE3
	Last Pref.	DE4	DE3	DE1	DE2	DE3	DE4	DE4
FL	Ist Pref.	FL1	FL4	FL4	FL1	FL6	FL1/FL4	FL4
	IInd Pref.	FL4	FL1	FL1	FL4/FL5	FL1	FL2/FL5	FL1
	Last Pref.	FL2	FL2	FL3	FL2	FL3	FL3	FL2
RR	Ist Pref.	RR2	RR2/RR3/RR4	RR2	RR2	RR1	RR4	RR3
	IInd Pref.	RR3	RR1	RR4	RR3	RR3	RR2	RR2
	Last Pref.	RR4	-	RR3	RR1/RR4	RR4	RR1	RR4
MA	Ist Pref.	MA4	MA4	MA1	MA1	MA4	MA2	MA1/MA4
	IInd Pref.	MA2	MA1	MA2	MA4	MA2	MA1	MA2
	Last Pref.	MA3	MA3	MA3	MA3	MA1	MA3	MA3
SS	Ist Pref.	SS1	SS1	SS1	SS2/SS1	SS1	SS3/SS4	SS1
	IInd Pref.	SS2	SS4	SS3/SS2	SS4	SS2	SS1	SS2
	Last Pref.	SS3	SS3	SS4	SS3	SS3	SS2	SS4
EM	Ist Pref.	EM1	EM1	EM3	EM1	EM1	EM1	EM2
	IInd Pref.	EM2	EM3	EM1	EM2	EM3	EM2	EM1
	Last Pref.	EM6	EM6	EM4	EM5	EM6	EM6	EM6

To select the effective indicators, experts developed a scale that carries the five categories namely not suitable, less suitable, moderately suitable, suitable, and highly suitable. The scale has the range of 0-0.20 for not suitable, 0.20-0.40 for less suitable, 0.40-0.60 for moderately suitable, 0.60-0.80 for suitable, and 0.80-1.00 for the highly suitable category as shown in Table 3.7.

Table 3.7: Classification scale of sustainability importance index

Importance Index Range (%)	Filtered Criteria	Nomenclature
0 – 0.20	0	Not suitable
0.20 – 0.40	0	Less suitable
0.40 – 0.60	18	Moderate suitable
0.60 – 0.80	49	Suitable
0.80 – 1.00	26	Highly suitable

A total of 93 indicators related to 15 categories are included in the survey. Among the 93 indicators, none of the indicators lies in the not suitable and less suitable category. The moderate suitable, suitable, and highly suitable category considers the 18, 49, and 26 indicators respectively. Table 3.8 shows the considered total indicators and selected indicators in each main category. Similarly, Fig. 3.18 graphically shows the importance index of sustainability indicators with an appropriate symbol. The indicators with an SII of 0.80 and higher are considered a highly suitable category and considered for further future analysis.

As the highly suitable category carries the 26 indicators, these indicators are corresponding to economic, technical, environmental, social, political, and flexible categories. In the economic category, seven indicators, i.e., capital cost (EC1), O & M cost (EC2), payback period (EC4), Levelized cost of energy (EC5), operational/useful life (EC6), fuel cost (EC7), availability of funds and incentives (EC10) are selected in the highly suitable category. The technical category carries the technology maturity (TE1), efficiency (TE2), capacity factor (TE3), reliability (TE4), and deployment time (TE5). The social category includes the factors of social benefits (SO1), job creation (SO2), social acceptability (SO3), and impact on human health (SO4). Factors of land requirement (EN1), pollutant emission (EN2), impact on the ecosystem (EN3), and climate change (EN8) are selected in the environment category. Political acceptance (PO1), foreign dependency (PO2), compatibility with national energy policy (PO5), and fuel reserve years (PO7) indicators are given high importance in the political category. The flexible category considers the two indicators i.e., integration with another source (FL1) and fulfilling the peak load demand (FL4). Fig. 3.19 explains that the evaluation of sustainable energy requires sustainability indicators with the criteria and their relevant sub-criteria. This study finalized the six criteria and their relevant twenty-six sub-criteria as the sustainability indicator for the evaluation of sustainable energy sources in India.

Table 3.8: Summary of sustainability importance index analysis

Criteria	Number of indicators	Selected indicators	Highly suitable	Suitable	Moderate suitable	Less suitable	Not suitable
Economic	12	7	7	5	-	-	-
Technical	14	5	5	6	3	-	-
Social	7	4	4	2	1	-	-
Environmental	10	4	4	2	4	-	-
Political	8	4	4	2	2	-	-
Quality	3	-	-	3	-	-	-
Natural	3	-	-	2	1	-	-
Risk	6	-	-	3	3	-	-
Usability	3	-	-	1	2	-	-
Decommission	4	-	-	4	-	-	-
Flexibility	5	2	2	3	-	-	-
Resource required	4	-	-	4	-	-	-
Market	4	-	-	3	1	-	-
Supply Security	4	-	-	4	-	-	-
Emission	6	-	-	5	1	-	-

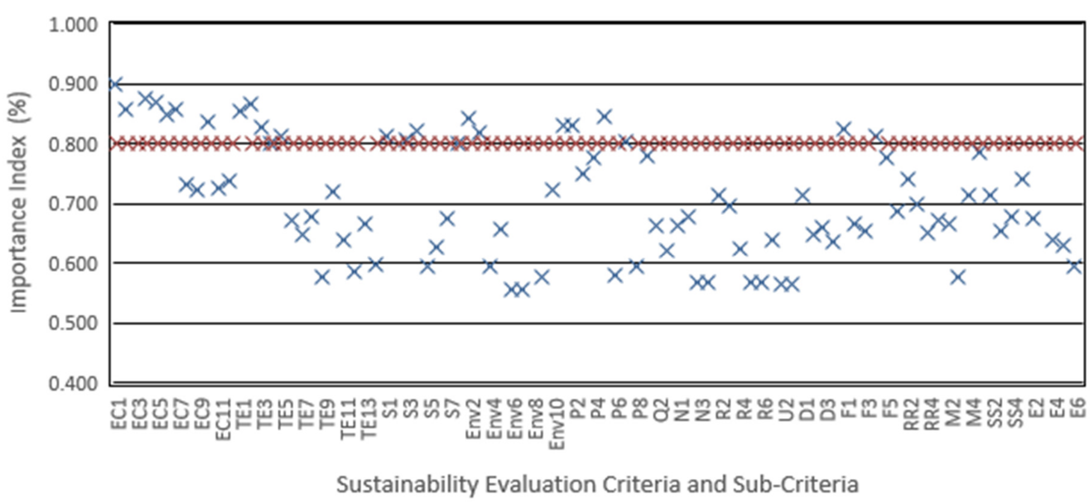


Fig. 3.18: Sustainability importance index of the considered indicators

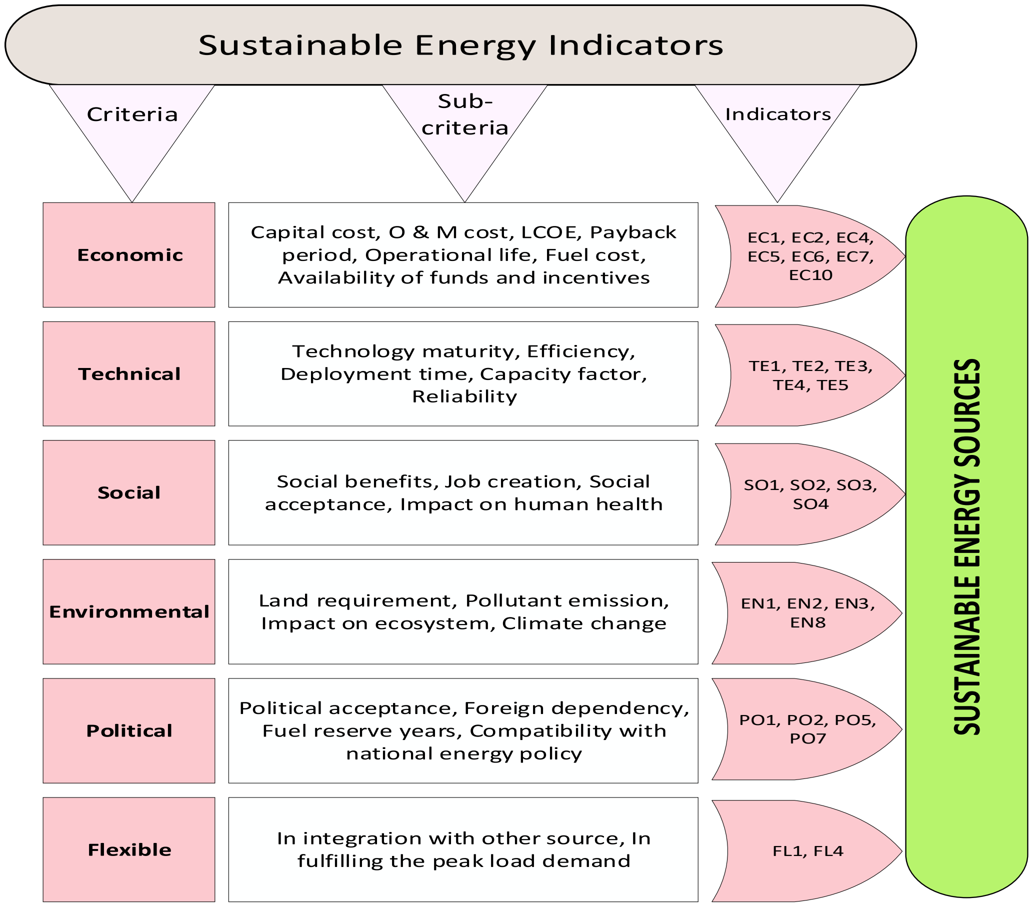


Fig. 3.19: Final sustainability criteria and sub-criteria

3.5 STATISTICAL ANALYSIS TO VALIDATE THE SURVEY OUTCOME

The discussed research work follows the Hair et al. [280] and Flynn et al. [279]general rules for the appropriate and justified results. Hair et al. [280] suggested that the observations must be for at least five times the considered variables. Similarly, Flynn et al. [279] suggested that each category has a sample size of 30 or more is statistically sufficient for the analysis. Further to measure the preciseness of the research findings the authors suggested statistically validating the survey results. The statistical analysis was carried out using SPSS 20.0 software package. The analysis was performed in three consecutive steps reliability analysis, item analysis, and validity assessment which are briefly discussed in the following sections.

Reliability is the degree to which the observed variables measure the "true" value and are "error-free," even if the measure is repeated [280,281]. To check the reliability of the indicators, an internal consistency analysis was performed for the selected indicators using SPSS 20.0 computer tool. The reliability is measured using Cronbach's (α) coefficient. The values of Cronbach's (α) coefficient varies between 0.6 and 0.7 for being an acceptable range and higher than 0.7 for good reliability. The values of Cronbach's (α) coefficient varied between 0.628 and 0.95 for the ten acceptable categories. While five categories less than 0.60 Cronbach's alpha are eliminated from further analysis.

After introducing the reliability of variables, a detailed item analysis is performed on ten categories as discussed earlier for the deletion or retention of indicators. The item analysis excluded the indicators through the establishment of interpreting inter-item correlation matrix or corrected item-total correlation. Here, the inter-item correlation matrix describes the way the particular indicator (sub-criteria) is related to other indicators (sub-criteria). A rule of thumb is that the sub-criteria that's correlation less than 0.40 is not adequately related and therefore does not contribute to the measurement of the core category. The three sub-factors of the emission category particularly have the less correlation index. Therefore, these three sub-criteria are not carried out for further analysis. The complete details about Cronbach's alpha and item analysis are provided in Table 3.9.

Table 3.9: Results of reliability and item analysis

Criteria	Total number of sub-criteria (original)	Total number of sub-criteria deleted	Number of sub-criteria (remaining)	Cronbach's Alpha	Item analysis	Number of sub-criteria after item analysis (remaining)
Economic	12	3	9	0.882	√	9
Technical	14	2	12	0.95	√	12
Social	7	2	5	0.706	√	5
Environmental	10	5	5	0.815	√	5
Political	8	3	5	0.719	√	5
Quality	3	3	0	0.435	×	0
Natural	3	3	0	0.512	×	0
Risk	6	3	3	0.817	√	3
Usability	3	3	0	0.358	×	0
Decommission	4	2	2	0.628	√	2
Flexibility	5	2	3	0.651	√	3
Resource required	4	2	2	0.681	√	2
Market	4	4	0	0.401	×	0
Supply Security	4	4	0	0.483	×	0
Emission	6	0	6	0.773	√	3

In the third step, the outcome is validated in terms of content and construct validation [278]. The content validation is carried out with the help of senior experts who have sufficient knowledge or experience in the field of sustainability or the energy sector. While to determine the construct validation, factor analysis is generally carried out [282]. Prior to applying factor analysis to the categories, it is necessary to first examine the strength of the relationship among the indicators. To determine the strength of the relationship among the indicators, the literature recommended three measures of sampling adequacy, Bartlett's test of sphericity, correlation matrix, and Kaiser-Meyer-Olkin (KMO) test. The results of KMO are found between 0.636 and 0.902, which is above 0.60 and considered suitable for performing the factor analysis [283]. Here, two categories decommission and resources required have KMO values less than 0.6. Therefore, these two categories are excluded from further analysis.

Further to the above, factor analysis is conducted on the sub-criteria level under each category based on the principal component analysis with varimax rotation using the statistical computing package SPSS 20. For each category, this analysis is carried out and the number of components extracted in each analysis is determined for eigenvalue greater than 1. The total variance explained is analyzed with varimax rotation on all eight categories. The variance is a value that represents the total amount of dispersion of values for a single variable about the mean. This variance explains how much of a variable's variance is shared with other variables in that factor [284]. In the economic category, seven sub-factors are extracted with an eigenvalue greater than 1 explaining that 57.887 percent of a variable's variance is shared with other variables. While in the technical category, eight sub-criteria are extracted with a percentage variance of 72.057. Social and political categories extracted four sub-criteria with a percentage variance of 53.142 and 58.124 respectively. While all sub-criteria of environmental, risk, flexibility, and emission categories have an eigenvalue higher than 1, these are considered for further analysis.

Whereas, a factor loading represents the correlation between the indicators and their respective categories. The squared loading is the amount of the indicator's total variance accounted for in the category [284]. For a sample size of 93, factor loading is considered to be significant, if loadings are greater than ±0.50 [284]. The factor loading for all the indicators (sub-criteria) under this study is above this specified threshold limit (Table 3.10). Hence, the findings indicate that all the categories or criteria have construct validity.

Table 3.10: Summary of KMO and factor analysis

Criteria	KMO	Item loading range	Eigen value	%variance explained	Category extracted	Sub-criteria in category	Sub-criteria extracted
Economic	0.856	0.663-0.838	4.052	57.887	√	7	EC1, EC2, EC4, EC5, EC6, EC7, EC10
Technical	0.902	0.722-0.895	5.765	72.057	√	8	TE1, TE2, TE3, TE4, TE5, TE8, TE10, TE13
Social	0.636	0.579-0.826	2.126	53.142	√	4	SO1, SO2, SO3, SO4
Environmental	0.796	0.684-0.824	2.88	57.596	√	5	ENV1, ENV2, ENV3, ENV8, ENV10,
Political	0.657	0.579-0.826	2.325	58.124	√	4	PO1, PO2, PO5, PO7,
Quality	-	-	-	-	-	-	-
Natural	-	-	-	-	-	-	-
Risk	0.71	0.827-0.873	2.208	73.586	√	3	RI1, RI2, RI3
Usability	-	-	-	-	-	-	-
Decommission	-	-	-	-	-	-	-
Flexibility	0.694	0.811-0.866	2.1	70.014	√	3	FL1, FL3, FL4
Resource required	-	-	-	-	-	-	-
Market	-	-	-	-	-	-	-
Supply Security	-	-	-	-	-	-	-
Emission	0.734	0.884-0.934	2.506	83.517	√	3	EM1, EM3, EM6

The analytical and statistical test results establish that the categories and the indicators considered in the study are reliable and valid. Thus, the validated factors considered in the study will be useful as an effective tool for the evaluation and assessment of sustainable energy sources in India. It will also be useful for policy and decision-makers in the formulation of policies and plans for the sustainable development of the country.

3.6 SUMMARY

The present chapter analysed a set of sustainability indicators in the Indian context in order to assess India's sustainable energy sources. The study did this by doing a thorough literature search using terms like "sustainability indicators," "Indian energy indicators," "economic indicators," "environmental indicators," and so on. A total of 767 indicators are gathered through a large survey. These indicators are reviewed and evaluated by a panel of experts & specialists, and finally, 93 indicators representing 15 categories are chosen for further analysis. The indicators are then prepared in the form of a survey, with responses gathered from around the country. Finally, 442 responses are received, with 309 male respondents and 133 female respondents The specialists come from the NGO's academic, environmental, investment, and engineering areas. Their responses are studied cumulatively and categorically in order to determine their perspectives on indicators and technology. The SII is calculated based on their collective judgments. The survey results (SII) are validated further by statistical analysis with the SPSS 20 software tool. To validate the survey results, statistical analysis undertakes reliability analysis, item analysis, and validity assessment. Finally, 26 indicators pertaining to economic, technical, social, environmental, political, and flexible categories are selected which will be used in further studies.

The results of the study will serve as a guide for international agencies and government communities in developing standard or globally acknowledged sustainability indicators. In addition, the study assists scholars, governments, policymakers, and decision-makers in achieving the aim of sustainable development while adhering to international obligations. A typical survey approach is also described in this study, which involves searching for indicators, assessing originality, duplication, and irrelevance, and assessing simplicity and adequacy, and will serve as a guide for researchers, managers, academics, and businesspeople.

CHAPTER – 4

EVALUATION OF SUSTAINABLE ENERGY ALTERNATIVES IN INDIA: AN FUZZY INTEGRATED MULTI-CRITERIA DECISION-MAKING APPROACHES

The present chapter provides a brief overview of the Indian energy sector and evaluates India's sustainable energy sources using fuzzy MCDM techniques. In addition, determine the optimum energy mix scenario for India for the time frame of the year 2030.

4.1 INTRODUCTION

Decisions regarding the evaluation of the most sustainable alternative energy sources in India are crucial and complex due to multi-aspect problems. As in the preceding Chapter 3, the study identified 26 sustainability indicators pertaining to the economic, technical, social, environmental, political, and flexible categories. Therefore, in order to deal with multi-aspect decision problems, it is necessarily useful and appropriate to use multi-criteria decision making (MCDM) analysis. The brief details about the MCDM approaches are as follows.

MCDM is a subset of a broader class of operation research models that provide solutions for decision assistance and evaluation of complicated issues with competing criteria and significant uncertainty [35,95]. In other words, MCDM is a technique for determining the best option, ordering, ranking, and sorting the alternatives. Since the 1970s, it has been a powerful tool in the field of decision-making, value judgment, and evaluation [285]. Furthermore, MCDM techniques are commonly used due to their capacity to address complicated problems with inadequate data systems [63,286]. The decision-making process in the MCDM approach has five sequential steps, (i) to define the goal or problem, (ii) to generate the alternatives, (iii) to select the criteria and sub-criteria to evaluate the alternatives, (iv) to collect the judgment regarding the importance, the relative importance of criteria, and (v) finally, the ranking of alternatives [249]. These steps are graphically shown in Fig. 4.1.

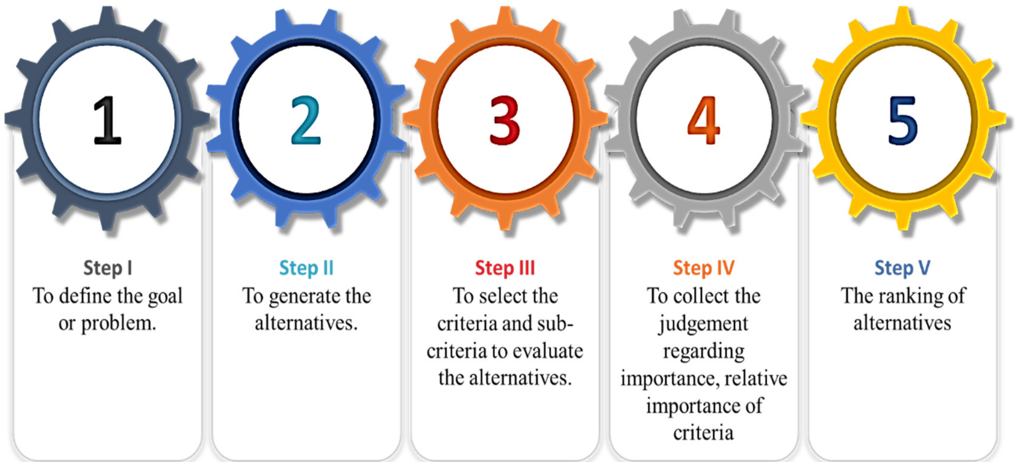


Fig. 4.1: Five sequential steps of the MCDM approach [249]

There are various decision-making methodologies developed by researchers in the literature [38,57,63]. Among the most used MCDM methods for energy-related decisions are counted as Analytic Hierarchy Process (AHP), Analytic Network Process (ANP), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), the Elimination and Choice Translating Reality (ELECTRE), a hybrid of ELECTRE III, and PROMETHEE II, and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Each approach has its advantage and limitations, which are briefly compiled in Appendix VI. Since each method has its properties to select the best alternative, different ranking orders of alternatives can be obtained [67]. The conventional MCDM methods are seen as inadequate to handle uncertainty in crisp numeric weights [63,250]. Hence, it is proposed to apply MCDM methods with linguistic weights to cope with vagueness in a decision-making process. Furthermore, these linguistic judgments MCDM approaches enable to obtain more robust results.

In the present study, an integrated Shannon's entropy multi-criteria decision making (MCDM) method has been utilized for weight calculation of the criteria and ranking the energy sources. The overall objectives of the present chapter are as follows.

- To evaluate the energy sources for the sustainable development of India.
- To employ several integrated MCDM approaches for the comparison and validation of the findings.
- To evaluate the optimal energy mix scenario for the sustainable development of India.

The sustainable energy sources are evaluated using Shannon's entropy integrated fuzzy AHP approach. Afterward, the outcome is compared and validated with six well-known MCDM approaches i.e., TOPSIS, VIKOR, PROMETHEE-II, WSM, WPM, and WASPAS. According to the best of the author's knowledge, this is the highest number of MCDM approaches employed on a single application. In continuation, the study formulated fourteen optimal energy mix scenarios and analysed them. These steps are discussed in detail in the following steps.

4.2 RESEARCH METHODOLOGY

The various steps involved in the proposed model for the evaluation of sustainable energy resources and optimal energy mix scenario in India are shown in Fig. 4.2. The three steps are depicted in the methodology flow chart (Fig. 4.2). Step I involved a thorough examination of the Indian energy sector in order to find potential alternatives. The explanation of the goal, criteria and their related sub-criteria, MCDM techniques, ranking of alternatives, and sensitivity analysis are all covered in step II. Finally, in phase III, the fourteen scenarios were constructed and evaluated in order to choose the best energy mix scenario.

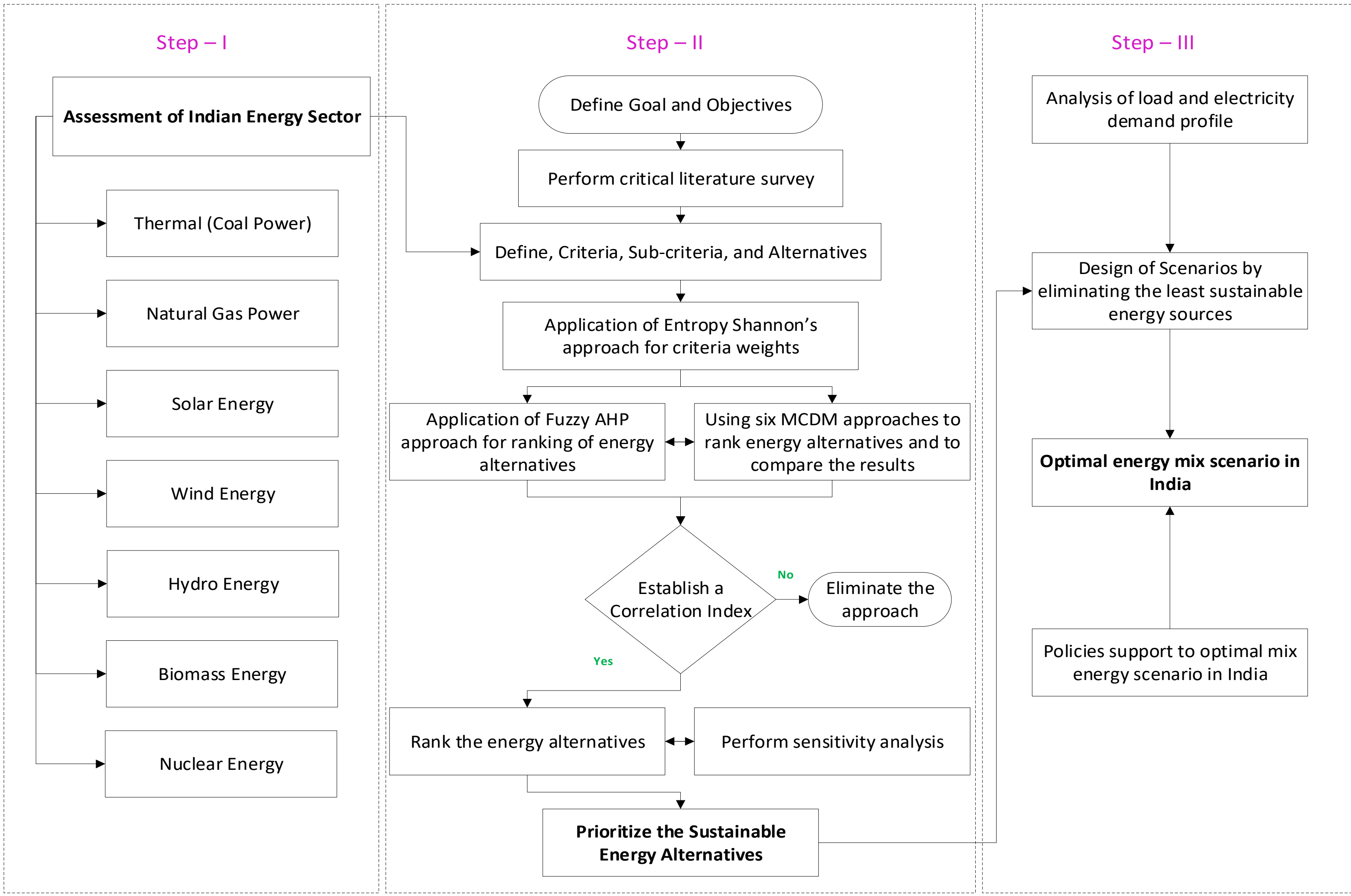


Fig. 4.2: Proposed methodology

4.2.1 Indian Energy Structure and Potential

As earlier discussed, the Indian energy sector predominantly depends on the seven major energy sources: thermal (coal), gas power, solar energy, wind energy, hydro energy, biomass energy, and nuclear energy. These energy sources are briefly discussed in the following sections.

4.2.1.1 Thermal power plants

Thermal power plants are the backbone of the Indian power sector. It is a major source of electricity generation in India with a share of 60% of the overall installed capacity of India. A thermal power plant converts high calorific value fuel into heat or energy. Coal, natural gas, and petroleum products are used as fuel in thermal power plants. Coal was the first fuel used in Indian thermal power plants and is still king of Indian power plants. Coal and lignite have an installed capacity of 208614 MW its share in the overall installed capacity is 53.77% [20].

Coal is a widely used fuel in thermal power plants because of its reliability, cheapness, and abundant availability in the country. India is the second-largest coal producer in the world. In 2017, India produced 716 MT of coal which was 9.3% of the overall production of the world. India is also ranked fifth largest (98 billion tons) coal reserve in the world [18]. The states of Jharkhand, Odisha, Chhattisgarh, West Bengal, Madhya Pradesh, Telangana, and Maharashtra are the major coal-producing states in India [287]. Lignite is available at limited locations like Tamil Nadu (Neyveli), Gujarat (Akrimota and Surat), and Rajasthan (Bithnok, Barsingsar, and Palana). As coal contains a high amount of carbon contents, Sulphur, and nitrogen similar to other fossil fuels. The combustion of coal releases gases (oxides of carbon, Sulphur, nitrogen, and ash) that are hazardous to the atmosphere and human lives. It will create problems of acid rain, global warming, etc.

4.2.1.2 Natural gas power plants

Natural gas is one of the cleanest, safest, and most useful energy sources. Natural gas power plants generate electricity by burning natural gas as a fuel. India has an estimated reserve of 1227.23 billion cubic meters of natural gas until the year 2016. Maximum reserves of natural gas were identified in eastern offshore (36.79%) and western offshore (23.95%) [287]. Natural gas power plants have less gestation period and high thermodynamic efficiency as compared to other power plants. It has also the capability to quickly ramp up and ramp down so that it will help in fulfilling the peak demand. Modern combined cycle gas power plant has high thermodynamic efficiency. As natural gas contains hydrocarbons, hydrosulphide, nitrogen, and higher alkanes. Therefore, by combustion of natural gas emission of oxides of carbon, nitrogen, and Sulphur [20,86].

4.2.1.3 Solar energy

Solar energy is a renewable energy source that is obtained from sun radiation. Sun radiation is converted into usable forms such as heat or electricity by using a solar thermal system or solar photovoltaic cells. Solar radiation received on the earth's surface depends on latitude & longitude, seasons, altitude, air humidity, and local weather [74]. Fortunately, India lies in between the Tropic of Cancer and the Equator. Therefore, India receives a global solar radiation intensity of 1200 kWh/m^2/year to 2300 kWh/m^2/year [83]. India has an estimated solar energy potential of 750 GW which is the highest in the world [288]. In terms of solar energy potential, the Rajasthan state leads at the first position with an exploitable energy capacity of 142 GW, followed by the Jammu & Kashmir state with a capacity of 111 GW [289].

Solar energy generation is accelerated under the Jawaharlal Nehru National Solar Mission [JNNSM]. JNNSM implemented solar energy generation in 2010 by the National Action Plan on Climate Change (NAPCC) to promote and develop solar energy resources in India [290]. Under JNNSM, an ambitious target of 20 GW of grid-connected solar power, and 2 GW off-grid solar power including 20 million solar lighting systems until 2022 is set [20]. Solar energy is considered the cleanest technology for energy generation, but it has some levels of emission such as the use of cadmium and mercury in the production of a solar cell [20,61].

4.2.1.4 Wind energy

Wind energy is the most technically mature, clean, and cheap energy source. Therefore, it is considered an alternative to fossil fuels [36]. The air-flowing phenomenon occurs due to uneven heating of the earth's surface. Wind energy is produced by the conversion of the kinetic energy of flowing air using wind turbines. National Institute of Wind Energy (NIWE), India has estimated a wind energy potential of 49.13 GW in 2012. Similarly, the Indian Wind Turbine Manufacturer Association [IWTMA] and World

Institute for Sustainable Energy (WISE) have estimated wind energy potential of 65-70 GW and 100 GW respectively [291]. Whereas, another recent study calculated region-wise total wind power potential such as eastern region – 155 GW, western region – 914 GW, northern region – 397 GW, southern region – 1265 GW, and north-eastern region – 8 GW [292]. India is the fifth-largest country in the world in the installed capacity of wind energy. Tamil Nadu, Gujarat, Rajasthan, Maharashtra, and Karnataka are the major states of wind energy generation in India [20]. To estimate wind energy potential, 794 dedicated wind monitoring stations have been installed at different heights of 20 m to 120 m [293]. The government of India put an ambitious target to set up 175 GW capacity of renewable energy by 2022. This target will be covered by 100 GW of solar energy capacity, 60 GW of wind energy capacity, 10 GW of small hydro, and 5 GW of biomass power [294]. As an environmental effect, Wind turbines (gearbox and generator) produce noise pollution. A single wind turbine has a noise intensity of 50-60 dB at a buffer distance of 40 m [20].

4.2.1.5 Hydro energy

A hydroelectric power plant converts the potential energy of water into electrical energy. India's first hydroelectric power plant with a capacity of 130 kW is commissioned at Darjeeling in 1879 [295]. India has an estimated hydroelectric power potential of 84044 MW at a 60% plant load factor [296]. Public sector units such as National Hydroelectric Power Corporation (NHPC), NTPC- Hydro, Tehri Hydro Development Corporation, Northeast Electric Power Company, Satluj Jal Vidhyut Nigam (SJVN) are engaged in the development of hydroelectric power plants in India [20]. Hydroelectric power projects have the advantages of easily on/off, quick response to peak load events, and energy storage for daily/seasonally/peak load demand [74]. Hydroelectric power projects had a high gestation period and required high capital investment. The installation of hydroelectric power plants has fewer greenhouse gases, NOx, and SOx emissions. It disturbs the socio-environment system by affecting agriculture and irrigation patterns, land acquisition, environmental clearance, rehabilitation, and resettlement of people [20,74].

4.2.1.6 Biomass energy

As India is predominantly an agricultural economy, it is rich in the availability of biomass resources in the form of agriculture waste, animal dung, organic components found in municipal and industrial waste [293]. Biomass can be converted into a suitable form of energy through different conversion technologies. India has a huge biomass power potential from agriculture wastes (17538 MW), bagasse cogeneration (5000 MW), and organic and municipal waste (2556 MW) [83]. States of India such as Punjab, Bihar, Uttar Pradesh, Gujarat, Karnataka, Andhra Pradesh, and Tamil Nadu have the highest biomass energy potential [293]. Biomass energy has some negative environmental effects such as the emission of greenhouse gases and some amount of NOx and SOx [20,83].

4.2.1.7 Nuclear energy

Nuclear energy is the energy released due to the splitting or merging of the nucleus of an atom. Nuclear energy is the fourth largest energy source in India after thermal, renewable, and hydro energy [20]. Nuclear power has an installed capacity of 6780 MW which covers a share of 2% of the overall installed capacity [19]. A target of capacity addition of 5300 MW under the 12th five-year plan (2012-2017) is set. The Nuclear Power Corporation of India Ltd. (NPCIL) is responsible for the design, planning, construction, commissioning, and operation and maintenance of nuclear power plants in India. Nuclear power is a controversial power generation source. Many organizations, people, environmental analysts, and socialists are highly concerned about radioactive fuel and the radioactive waste of nuclear power. Nuclear energy has very less social acceptability in India due to the fear of radioactive fuel and awareness about nuclear energy [20].

Apart from the above sources, many other sources viz. geothermal, hydrogen, tidal, and wave energy. But the scope of the present work is limited to only seven major energy alternatives. Therefore, in order to assess the sustainability of energy sources, seven energy alternatives namely thermal, gas power, nuclear, solar, wind, hydro, and biomass are considered. In the present study, for the simplification purpose, only a large hydro energy source is considered and a micro or mini-hydro energy source is excluded. Biogas, biomass, and municipal solid waste are collectively considered in biomass energy. In solar energy, special focus is given to solar PV technology and for thermal energy, only the coal-based energy source is considered.

4.2.2 Sustainability Criteria and Sub-Criteria

The study has earlier identified 26 sub-criteria in the six categories of economic, technical, social, environmental, political, and flexible. Brief details about the criteria and sub-criteria are provided in the following section.

The criteria and the sub-criteria that will be used to evaluate sustainable energy alternatives are briefly explained in the following Table 4.1.

Table 4.1: List of criteria and their relevant sub-criteria with their references

Criteria	Sub-Criteria	References
Economic	**Capital Cost/ Investment Cost (C1):** Total amount of money required to install a power plant.	[38,76,251]
	Operation & Maintenance Cost (C2): It consists of employees' wages, costs of products and equipment, operation costs, energy expenses, and the maintenance cost of equipment.	[37,75]
	Payback period (C3): Time period required for the return of the overall investment of the project.	[71,79]
	Levelized Cost of Electricity (C4): This criterion refers to per unit energy generation cost. It represents in Rs./kWh or $/kWh.	[30,256,297]
	Useful/operational Life (C5): The expected lifetime of a power plant, the time period between installation and decommissioning.	[66,67,250]
	Fuel Cost (C6): The amount of funds spent on the processes of mining, extraction, fuel processing, and transportation cost of the fuel. It is expressed in Rs./liter or $/liter.	[53,62,71,75,92]
	Availability of Funds/Incentives (C7): The economic support of government and funds are given by national and international agencies.	[58,74,298]
Technical	**Technology Maturity (C8):** It shows the easy availability of technology at local, national, and international markets.	[61,73,74,92]
	Efficiency (C9): It is the ratio of final obtained energy and the overall available energy.	[79,92,255]
	Capacity Factor (C10): It is the ratio of actual energy output in a given time period to the theoretical energy output.	[36,62,66,76,83,255]
	Reliability (C11): A system continuously performing well, which means it has higher reliability. In general words, reliability means the probability of failure.	[71,81]
	Deployment Time (C12): The time required to install a power plant until it starts power production.	[65,251]

Criteria	Sub-Criteria	References
Social	**Social benefits (C13):** Social benefits represent the development of the social community and region by introducing an energy project. Social benefits in the form of job creations, local income, and social welfare aspects.	[54,74]
	Job creation (C14): It includes direct or indirect jobs created during the life cycle (install, operations, and decommissioning) of an energy source.	[53,56,59,249]
	Social acceptance (C15): It is related to the opinions of acceptance and rejection of local social groups, authorities, and stakeholders about the energy system.	[38,92,299]
	Impact on human health (C16): It is a qualitative assessment based on the emission of harmful products. It is analyzed based on the problems of cancer, skin diseases, and respiratory.	[92,249,255]
Environmental	**Land requirement (C17):** It considers the requirement of land (km^2) to install an energy source (GW).	[30,40,80,261,298]
	Pollutant Emission (C18): It considers the emission of all the harmful products in the atmosphere, such as greenhouse gases, solid and liquid waste.	[57,92]
	Impact on ecosystem (C19): It mainly covers ground contamination, land use, water consumption, liquid and solid waste, visual and noise pollution.	[37,79,96]
	Climate change (C20): It is a phenomenon that will happen due to the harmful emission in the environment by the power plants.	[32,54,252]
Political	**Political acceptance (C21):** Political acceptance is the government support given in policies or technologies developed by its compatibility in administration, legislation, and political situations.	[37,84]
	Foreign dependency (C22): It mainly analyzes the dependency of fuel import from foreign countries.	[57,74,81]
	Compatibility with national energy policy (C23): Fuel reserve year is defined as a duration of the time period until fossil fuels completely depleted on the earth.	[57,74,86]
	Fuel reserve years (C24): Higher compatibility with national energy policy will get higher support from government and organizational institutes.	[62]
Flexibility	**In integration with another source (C25):** It shows the capability of an energy source to generate power with the integration of another source. It mainly considers increasing the availability of energy sources and the maximum utilization of available resources.	[271,272]
	In fulfilling the peak load demand (C26): It considers the ability of the power plant to respond to the peak load events or change in demand variation.	[39,56,255]

4.2.3 Criteria Weight Calculation and Ranking the Alternatives

MCDM methodology requires the identification of criteria, sub-criteria, and alternatives related to a goal, followed by assigning numerical measures to evaluate the importance of criteria and alternatives, and finally, the alternatives are prioritized and ranked. In this study, Shannon's entropy method is applied to determine the weights of decision criteria, and a fuzzy analytical hierarchy process (AHP) is applied to prioritize sustainable energy alternatives. The concept was developed by Shannon and Weaver in 1947. Shannon and Weaver applied it to solve the information problems. According to the entropy theory, a less entropy value means higher criterion weights and more information available [36,300]. Shannon's concept is employed to calculate criteria weights because of the capabilities to analyze subjective and objective expert's opinions [300].

4.2.3.1 Shannon's entropy method

The equations are adapted from the study of Lee and Chang [36], which are discussed in the following steps.

Step – I Normalize the decision matrix

$$n_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}} \qquad i = 1, 2 \dots \dots m \tag{4.1}$$

Step – II Compute the entropy for each column

$$e_j = -K \sum_{i=1}^{m} n_{ij} . \ln n_{ij} \qquad j = 1, 2 \dots \dots n \tag{4.2}$$

where $K = -\frac{1}{\ln m}$ is defined as the entropy constant.

Step – III Calculation of diversification factor for each column

$$d_j = 1 - e_j \tag{4.3}$$

Step – IV Compute the normalized weight vector

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \qquad j = 1, 2 \dots \dots n \tag{4.4}$$

4.2.3.2 Fuzzy analytical hierarchy process (AHP)

Prof. Saaty developed the AHP approach in 1980. AHP is becoming quite popular in the MCDM research domain as it uses a hierarchical or network-based structure. In the hierarchal network model, the top level contains the goal of the analysis, the middle level contains the criteria and sub-criteria used for the analysis and the bottom level contains the energy alternatives used for evaluation. It decomposed the problem into many sub-problems, which are analysed or solved separately [54]. The fuzzy AHP approach uses the pair-wise comparison to assign the weights to consider the criteria and ranks to different energy alternatives.

Step – I Research work was carried out with the fuzzy AHP approach proposed by Buckley in 1985.

Step – II Relative importance of sustainable energy alternatives is obtained by making the pair-wise comparison. The weights are calculated using the fuzzy geometric mean method and the equations are as follows

$$a = (p_1 \times p_2 \times \ldots \times p_n), b = (q_1 \times q_2 \times \ldots \times q_n), c = (r_1 \times r_2 \times \ldots \times r_n) \quad (4.5)$$

n = number of criteria

Step – III Fuzzy weights are obtained by multiplication of fuzzy geometric mean and reciprocal of summation of those fuzzy geometric mean values as explained in Eq. 4.6.

$$w_l = a_l(a_1 + a_2 + \cdots + a_n)^{-1},\ w_m = a_m(a_1 + a_2 + \cdots + a_n)^{-1},\ w_u = a_u(a_1 + a_2 + \ldots + a_n)^{-1} \quad (4.6)$$

Step – IV De-fuzzified crisp numeric values (DCNV) are obtained by an average of the fuzzy lower, medium, and higher values as given in Eq. 4.7.

$$DCNV = \frac{w_l + w_m + w_u}{3} \quad (4.7)$$

Step – V To validate the expert's judgment consistency ratio has been checked. The consistency ratio should be less than 0.1 for true criteria weight.

$$CR = \frac{CI}{RI} \quad (4.8)$$

$$CI = (\lambda_{max.} - n)/(n - 1) \quad (4.9)$$

where *CI* = consistency index, *RI* = random index, λ_{max} = maximum eigenvalue, *n* = number of criteria

4.2.3.3 Fuzzy MCDM approaches for comparison and validation

In order to validate the output of the proposed model, the model is compared with six fuzzy MCDM techniques namely TOPSIS, VIKOR, PROMETHEE – II, WSM, WPM, WASPAS. Among the considered MCDM approaches, TOPSIS approach was developed by Hwang and Yoon, VIKOR approach was introduced by Opricovic and Tzeng, PROMETHEE-II was developed by the J. P. Brans, and WASPAS was proposed by the Zavadskas et al. [36,53,274]. The steps followed for analysis are described in Appendices VII and VIII. Next, the Results and discussion section gave the results of these analyses.

4.3 RESULTS AND DISCUSSION

The aims of the chapter are: (i) to evaluate the energy sources for the sustainable development of India, and (ii) to identify the optimal energy mix scenario for the sustainable development of the country. Whereas, in the objective first, the evaluation is carried out in two ways (a) Shannon's entropy integrated MCDM approaches, and (b) fuzzy AHP integrated MCDM approaches. Here, both Shannon's entropy and fuzzy AHP approaches are employed to assign weights to the criteria, while the alternatives ranking from other MCDM are identical in both approaches. The brief details are provided in the following sub-sections.

4.3.1 Evaluation of Sustainable Energy Sources: Shannon's Entropy Integrated MCDM Approaches

Owing to the difficulty in the evaluation of sustainable energy sources among various renewable and non-renewable energy sources, this study used twenty-six sub-criteria in six categories to evaluate seven energy alternatives. Expert's opinions were collected by performing a survey among the academicians and industry experts. The subjective weight is given to evaluate the performance of a particular energy source.

The section consists of five parts: criteria weights obtained from Shannon's entropy approach, the ranking of alternatives using the fuzzy AHP approach, comparative studies, validation of the results, and sensitivity analysis which are briefly discussed below.

4.3.1.1 Criteria weights

The criteria weights are calculated by using Shannon's entropy approach, the results indicate that the economic and environmental criteria are the most important criteria with a relative weight of 0.281 and 0.185 respectively. The technical criterion emerges as the third important criterion with a preference score of 0.175. Political, social, and flexible criteria are the three least important criteria. In addition, efficiency (C9) and emission reduction (C18) are the two most important sub-criteria for sustainability assessment as shown in Fig. 4.3. The complete details of criteria weights and ranking of criteria are shown in Table 4.2.

Table 4.2: Shannon's entropy criteria and sub-criteria weights

Criteria	Sub-Criteria	Weight	Rank	Weight	Ranks
Economical	Capital cost/investment cost (C1)	0.0488	6	0.281	1
	Operations and maintenance cost, (C2)	0.0588	3		
	Levelized cost of energy, (C3)	0.0319	17		
	Payback Period, (C4)	0.0400	12		
	Operational life, (C5)	0.0201	25		
	Fuel cost, (C6)	0.0343	15		
	Availability of funds and incentives, (C7)	0.0473	7		
Technical	Technology maturity, (C8)	0.0235	21	0.175	3
	Efficiency, (C9)	0.0653	1		
	Deployment time, (C10)	0.0449	10		
	Capacity factor, (C11)	0.0184	26		
	Technology reliability (risk of accidents) (C12)	0.0233	22		
Social	Social benefits (education, science, and culture) (C13)	0.0273	20	0.126	5
	Job creation, (C14)	0.0451	9		
	Social acceptance, (C15)	0.0231	23		
	Impact on human health, (C16)	0.0303	18		
Environment	Land requirement, (C17)	0.0379	13	0.185	2
	Emission reduction, (C18)	0.0622	2		
	Impact on ecosystem, (C19)	0.0558	4		

Criteria	Sub-Criteria	Weight	Rank	Weight	Ranks
	Climate Change (C20)	0.0294	19		
Political	Political acceptance, (C21)	0.0379	14	0.161	4
	Foreign dependency, (C22)	0.0447	11		
	Fuel reserve years, (C23)	0.0466	8		
	Compatibility with national energy policy (C24)	0.0320	16		
Flexible	In integration with other sources, (C25)	0.0218	24	0.071	6
	In fulfilling the peak load demand, (C26)	0.0494	5		

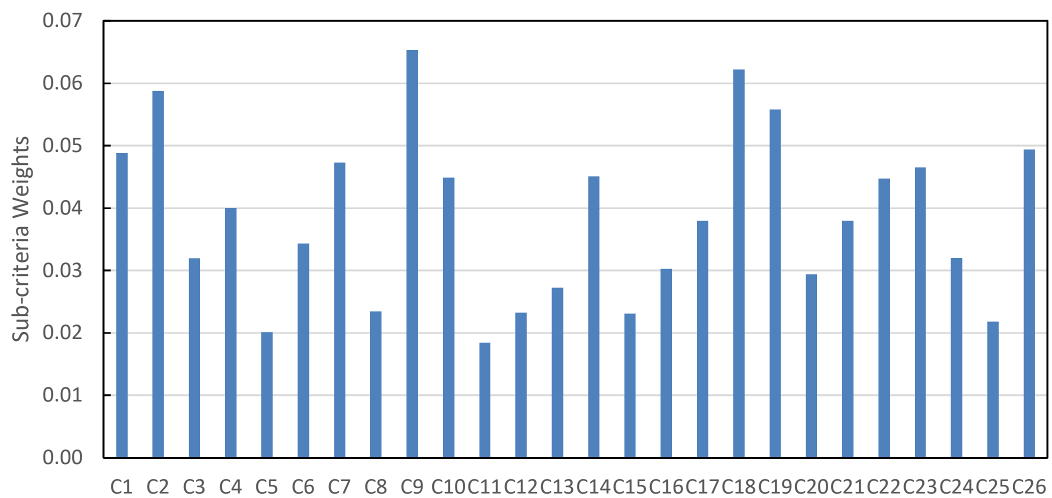


Fig. 4.3: Representation of Shannon's entropy sub-criteria weights

4.3.1.2 Ranking of alternatives

Using Shannon's entropy criteria weights, the fuzzy AHP approach is used for the ranking of the energy alternatives. A pair-wise comparison is done among the energy alternatives for each criterion and obtained the preference scores of energy alternatives. The product of Shannon's entropy criteria weights and fuzzy AHP has given energy alternatives preference score will give the final de-fuzzified weights. Table 4.3 shows the final de-fuzzified weights, and the final ranking of the energy alternatives using the fuzzy AHP approach.

The energy alternatives are ranked based on the higher de-fuzzified final weights such as solar energy ranked first with the highest final weight of 0.197. Wind energy achieved the second rank with a weight of 0.175, and the third rank was obtained by hydro energy with a weight of 0.144. Biomass, gas power, thermal, and nuclear energy obtained the fourth, fifth, sixth, and seventh ranks respectively as shown in Fig. 4.4.

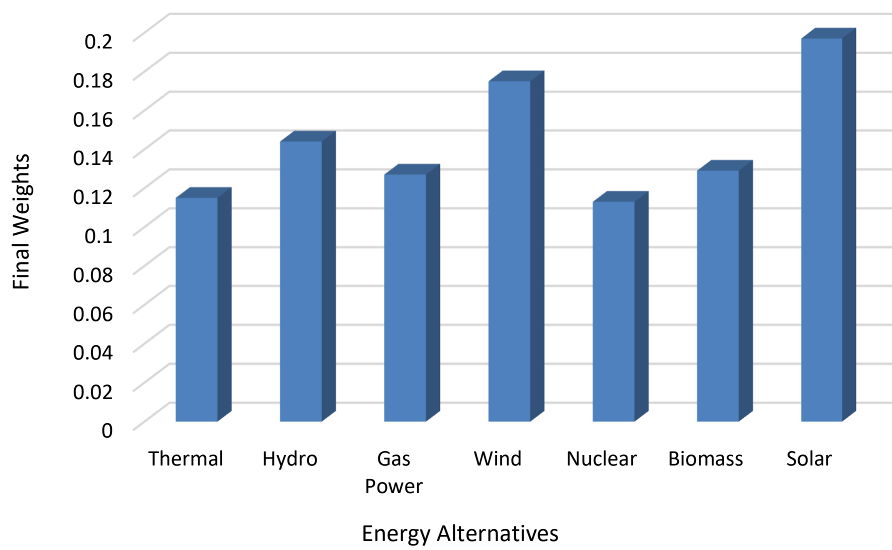


Fig. 4.4: De-fuzzified weights of energy alternatives using fuzzy AHP approach

4.3.1.3 Comparative analysis

To compare and validate the results of the fuzzy AHP approach, six different fuzzy MCDM approaches have been employed. Firstly, the fuzzy TOPSIS approach has been employed to rank energy alternatives. Initially, a fuzzy positive ideal solution (FPIS), a fuzzy negative ideal solution (FNIS), and a closeness coefficient (CC) are determined for each energy alternative. Table 4.4 shows the results of the fuzzy TOPSIS approach. Solar energy has the highest closeness coefficient from the fuzzy negative ideal solution. While wind energy and hydro energy carries the second and third highest closeness distance of 0.723 and 0.639 respectively.

Table 4.3: Ranking of energy alternatives using fuzzy AHP approach

	Economic	Technical	Environmental	Social	Political	Flexibility	Final Weightage	Final Ranking
Thermal	0.281 × 0.149	0.175 × 0.123	0.185 × 0.088	0.126 × 0.102	0.161 × 0.0924	0.071 × 0.100	0.115	**6**
Hydro	0.281 × 0.137	0.175 × 0.113	0.185 × 0.156	0.126 × 0.160	0.161 × 0.1483	0.071 × 0.184	0.144	**3**
Gas	0.281 × 0.124	0.175 × 0.123	0.185 × 0.128	0.126 × 0.145	0.161 × 0.1034	0.071 × 0.173	0.127	**5**
Wind	0.281 × 0.177	0.175 × 0.176	0.185 × 0.178	0.126 × 0.180	0.161 × 0.1782	0.071 × 0.144	0.175	**2**
Nuclear	0.281 × 0.102	0.175 × 0.110	0.185 × 0.126	0.126 × 0.097	0.161 × 0.1251	0.071 × 0.114	0.113	**7**
Biomass	0.281 × 0.116	0.175 × 0.144	0.185 × 0.116	0.126 × 0.127	0.161 × 0.1558	0.071 × 0.126	0.129	**4**
Solar	0.281 × 0.195	0.175 × 0.210	0.185 × 0.208	0.126 × 0.190	0.161 × 0.1968	0.071 × 0.160	0.197	**1**

Table 4.4: Ranking of energy alternatives using fuzzy TOPSIS approach

	Thermal		**Hydro**		**Gas power**		**Wind**		**Nuclear**		**Biomass**		**Solar**	
	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS	FPIS	FNIS
	0.655	0.457	0.396	0.701	0.571	0.537	0.298	0.777	0.597	0.500	0.438	0.665	0.262	0.799
Total	1.112		1.097		1.108		1.075		1.097		1.104		1.062	
CC	0.411		0.639		0.485		0.723		0.456		0.603		0.753	
Ranks	**7**		**3**		**5**		**2**		**6**		**4**		**1**	

Note: FPIS-Fuzzy Positive Ideal Solution, FNIS-Fuzzy Negative Ideal Solution, CC-Closeness Coefficient

Next, the fuzzy VIKOR approach is used to rank the energy alternatives. Results are obtained in terms of usefulness (Si) and discomforts (Ri) with their minimum (S* and R*) and maximum (S^- and R^-) values. Energy alternatives are ranked on the basis of least to highest values of the fuzzy VIKOR index (Qi). Solar energy has obtained the least fuzzy VIKOR index value. Whereas, thermal energy is the least preferred alternative source as shown in Table 4.5.

Table 4.5: Ranking of energy alternatives using fuzzy VIKOR approach

	Si	Ri	S*	R*	S-	R-	Qi	Ranks
Thermal	0.700	0.062	0.147	0.050	0.700	0.062	0.975	7
Hydro	0.341	0.054	0.147	0.050	0.700	0.062	0.345	3
Gas power	0.586	0.056	0.147	0.050	0.700	0.062	0.631	5
Wind	0.198	0.050	0.147	0.050	0.700	0.062	0.046	2
Nuclear	0.615	0.062	0.147	0.050	0.700	0.062	0.923	6
Biomass	0.390	0.059	0.147	0.050	0.700	0.062	0.599	4
Solar	0.147	0.050	0.147	0.050	0.700	0.062	0.000	1

Sequentially, the fuzzy PROMETHEE-II approach ranks the energy alternative on the basis of net outranking flow (ϕ). The highest positive value of net outranking flow will provide the most sustainable solution. Solar energy and wind energy alternatives have the highest positive values of 0.301 and 0.252, respectively, which means solar energy and wind energy are the most sustainable energy alternatives. Table 4.6 below shows the results of the analysis.

Table 4.6: Ranking of energy alternatives using fuzzy PROMETHEE-II approach

	Leaving Flow ϕ^+	Entering flow ϕ-	Net Flow (ϕ)	Ranks
Thermal	0.105	0.423	-0.318	7
Hydro	0.286	0.155	0.131	3
Gas power	0.141	0.340	-0.199	5
Wind	0.340	0.088	0.252	2
Nuclear	0.139	0.358	-0.219	6
Biomass	0.240	0.189	0.051	4
Solar	0.387	0.086	0.301	1

Furthermore, research work proceeds with three other well-known fuzzy MCDM approach namely WSM, WPM, and WASPAS. In all these three approaches, alternatives are ranked on the basis of the highest to lowest weighted normalized index. In all three approaches, solar energy obtained the highest preference score which indicates that solar energy is the most sustainable energy source in all three approaches. Table 4.7 below shows the ranking order of alternatives in all the approaches.

Table 4.7: Ranking of energy alternatives using fuzzy WSM, fuzzy WPM, and fuzzy WASPAS approach

	WSM	WPM	WASPAS	Ranks
Thermal	0.392	0.343	0.368	7
Hydro	0.669	0.613	0.641	3
Gas power	0.484	0.425	0.455	5
Wind	0.757	0.709	0.733	2
Nuclear	0.452	0.370	0.411	6
Biomass	0.630	0.571	0.600	4
Solar	0.788	0.716	0.752	1

Results of all six MCDM techniques show that the ranking of the energy alternatives is completely the same and consistent. Referring to Fig. 4.5, the results indicate that solar energy is the most sustainable alternative energy source. Wind energy shows efficient performance and is chosen as the second most alternative energy source. Other renewable energy sources hydro and biomass achieved the third and fourth positions. Similarly, conventional energy sources gas power, nuclear energy, and thermal energy sources are the least preferred energy sources.

4.3.1.4 Validation of results

To analyze the consistency and correlation between the proposed decision-making approach and six comparative MCDM approaches, Spearman's rank, and Karl's Pearson correlation coefficient has been implemented. The analysis was done using IBM SPSS statistics 20 software. Table 4.8 demonstrated the Spearman's rank (r_{SR}) difference and Karl's Pearson (r_{KP}) correlation coefficients between the proposed decision-making approach and six comparative MCDM approaches.

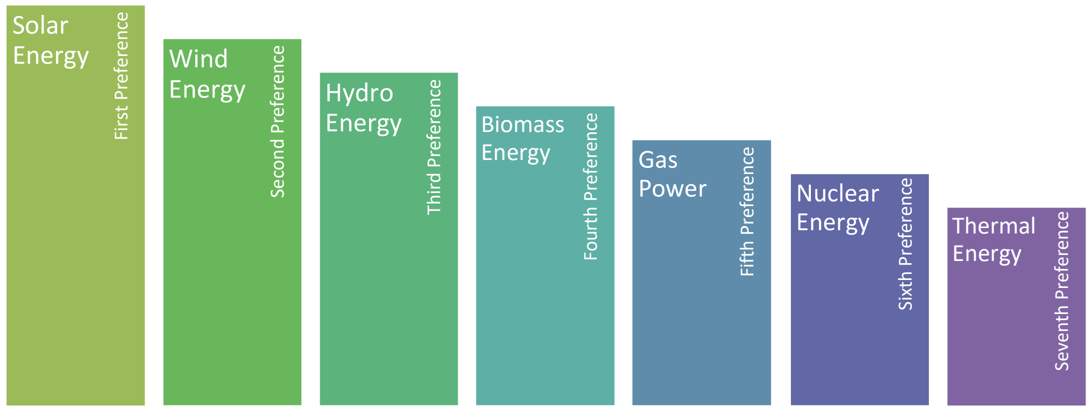


Fig. 4.5: Sustainably ranking of energy alternatives

Table 4.8. Validation through correlation coefficients among the proposed model and six MCDM approaches

		Proposed Model	TOPSIS	VIKOR	PROMETHEE-II	WSM	WPM	WASPAS
Proposed Model	Spearman's	1	0.883	-0.964	0.964	0.964	0.964	0.964
	Karl's	1	0.925	-0.956	0.903	0.910	0.905	0.909
TOPSIS	Spearman's		1	-0.937	0.937	0.937	0.937	0.937
	Karl's		1	-0.970	0.998	0.999	0.996	0.999
VIKOR	Spearman's			1	-1	-1	-1	-1
	Karl's			1	-0.957	-0.964	-0.967	-0.967
PROMETHEE-II	Spearman's				1	1	1	1
	Karl's				1	0.999	0.995	0.998
WSM	Spearman's					1	1	1
	Karl's					1	0.997	0.999
WPM	Spearman's						1	1
	Karl's						1	0.999
WASPAS	Spearman's							1
	Karl's							1

The proposed model has a strong correlation r_{SR} =0.883, r_{KP} = 0.925, and $p < 0.05$ with the TOPSIS approach. The proposed model and VIKOR approaches have very strong negative correlation coefficients of r_{SR} =0.964, and r_{KP} = 0.956 with a p-value of less than 0.05. While PROMETHEE-II approach validated the results with 0.964 Spearman's rank (r_{SR}) and 0.903 Karl's Pearson (r_{KP}) correlation coefficient values. Three different MCDM approaches (WSM, WPM, and WASPAS) from the same family have the same strong Spearman's rank (r_{SR}) correlation coefficient value of 0.964 with the proposed approach. While, WSM, WPM, and WASPAS approaches have 0.910, 0.905, and 0.901Karl's Pearson (r_{KP}) correlation coefficient value with the proposed model. Though, the analysis validated a strong and consistent relationship between the proposed approach and validating six MCDM approaches.

During the comparison and validation, it is observed that the outcome of MCDM approaches is largely depending on its characteristics, viz., criteria weights, expert's judgment, alternative assessment of conflicting criteria, and sometimes on an approach used [301]. Hence, the outcome of any original research study may only be validated with correlation establishment or sensitivity analysis. Therefore, the current research study compared and validated their outcome with a strong and consistent correlation establishment as well as a wide and deep sensitivity analysis.

4.3.1.5 Sensitivity analysis

To highlight the stability of ranking, sensitivity analysis is essential. In this regard, seven different cases are analyzed by changing the weights of the main criteria. The weights of these criteria were obtained by dividing the total weight by a number of criteria in the analysis. Table 4.9 shows the considered cases and weights in the analysis.

Table 4.9: Criteria weight for different cases

Criteria	Case – I Equal Weight	Case – II Economic	Case – III Technical	Case – IV Social	Case – V Environmental	Case – VI Political	Case – VII Flexible
Economic	0.167	0.5	0.1	0.1	0.1	0.1	0.1
Technical	0.167	0.1	0.5	0.1	0.1	0.1	0.1
Social	0.167	0.1	0.1	0.5	0.1	0.1	0.1
Environmental	0.167	0.1	0.1	0.1	0.5	0.1	0.1
Political	0.167	0.1	0.1	0.1	0.1	0.5	0.1
Flexible	0.167	0.1	0.1	0.1	0.1	0.1	0.5

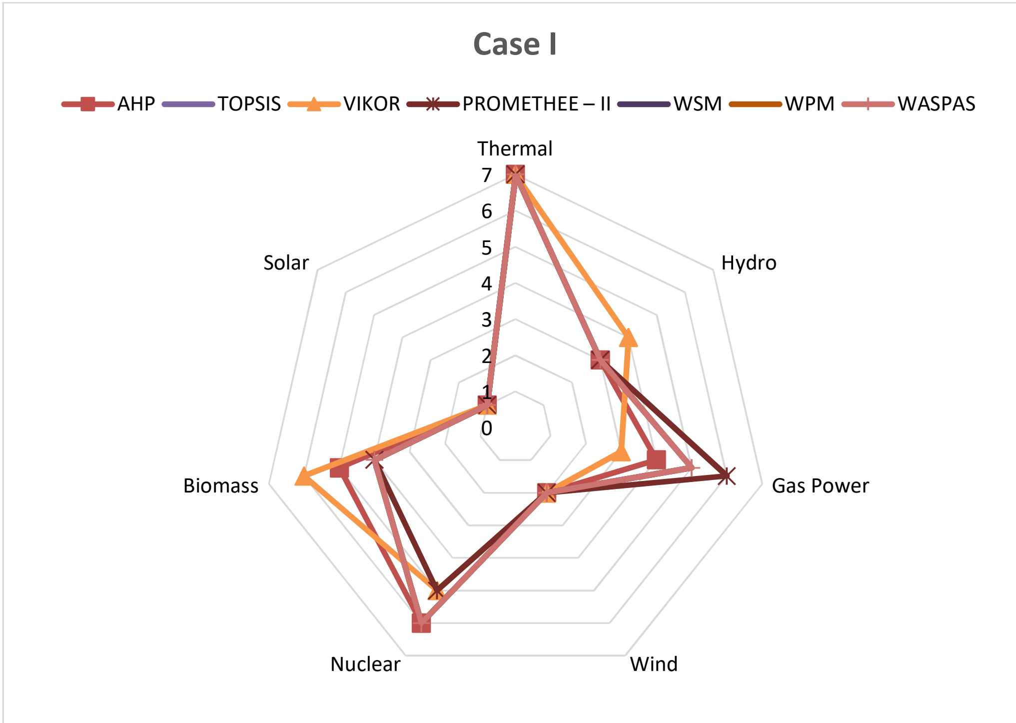
The ranks of different energy alternatives in different methods for different cases are shown in Table 4.10 and by the radar chart in Fig. 4.6. In case I, solar energy is chosen as the most sustainable energy alternative. The possible reason should be economic feasibility, highly social acceptability, comparative environment-friendly, politically acceptable, and promoted. The least sustainable energy is the thermal energy alternative because of greenhouse gas emissions, impact on human health, and scarcity in the availability of fuel. From an economic perspective, solar energy is the most economic energy source, followed by wind, and hydro energy. Solar energy is given preference due to its low capital cost, minimum payback period, least Levelized cost of energy, availability of large funds, and incentives by the government. Thermal energy is the least economically feasible option due to factors of scarcity in the availability of fuel, a huge increase in fuel price, and large capital investment.

Table 4.10: Ranks of energy alternatives in different methods and cases

	Method	Ranks						
		1	2	3	4	5	6	7
Case – I Equal Weight	AHP	Solar	Wind	Hydro	Gas power	Biomass	Nuclear	Thermal
	TOPSIS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	VIKOR	Solar	Wind	Gas power	Hydro	Nuclear	Biomass	Thermal
	PROMETHE E – II	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
	WSM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WPM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WASPAS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
Case – II Economic	AHP	Solar	Wind	Hydro	Gas power	Biomass / thermal	Nuclear	---
	TOPSIS	Solar	Wind	Hydro	Biomass	Gas Power	Thermal	Nuclear
	VIKOR	Hydro	Solar	Wind	Biomass	Gas Power	Thermal	Nuclear
	PROMETHE E – II	Solar	Wind	Hydro	Biomass	Nuclear	Gas power	Thermal
	WSM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WPM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WASPAS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
Case – III	AHP	Solar	Wind	Biomas	Hydro	Gas	Thermal	Nuclear

	Method	Ranks						
		1	2	3	4	5	6	7
Case – I Equal Weight	AHP	Solar	Wind	Hydro	Gas power	Biomass	Nuclear	Thermal
	TOPSIS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	VIKOR	Solar	Wind	Gas power	Hydro	Nuclear	Biomass	Thermal
	PROMETHEE – II	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
	WSM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WPM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WASPAS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
Technical				s		power		
	TOPSIS	Wind	Solar	Hydro	Biomass	Gas Power	Thermal	Nuclear
	VIKOR	Hydro	Biomass	Wind	Solar	Thermal	Gas Power	Nuclear
	PROMETHEE – II	Hydro	Wind	Solar	Biomass	Thermal	Gas Power	Nuclear
	WSM	Wind	Solar	Hydro	Biomass	Gas Power	Thermal	Nuclear
	WPM	Wind	Hydro	Solar	Biomass	Gas Power	Nuclear	Thermal
	WASPAS	Wind	Hydro	Solar	Biomass	Gas Power	Thermal	Nuclear
Case – IV Social	AHP	Solar	Wind	Hydro	Gas power	Biomass	Nuclear / Thermal	---
	TOPSIS	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
	VIKOR	Solar	Wind	Biomass	Hydro	Nuclear	Gas Power	Thermal
	PROMETHEE – II	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
	WSM	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
	WPM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WASPAS	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
Case – V Environmental	AHP	Solar	Wind	Hydro	Gas power	Biomass	Nuclear	Thermal
	TOPSIS	Solar	Wind	Hydro	Nuclear	Biomass	Gas power	Thermal
	VIKOR	Solar	Wind	Nuclear	Gas Power	Hydro	Biomass	Thermal
	PROMETHEE – II	Solar	Wind	Hydro	Nuclear	Biomass	Gas Power	Thermal
	WSM	Solar	Wind	Hydro	Nuclear	Biomass	Gas	Thermal

	Method	Ranks						
		1	2	3	4	5	6	7
Case – I Equal Weight	AHP	Solar	Wind	Hydro	Gas power	Biomass	Nuclear	Thermal
	TOPSIS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	VIKOR	Solar	Wind	Gas power	Hydro	Nuclear	Biomass	Thermal
	PROMETHE E – II	Solar	Wind	Hydro	Biomass	Nuclear	Gas Power	Thermal
	WSM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WPM	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
	WASPAS	Solar	Wind	Hydro	Biomass	Gas Power	Nuclear	Thermal
							Power	
	WPM	Solar	Wind	Hydro	Nuclear	Biomass	Gas Power	Thermal
	WASPAS	Solar	Wind	Hydro	Nuclear	Biomass	Gas Power	Thermal
Case – VI Political	AHP	Solar	Wind	Hydro	Biomas s	Gas power	Nuclear	Thermal
	TOPSIS	Solar	Wind	Hydro	Biomas s	Nuclear	Thermal	Gas Power
	VIKOR	Solar	Wind	Hydro	Biomas s	Nuclear	Thermal	Gas Power
	PROMETHE E – II	Solar	Wind	Hydro	Biomas s	Nuclear	Thermal	Gas Power
	WSM	Solar	Wind	Hydro	Biomas s	Nuclear	Thermal	Gas Power
	WPM	Solar	Wind	Hydro	Biomas s	Nuclear	Thermal	Gas Power
	WASPAS	Solar	Wind	Hydro	Biomas s	Nuclear	Thermal	Gas Power
Case – VII Flexible	AHP	Solar	Hydro	Wind	Gas power	Biomass	Nuclear	Thermal
	TOPSIS	Wind	Solar	Hydro	Gas Power	Biomass	Thermal	Nuclear
	VIKOR	Gas Power	Solar	Wind	Thermal	Hydro	Nuclear	Biomas s
	PROMETHE E – II	Hydro	Solar	Wind	Gas Power	Thermal	Biomass	Nuclear
	WSM	Wind	Solar	Hydro	Gas Power	Biomass	Thermal	Nuclear
	WPM	Hydro	Wind	Gas Power	Solar	Biomass	Thermal	Nuclear
	WASPAS	Hydro	Wind	Gas Power	Solar	Biomass	Thermal	Nuclear


Case I
AHP
TOPSIS
VIKOR
PROMETHEE – II
WSM
WPM
WASPAS
Thermal
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Gas Power
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Nuclear
Biomass
Solar
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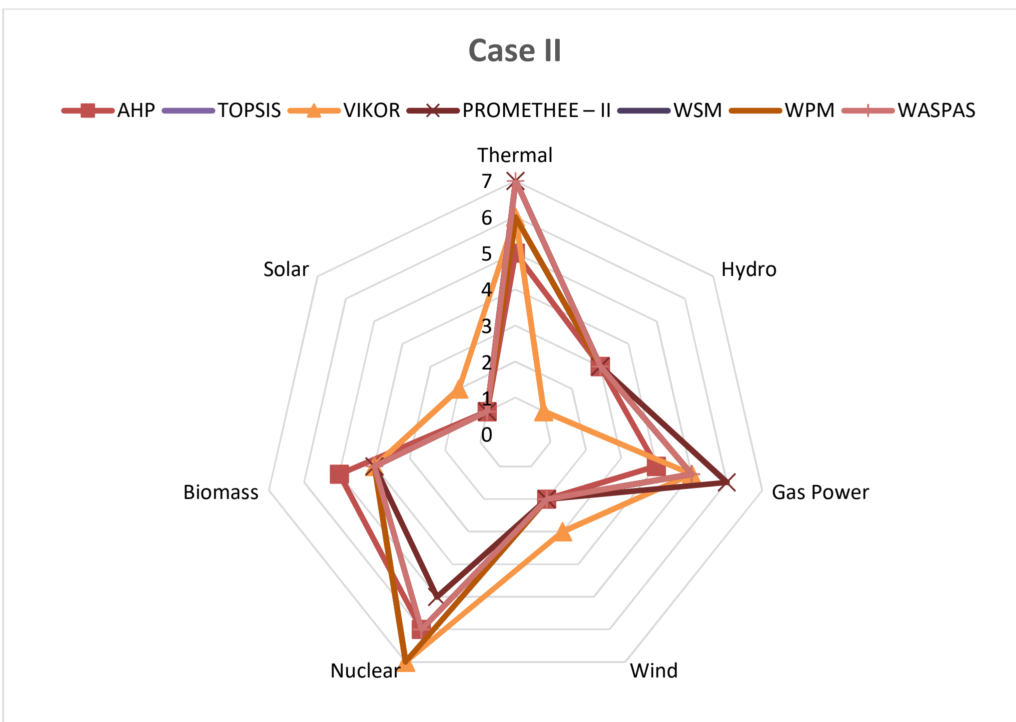
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AHP
TOPSIS
VIKOR
PROMETHEE – II
WSM
WPM
WASPAS
Thermal
Hydro
Gas Power
Wind
Nuclear
Biomass
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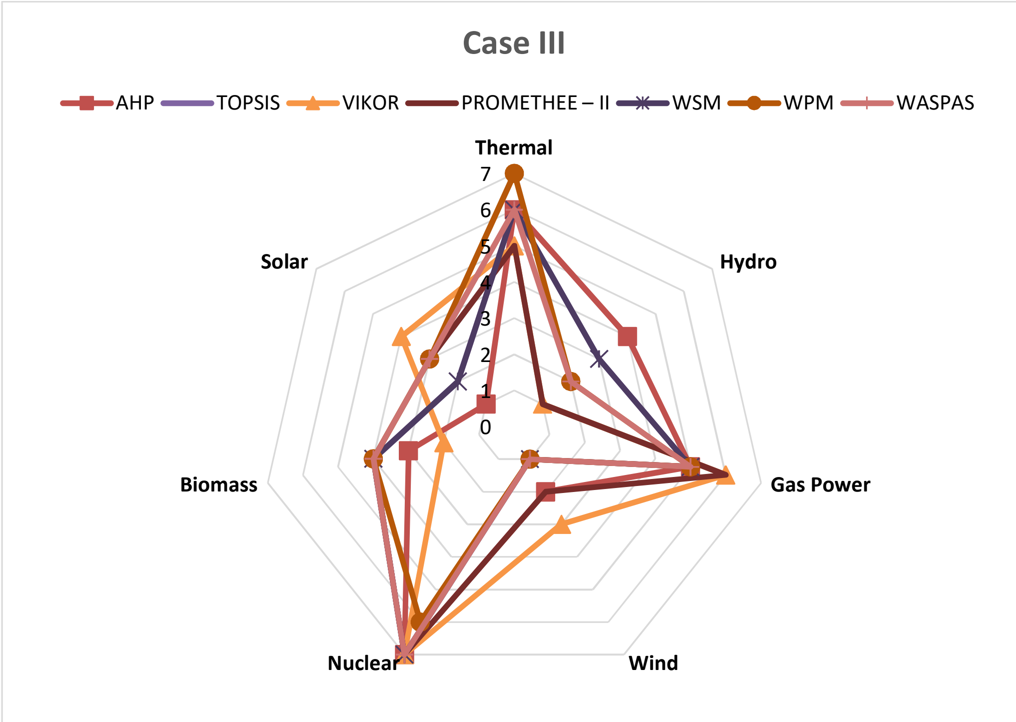
Case III
AHP
TOPSIS
VIKOR
PROMETHEE – II
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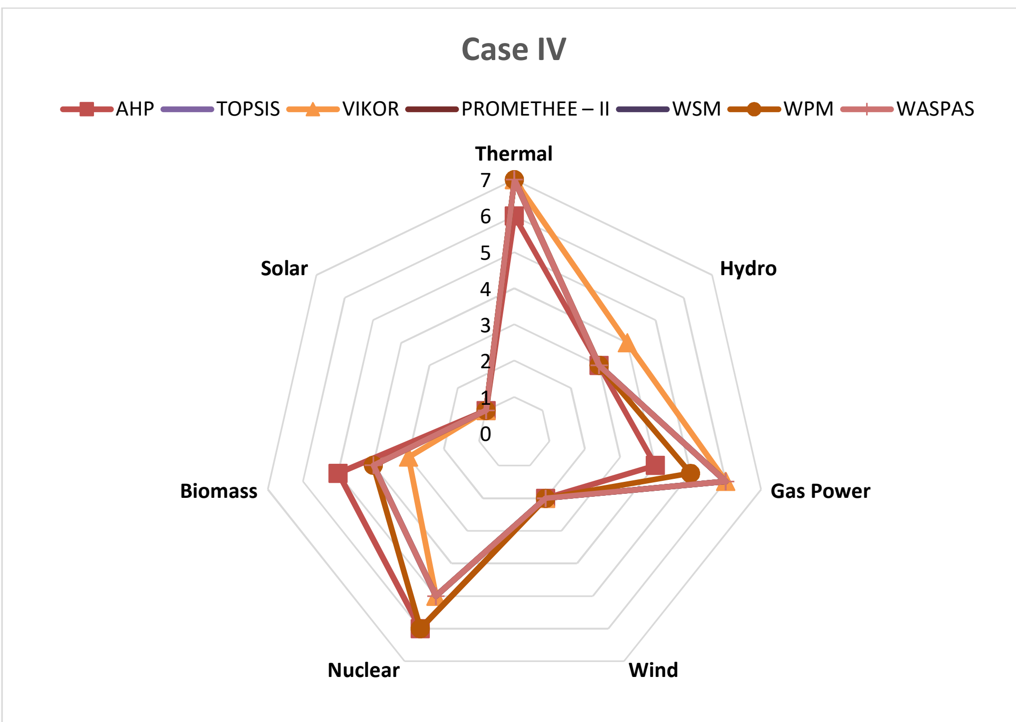
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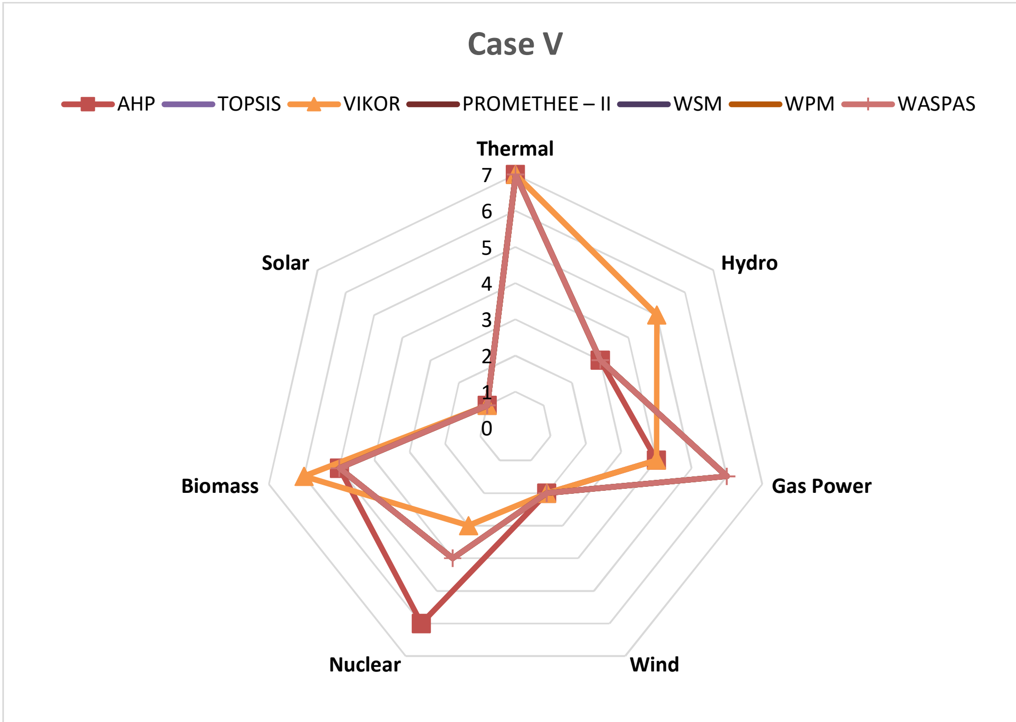

Case V
AHP
TOPSIS
VIKOR
PROMETHEE – II
WSM
WPM
WASPAS
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Hydro
Gas Power
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Nuclear
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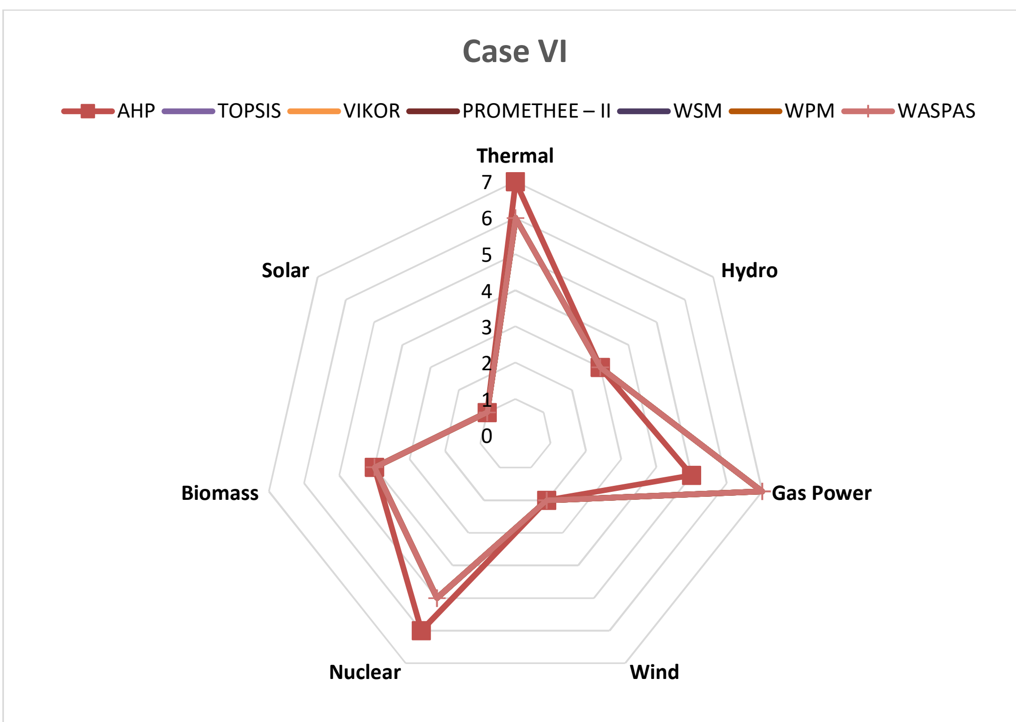

Case VI
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TOPSIS
VIKOR
PROMETHEE – II
WSM
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WASPAS
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Gas Power
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Nuclear
Biomass
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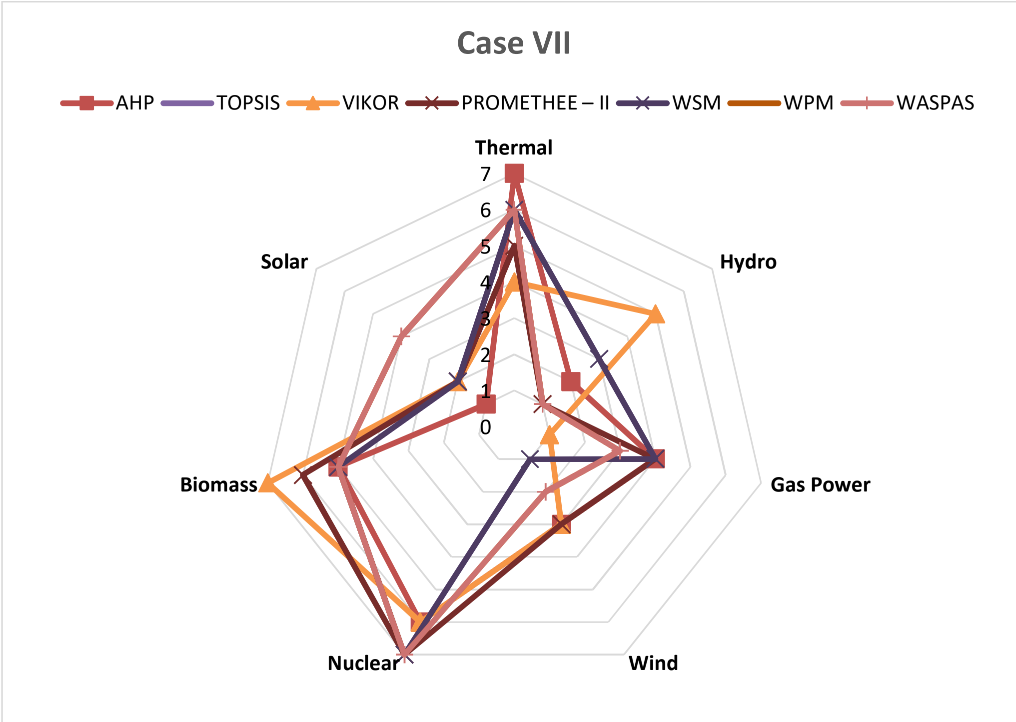


Fig. 4.6: Ranking of energy alternatives in different sensitivity cases

In scenario III, wind energy is the most attractive option. In the available renewable energy alternatives, wind energy is the most technically mature, efficient, and reliable energy source. Wind energy also has less deployment time as compared to other alternatives. The nuclear power plant is considered to be the least preferred energy source because of the large deployment time, and availability of less efficient technology. From a social perspective, solar energy is the most accepted energy source. The reasons may be high social acceptance and benefits, fewer impacts on human health, and more job creation at the local level. Thermal energy has high adverse impacts on human health and therefore less socially accepted energy source.

From an environmental point of view, solar energy is a highly environmentally friendly energy source. The reasons should be less impact on climate change and ecosystem, and a negligible amount of pollutant emission. Thermal energy is the least environmentally friendly source due to the emission of greenhouse gases, SOx, and NOx, which are responsible for climate change and global warming issues. In case VI, solar energy is given first preference might be, because of highly compatible with national energy policies, political will, and highly promotion of to use of solar energy resources. Similarly, gas power is the least preferred because of high foreign dependency. From the flexibility aspect, hydro, wind, and gas power are most preferred due to the ability to fulfill the peak load demand. The least preference is given to nuclear, thermal, and biomass power plants.

4.3.2 Evaluation of Sustainable Energy Sources: Fuzzy AHP Integrated MCDM Approaches

In the developed model fuzzy AHP method is applied to determine the weights of the sustainability factors. In this regard, a pair-wise comparison is made at each level of the model to state the importance of one factor on another factor. A survey instrument is developed to collect the subjective weights from the experts of academics and industries. Experts were instructed to make the pair-wise comparison among the criteria.

The section consists of five parts: criteria weights obtained from Shannon's entropy approach, the ranking of alternatives using the fuzzy AHP approach, comparative studies, validation of the results, and sensitivity analysis which are briefly discussed below.

4.3.2.1 Criteria weight

The result shows that the economic and environmental criteria are the most important factors for the assessment of sustainable energy sources with a weight share of 0.194, and 0.188 respectively. The third highest preference is given to technical criterion with a weighted score of 0.178. Political and social criteria follow the order and achieved the fourth and fifth reference positions as shown in Table 4.11. The least preference is given to a flexible criterion with a weight of 0.113.

Table 4.11: Determination of the criteria weights using fuzzy AHP approach

Criteria	A fuzzy geometric mean value	Fuzzy weights	COA (center of area)	Ranking
Economic	(1.026, 1.098, 1.380)	(0.147, 0.186, 0.268)	0.194	1
Technical	(0.920, 1.076, 1.215)	(0.132, 0.183, 0.236)	0.178	3
Social	(0.800, 0.987, 1.089)	(0.115, 0.168, 0.211)	0.160	5
Environmental	(0.987, 1.076, 1.328)	(0.142, 0.183, 0.257)	0.188	2
Political	(0.891, 0.981, 1.127)	(0.128, 0.167, 0.219)	0.167	4
Flexible	(0.531, 0.671, 0.826)	(0.076, 0.114, 0.160)	0.113	6
Consistency Ratio = 0.0208 < 0.10				

In terms of global weights, capital cost, and operation and maintenance cost sub-criteria are the important factors in the economic category. While operational life is the least important factor in the economic category. In the technical category, the deployment time criterion is the highest weight criterion, followed by the efficiency criterion. Job creation and impact on human health are the highest and lowest preference criterion in the social category. Moreover, emission reduction, fuel reserve years, and in fulfilling the peak load demand criterion are the highest weight criterion in the environmental, political, and flexibility categories. Table 4.12 shows the local and global weights of the criteria considered in the analysis.

Table 4.12: Determination of global weights of considered sub-criteria

Criteria	Local Weights	Sub-Criteria	Local Weights	Global Weights
Economic	0.194	Capital cost/investment cost (C1)	0.176	0.0341
		Operation and maintenance cost, (C2)	0.158	0.0307
		Levelized cost of energy, (C3)	0.135	0.0262
		Payback Period, (C4)	0.125	0.0243
		Operational life, (C5)	0.109	0.0211
		Fuel cost, (C6)	0.143	0.0277
		Availability of funds and incentives, (C7)	0.154	0.0299
Technical	0.178	Technology maturity, (C8)	0.182	0.0324
		Efficiency, (C9)	0.218	0.0388
		Deployment time, (C10)	0.243	0.0433
		Capacity factor, (C11)	0.202	0.0360
		Technology reliability (risk of accidents) (C12)	0.155	0.0276
Social	0.160	Social benefits (education, science, and culture) (C13)	0.261	0.0418
		Job creation, (C14)	0.271	0.0434
		Social acceptance, (C15)	0.260	0.0416
		Impact on human health, (C16)	0.208	0.0333
Environment	0.188	Land requirement, (C17)	0.167	0.0314
		Emission reduction, (C18)	0.350	0.0658
		Impact on ecosystem, (C19)	0.268	0.0504
		Climate Change (C20)	0.215	0.0404
Political	0.167	Political acceptance, (C21)	0.186	0.0311
		Foreign dependency, (C22)	0.261	0.0436
		Fuel reserve years, (C23)	0.329	0.0549
		Compatibility with national energy policy (C24)	0.224	0.0374
Flexible	0.113	In integration with other sources, (C25)	0.432	0.0488
		In fulfilling the peak load demand, (C26)	0.568	0.0642

4.3.2.2 Ranking of alternatives

The fuzzy WASPAS approach is a unique combination of two well-known MCDM approaches fuzzy WSM and fuzzy WPM. Initially, fuzzy WSM and fuzzy WPM approaches were given the separately ranking based on the weighted normalized index. Then exploring the fuzzy WSM, and fuzzy WPM results obtained the results for the fuzzy WASPAS approach. The fuzzy WASPAS approach was given the ranking based on the values of the weighted normalized index. The higher the value of the weighted normalized index was given the higher preference or ranking such as solar energy is the highest sustainable energy source with the highest weighted normalized index of 0.7404. The second preference is given to wind energy with a score of 0.7337. Hydro energy at the third position, fourth-ranking is given to biomass energy resources. Gas power and nuclear energy achieved fifth and sixth positions respectively. Thermal energy is at the least position with a weighted normalized index of 0.3967. Table 4.13 and Fig. 4.7 show the weighted normalized index and ranking of energy alternatives in fuzzy WSM, fuzzy WPM, and fuzzy WASPAS MCDM approaches.

Table 4.13: Ranking of energy alternatives using fuzzy WSM, fuzzy WPM, and fuzzy WASPAS approach

Energy Alternatives	Fuzzy WSM	Fuzzy WPM	Fuzzy WASPAS	Ranking
Thermal Energy	0.4271	0.3664	0.3967	**7**
Hydro Energy	0.6746	0.6279	0.6513	**3**
Gas Power	0.4965	0.4362	0.4663	**5**
Wind Energy	0.7554	0.7120	0.7337	**2**
Nuclear Energy	0.4943	0.4219	0.4581	**6**
Biomass Energy	0.6251	0.5837	0.6044	**4**
Solar Energy	0.7743	0.7065	0.7404	**1**

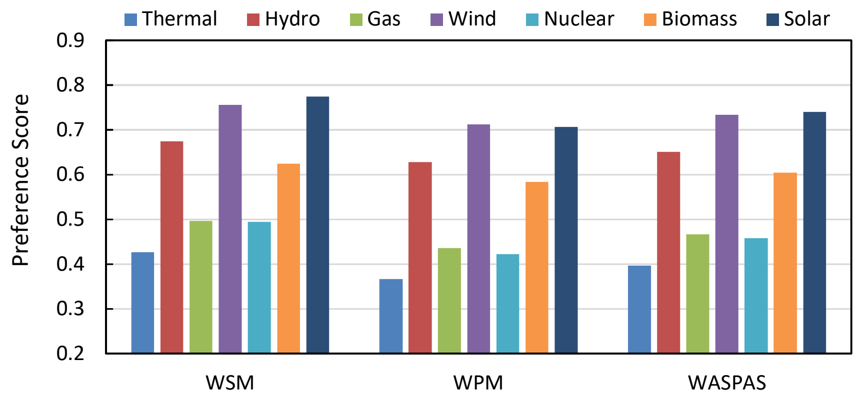


Fig. 4.7: Preference score of energy alternatives for the fuzzy WSM, fuzzy WPM, and fuzzy WASPAS MCDM approaches

4.3.2.3 Comparative analysis

The result of the proposed study is validated by "Fuzzy AHP integrated MCDM approaches" in which criteria weights are given by the fuzzy AHP approach while the ranking of energy alternatives was given by the three other well-known approaches viz. TOPSIS, VIKOR, and PROMETHEE-II.

Firstly, the fuzzy TOPSIS approach is employed that was developed by Hwang and Yoon [60]. TOPSIS approach analyses the alternatives based on the distance from fuzzy positive ideal solution (FPIS), and distance from fuzzy negative ideal solution (FNIS). Here, the higher the value of the closeness coefficient (CC) is to give higher preference such as solar energy has been chosen as the highest sustainable energy source with the highest CC value of 0.739. The second preference is given to wind energy (0.717), followed by hydro (0.642), biomass (0.596), and gas power (0.490). Nuclear and thermal energy is obtained the sixth and seventh least ranking respectively as shown in Table 4.14.

Table 4.14: Evaluation of energy alternatives using fuzzy TOPSIS MCDM approach

	FPIS	FNIS	Total	CC	Raking
Thermal	0.621	0.479	1.100	0.435	**7**
Hydro	0.389	0.696	1.085	0.642	**3**
Gas Power	0.561	0.540	1.101	0.490	**5**
Wind	0.302	0.767	1.068	0.717	**2**
Nuclear	0.560	0.532	1.092	0.487	**6**
Biomass	0.445	0.655	1.100	0.596	**4**
Solar	0.276	0.780	1.056	0.739	**1**

Secondly, the fuzzy VIKOR approach is used to determine the sustainability ranking of energy alternatives. It assigns the ranking to the alternatives based on the closeness from the ideal solution. The study employed the VIKOR approach developed by Opricovic and Tzeng. The complete statistical data of the calculation procedure is provided in Table 4.15. It ranks the alternatives based on the lower values of the fuzzy VIKOR index (Qi). According to the calculation, solar energy is the closest, and thermal energy is at the furthest distance to the ideal solution. Thus, solar energy is the first preference for sustainable energy sources while thermal energy at last. The fuzzy VIKOR approach given alternatives ranking has one major change it swipes the preference order of nuclear energy and gas power compared to the developed method.

Table 4.15: Ranking of energy alternatives using the fuzzy VIKOR approach

	Si	**Ri**	**S***	**R***	**S-**	**R-**	**Qi**	**Ranks**
Thermal Energy	0.6617	0.0658	0.1916	0.0406	0.6617	0.0658	1.0000	**7**
Hydro Energy	0.3470	0.0488	0.1916	0.0406	0.6617	0.0658	0.3289	**3**
Gas Power	0.5842	0.0549	0.1916	0.0406	0.6617	0.0658	0.7025	**6**
Wind Energy	0.2192	0.0406	0.1916	0.0406	0.6617	0.0658	0.0293	**2**
Nuclear Energy	0.5740	0.0498	0.1916	0.0406	0.6617	0.0658	0.5900	**5**
Biomass Energy	0.4193	0.0467	0.1916	0.0406	0.6617	0.0658	0.3635	**4**
Solar Energy	0.1916	0.0406	0.1916	0.0406	0.6617	0.0658	0.0000	**1**

Finally, the PROMETHEE-II approach is employed that is developed by J. P. Brans. PROMETHEE-II approach is widely employed over the PROMETHEE-I because it gives the full ranking of energy alternatives. The ranking is assigned based on the values of fuzzy net outranking flow (ϕ). Solar, wind, hydro, and biomass energy occupied the first, second, third, and fourth ranks with positive values of fuzzy net outranking flow (ϕ). While, nuclear, gas power, and thermal achieved the fifth, sixth, and seventh ranks with a negative valued fuzzy net outranking flow (ϕ). The details of leaving flow, entering flow, and fuzzy net outranking flows for each energy alternative are provided in Table 4.16.

Table 4.16: Ranking of energy alternatives using the fuzzy PROMETHEE-II approach

	Leaving Flow (ϕ^+)	**Entering flow (ϕ-)**	**Fuzzy Net Outranking Flow (ϕ)**	**Rank**
Thermal Energy	0.1296	0.3999	-0.2704	**7**
Hydro Energy	0.2791	0.1758	0.1032	**3**
Gas Power	0.1608	0.3343	-0.1735	**6**
Wind Energy	0.3297	0.0968	0.2330	**2**
Nuclear Energy	0.1517	0.3198	-0.1681	**5**
Biomass Energy	0.2174	0.1985	0.0188	**4**
Solar Energy	0.3713	0.1144	0.2569	**1**

4.3.2.4 Validation of results

Furthermore, Spearman's rank and Karl's Pearson correlation coefficient were used to examining the consistency and correlation between the suggested decision-making approach and six comparative MCDM approaches. Here, the IBM SPSS statistics 20 software was used for the analysis. The Spearman's rank (r_{SR}) difference and Karl's Pearson (r_{KP}) correlation coefficients between the suggested decision-making strategy and six comparative MCDM techniques were shown in Table 4.17.

Table 4.17: Validation through correlation coefficients among the proposed model and five MCDM approaches

		Proposed Model	TOPSIS	VIKOR	PROMETHEE-II	WSM	WPM
Proposed Model	Spearman's	1	1	-0.964	0.964	1	0.964
	Karl's	1	0.997	-0.974	0.998	0.999	0.999
TOPSIS	Spearman's		1	-0.964	0.964	1	0.964
	Karl's		1	-0.974	1	0.999	0.994
VIKOR	Spearman's			1	-1	-0.964	-0.928
	Karl's			1	-0.977	-0.978	-0.969
PROMETHEE-II	Spearman's				1	0.964	0.928
	Karl's				1	1	0.996
WSM	Spearman's					1	0.964
	Karl's					1	0.997
WPM	Spearman's						1
	Karl's						1

The proposed model has a strong correlation $r_{SR} = 1$, $r_{KP} = 0.997$, and $p < 0.05$ with the TOPSIS approach. The proposed model and VIKOR approaches have very strong negative correlation coefficients of r_{SR} =0.964, and r_{KP} = 0.974 with a p-value of less than 0.05. While PROMETHEE-II approach validated the results with 0.964 Spearman's rank (r_{SR}) and 0.998 Karl's Pearson (r_{KP}) correlation coefficient values. WSM and WPM, two different MCDM techniques, exhibit strong Spearman's rank (r_{SR}) correlation coefficient values of 1 and 0.964, respectively, with the suggested approach. While the proposed model has the same 0.999 Karl's Pearson (r_{KP}) correlation coefficient as the WSM and WPM approaches. The investigation did, however, confirm a significant and consistent link between the suggested strategy and the six MCDM techniques that were validated.

4.3.2.5 Sensitivity analysis

The fuzzy WASPAS approach carried out the analysis at the value of λ = 0.5. Hence, to analyze the robustness of the study outcome, the sensitivity analysis is performed by changing the values of the λ coefficient. For sensitivity analysis, the value of λ varies from λ = 0 to λ = 1 with an interval of 0.1. Table 4.18 shows the weighted normalized index of considered seven energy alternatives for different values of λ. The sensitivity results indicated that the final ranking of the energy alternatives is not sensitive to the values of λ.

Table 4.18: Weighted normalized index of energy alternatives for different values of λ

	λ = 0	**λ= 0.1**	**λ= 0.2**	**λ= 0.3**	**λ= 0.4**	**λ= 0.5**	**λ= 0.6**	**λ= 0.7**	**λ= 0.8**	**λ= 0.9**	**λ = 1**
A1	0.366	0.372	0.379	0.385	0.391	0.397	0.403	0.409	0.415	0.421	0.427
A2	0.628	0.633	0.637	0.642	0.647	0.651	0.656	0.661	0.665	0.670	0.675
A3	0.436	0.442	0.448	0.454	0.460	0.466	0.472	0.478	0.484	0.490	0.496
A4	0.712	0.716	0.721	0.725	0.729	0.734	0.738	0.742	0.747	0.751	0.755
A5	0.422	0.429	0.436	0.444	0.451	0.458	0.465	0.473	0.480	0.487	0.494
A6	0.584	0.588	0.592	0.596	0.600	0.604	0.609	0.613	0.617	0.621	0.625
A7	0.706	0.713	0.720	0.727	0.734	0.740	0.747	0.754	0.761	0.768	0.774

Finally, Solar energy is chosen as the most sustainable energy source in India. The reason behind solar energy as the most sustainable energy is its environment-friendly nature with very fewer pollutant emissions. It also gains special attention due to a sharp decrease in capital cost as well as the lowest Levelized cost of energy. Due to more job creation and social benefits, solar energy gets highly social acceptance. Whereas, due to the high willingness of the government, solar energy gets more benefits and incentives from the local and national organizations. Wind energy is chosen as the second most sustainable energy source in India may be due to the reason of potential for a reduction of greenhouse gas emissions. Wind energy is also enough mature and well-established energy source for the Indian energy sector. It has also a huge potential to fulfill the future energy demand as well as create more jobs at the local and regional levels. Due to government support and motivation, it has less overall investment cost and payback period. The government of India's policies for hybrid solar and wind resources installation makes them viable and reliable energy source. The integration of solar and wind energy resources may give a sustainable future by substituting fossil fuel resources.

The third preference is given to hydro energy sources because of their zero fuel cost, environment-friendly, capability to respond to peak load events, and highly efficient. It has some drawbacks of ecological imbalance, high initial investment, and a large installation period. Biomass energy occupied the fourth position due to the availability of its huge potential and negligible new carbon emission. The fifth preference is given to gas power due to its high efficiency and quickly respond to peak load events. At the same time, it has some drawbacks of less operational life and dependency on foreign countries for the availability of fuels. Nuclear energy is at the sixth position due to lower social acceptance, lesser efficiency, and high fuel cost. Whereas, thermal energy is at the least position due to the emission of greenhouse gas, scarcity in the availability of fuel, a huge increase in fuel price, and adverse impact on human health as well as climate. Fig. 4.8 shows the sustainability ranking of energy alternatives in India.

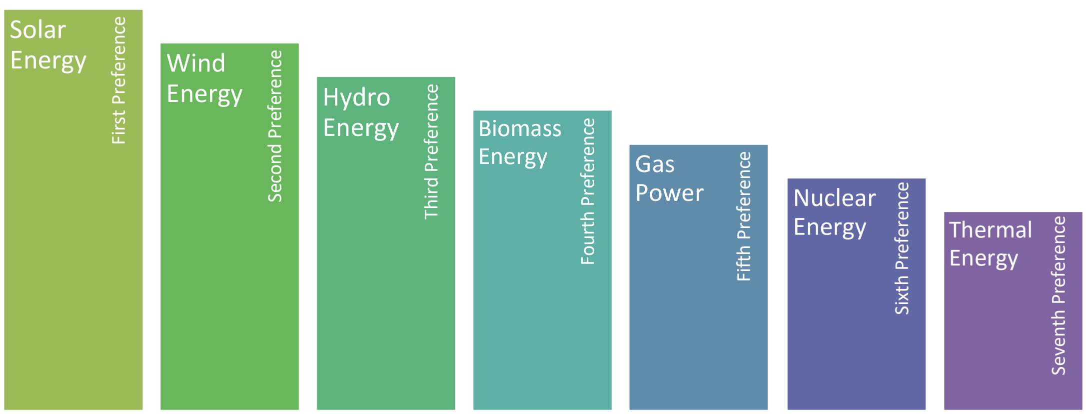


Fig. 4.8: Final prioritization order of sustainable energy sources

4.3.3 Evaluation of Optimal Energy Mix Scenario

The government of India (GOI) has made an international commitment to have about 40% cumulative electric power installed capacity from non-fossil fuel-based energy resources by the year 2030, and to reduce the emission intensity of its GDP by 33% - 35% by the year 2030 from the year 2005 level [302]. Therefore, to fulfill their commitment GOI is highly intended to achieve energy autonomy and to provide clean affordable, reliable, and sustainable power for all. The outcome of the study would facilitate the GOI to achieve its commitments by evaluating the sustainable energy sources in India.

To fulfill the commitment of GOI, the study planned to propose a future energy scenario through sustainable energy sources. The development faces the obstacles of instantaneous mismatch between supply and demand, fluctuating nature of renewable energy sources, and difficulties in energy storage. Therefore, these issues may develop the need to evaluate the optimal energy mix scenario in India for 2030. The optimal energy mix scenario for 2030 is optimized using the load or electricity demand profile, availability of generation resources, and monitoring of the network and system. These are briefly elaborated on in the following sections.

4.3.3.1 Electricity demand

The objective of this section is to analyse the current electrical load and generation profile to gain an understanding of the present demand and production pattern. Information about the electrical energy demand has been collected from the central electricity authority (CEA), the Indian national load dispatch center (NLDC), and annual statistical reports [303–305]. To draw the distribution profile of electricity, the study expected to grow the economy with a compound annual growth rate of 7.4% until 2030. The cumulative growth rate depends on the factors of human resources, energy resources, natural resources, capital formation, and some social and political factors. Among all the factors, the availability of energy resources or electricity directly influences the growth of a country because the industrial sector is the largest (42%) electricity consumer in the country. domestic and agriculture are the second (24%), and third (18%) electricity consumers. Whereas 9% of electricity is consumed in the commercial sector and 1% in traction and railway. The other resources such as cooking, telecom, and transportation consumed 6% of overall available electricity [303–305].

The industry sector in India doubled in value during 2000-01 to 2010-11 and grew at an annual growth rate of 7%. The seven sub-sectors cement, fertilizer, aluminium, textile, iron & steel, pulp & paper, and Chlor-alkali (chlorine and caustic soda) are the major electricity consumer. Here, a total approx. 564 TWh/yr of electricity demand will be generated in industries with the maximum possible improvement that can be possible to achieved in the industry sector [306]. The domestic sector currently accounts for 24% of the total electricity consumption, which is expected to increase substantially in near future due to government policies such as "24*7 power for all," and "housing for all achieved by the year 2022." The study assumed a well-structured domestic planning and aggressive growth rate and predicated an approx. 769 TWh of electricity demand annually [304,307].

In the agriculture sector, the major electricity demand is from agricultural pumps and tractors. The GOI is planning to electrify 25% of pump sets from solar photovoltaics and the remaining 75% from the grid electricity. While, in the case of tractors, more efficient and advanced technology tractors will replace the older version tractors. By employing the above-mentioned regulations, a total of 214 TWh of electricity demand is assumed per year in the agriculture sector [305]. Transport, telecom, and cooking sectors are in the 'others' category, which contribute 6% to the overall electricity demand. With a moderate growth rate in the transport, telecom, and cooking sector, a total of 397 TWh/yr of electricity consumption is calculated [306]. Therefore, summarizing the electricity load of each sector, a total of 2143 TWh of the electrical load is calculated [303,304].

4.3.3.2 Design of scenarios

Prior to constructing the scenarios, the authors scrutinized the scenarios published by various energy agencies, an international commitment made by GOI, and previously available studies. International energy agencies such as the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), and The Energy and Resources Institute (TERI) expect the vast capacity installation of renewable energy sources, especially solar PV and wind energy to overcome or minimize the emission of greenhouse gases [308,309]. In case of government commitments, GOI has submitted its Intended Nationally Determined Contribution (INDC) to UNFCCC. The key policies submitted in UNFCEE are, (i) to reduce the emission intensity of its GDP by 33% to 35% by 2030 from the 2005 level, (ii) to achieve about 40% electric power installed power capacity from non-fossil fuel-based energy resources by 2030, and (iii) to create an additional carbon sink of 2.5 to 3 billion tons of CO_2 equivalent through additional forest and tree cover by 2030 [310]. Some recent studies and reports suggested that the installed capacity of coal would be considered 240 GW for most of the scenarios. Whereas, Shearer et al. [311] and Pfeiffer et al. [312] suggested that to overcome the global warming issues, new investment in coal power plants should not be made from the year 2017. Finally, following the above-discussed literature and outcome of the current study, the present research work constructed the scenario by eliminating the least sustainable energy sources i.e., coal induced thermal power, and nuclear power. Here, a total of 14 scenarios are constructed to evaluate the optimal energy mix scenario for the year 2030.

Scenario 1 (SC 1):- It explores the high level of solar (SPV + CSP + roof top + solar water heater) and wind energy (onshore + off-shore) resources.

Scenario 2 (SC 2):- This scenario highly explores solar energy with hydro energy (small + large).

Scenario 3 (SC 3):- In this scenario, solar energy with gas power is highly explored.

Scenario 4 (SC 4):- This scenario combined explores the solar and biomass resources (biomass + biofuel).

Scenario 5 (SC 5):- In this scenario, wind energy is investigated with hydro energy.

Scenario 6 (SC 6):- Wind energy is explored with biomass energy resources.

Scenario 7 (SC 7):- This scenario explored the wind energy resources with the gas power.

Scenario 8 (SC 8):- High levels of solar, wind, and hydro energy resources are investigated.

Scenario 9 (SC 9):- A combination of a high level of solar, wind, and biomass energy are explored.

Scenario 10 (SC 10):- This scenario examines the high level of solar, wind, and gas power combination.

Scenario 11 (SC 11):- It explores the solar, wind, and hydro energy resources with the cross-border import-export of power.

Scenario 12 (SC 12):- This case jointly explored solar, wind, hydro, and biomass resources.

Scenario 13 (SC 13):- This scenario explores a combination of solar, wind, hydro, and gas power.

Scenario 14 (SC 14):- In this scenario, the default case is explored.

4.3.3.3 Electricity model description

For the development of discussed scenarios, the optimal energy mix scenario is modeled using the India Energy Security Scenario (IESS, 2047) tool developed by the GOI [313]. The tool has been developed in an Excel format with a web tool front end, which allows a user-friendly, dynamic, graphic representation of the chosen output of the energy demand and supply levels leading up to the selected terminal year. The tool is used to generate energy security and clean energy pathways for India based on the inputs from different demand and electricity generation scenarios. The tool has a special capability to calculate total electric power demand as well as electricity demand sector-wise. Whereas, the tool also has the inbuilt capability to fulfill the electric power demand from different energy sources [314,315].

4.3.3.4 Optimal energy mix scenario

To evaluate the optimal energy mix scenario, firstly each scenario is developed in the IESS tool calculator. A model can be developed using three steps: (i) calculation of electricity demand, (ii) growth or share of energy resources, and (iii) network and system configurations. The electrical power demand was predicated with an aggressive growth rate in the energy demand sector. Afterward, the output of the simulation was noted in terms of total generation (TWh/yr), over-generation or surplus (TWh/yr), fuel import cost (INR trillion/yr), per capita emission (tCO_2e/person per year), the land requirement (%), and total energy system costs (INR trillion, overall life span cost of the power plant). The outcome of each scenario is compiled in Table 4.19.

Table 4.19: Summary statistics of optimal energy mix scenarios

Scenarios	Resources	Total generation (included over generation, transmission and distribution losses etc.) (TWh/yr)	Over generation or surplus (TWh/yr)	Import cost (INR Trillion)	Per Capita Emission (tCO_2e/person per year)	Land required (%)	Total energy system cost (INR Trillion)
SC 1	Solar, wind	3058	646	12	2	4.20	55
SC 2	Solar, hydro	3003	590	12	2	3.70	56
SC 3	Solar, gas	2966	553	12	2.05	3.69	55
SC 4	Solar, bio	2961	548	12	1.95	4.69	55
SC 5	Wind, hydro	3053	640	12	2	4.08	56
SC 6	Wind, bio	3011	598	12	1.95	5.06	55
SC 7	Wind, gas	3016	603	12	2.05	4.06	55
SC 8	Solar, wind, hydro	3160	747	12	2	4.22	58
SC 9	Solar, wind, biomass	3118	705	12	1.95	5.21	57

Scenarios	Resources	Total generation (included over generation, transmission and distribution losses etc.) (TWh/yr)	Over generation or surplus (TWh/yr)	Import cost (INR Trillion)	Per Capita Emission (tCO_2e/person per year)	Land required (%)	Total energy system cost (INR Trillion)
SC 10	Solar, wind, gas	3123	711	12	2.05	4.20	57
SC 11	Solar, wind, hydro, cross border	3191	778	12	2	4.22	58
SC 12	Solar, wind, hydro, biomass,	3181	768	12	1.95	5.22	59
SC 13	Solar, wind, hydro, gas	3186	774	12	2.05	4.22	59
SC14	Default case	2832	420	12	2	3.54	53

To evaluate the optimal energy mix scenario, TOPSIS approach has been employed. TOPSIS approach identifies the best optimal energy mix scenario based on the maximum distance from a negative ideal solution. Prior to employ, the output factors are categorized into cost and benefit categories. The factors, total electricity supply, and over-generation or surplus power are in the benefits category which means the high values are preferred. Whereas, fuel import cost, per capita emission, land requirement, and total energy system costs are considered in the cost category. It is taken into consideration that the considered carries the same importance or weight.

For each scenario, positive ideal solution (PIS), negative ideal solution (NIS), and closeness coefficients (CC) are calculated. Among all the scenarios, SC 11 has the highest closeness coefficient value of 0.771, followed by SC 13 (0.756). Whereas, SC 4 is the least favorable option with a minimum closeness coefficient value of 0.357. The complete details of PIS, NIS, and CC are provided in Table 4.20.

Table 4.20: Calculated preference values of the TOPSIS approach for different energy scenarios

Scenarios	PIS (S_i^+)	NIS (S_i^-)	CC	Ranks
SC 1	0.012	0.020	0.624	6
SC 2	0.014	0.020	0.596	7
SC 3	0.016	0.019	0.537	10
SC 4	0.020	0.011	0.357	14
SC 5	0.012	0.020	0.631	5
SC 6	0.020	0.013	0.394	13
SC 7	0.014	0.018	0.566	9
SC 8	0.008	0.025	0.751	3
SC 9	0.018	0.020	0.524	11
SC 10	0.009	0.023	0.716	4
SC 11	0.008	0.027	0.771	1
SC 12	0.018	0.025	0.576	8
SC 13	0.009	0.027	0.756	2
SC 14	0.025	0.018	0.418	12

The optimal energy mix scenario carries the share of coal (49%), gas (4%), hydro (9%), small hydro (2%), nuclear (4%), solar (14%), wind (13%), biomass (2%), and imports (2%) as shown in Fig. 4.9. In terms of electricity, coal is generating the highest 1570 TWh of electricity, followed by solar energy (434 TWh). Wind energy is the third-largest electricity producer (407 TWh), the order follows by the hydro (293 TWh), nuclear (135 TWh), gas power (127 TWh), biomass (79 TWh), small hydro (71 TWh), and cross border imports (69 TWh). In the optimal energy mix scenario, the solar, wind, and hydro sustainable energy sources are maximum utilized. Here, coal power is still a leading energy source. To overcome or minimize the issues associated with coal power, new power units will be operated on ultra-supercritical technology that improves the efficiency of the plant. In continuation, carbon capture and storage technologies can also be promoted and employed, in order to address the hazardous crisis faced by coal power plants. Here, renewable power covers the major share of the overall capacity which means the intermittency, reliability, and peak load supply problems would occur. Thus, battery storage technology pumped hydro storage, and hydrogen production technologies can be promoted to address the issues associated with renewable energy sources.

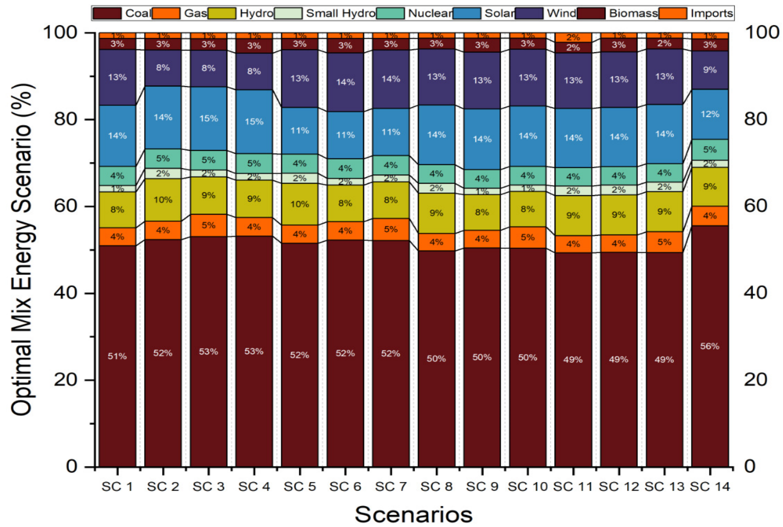


Fig. 4.9: Optimal energy mix scenario in India

Obtained results are compared with existing studies on optimal energy mix scenarios in the context of India, such as Laha and Chakraborty [307] reported 25.5 % to 41.2% availability of renewable energy sources in the optimal energy scenario. Whereas, Rhythm Singh [316] predicted a 29% share of renewable energy sources in the optimum mix scenario by 2030. Can et al. [315] concluded that renewable energy sources cover the 32% share in the optimal energy mix scenario. While another study predicted that biomass and hydro energy resources may play a crucial role in a sustainable mix energy scenario [317]. Following the comparative studies, the results of the present study were found consistent and within the range of results of these studies.

4.3.4 Policy Support

The growth of energy sources mainly depends on government policies as the policies attract investors to invest in the technologies. GOI has taken many milestone measures in the development of renewable energy sources such as the formation of a dedicated nodal ministry (Ministry of New and Renewable Energy) [318]. Several policies have been formulated viz. Electricity Act – 2003, National Water Policy – 2005, Integrated Energy Policy – 2006, National Rehabilitation & Resettlement Policy – 2007, National Action Plan on Climate Change (NAPCC – 2008), Generation Based Incentives for Solar Energy (GBI – 2009), National Clean Energy Fund (2010-11), Jawaharlal Nehru National Solar Mission (JNNSM – 2010-13), National Wind-Solar Hybrid Policy (2016), Policy for repowering of wind power projects (2016) [318–322] for the growth of energy sector in India.

4.4 SUMMARY

The purpose of this study is to examine the Indian energy sector in depth in order to determine its long-term viability. Furthermore, in order to address issues such as economic burden, climate change, global warming, foreign dependency, and so on, the current study attempted to determine India's sustainable energy sources and the optimal energy mix scenario for the year 2030. The analysis continues with the previously chosen 26 sustainability indicators pertaining to the economic, technical, social, environmental, political, and flexible categories, as well as with the 7 most developed and trustworthy energy alternatives. Since the analysis covers multiple factors, the study must use 'MCDM' methodologies to deal with them. Here, two MCDM technique combinations are used: (i) Shannon's integrated fuzzy MCDM approaches and (ii) hybrid fuzzy AHP and six MCDM approach. In these circumstances, Shannon's and fuzzy AHP are used to compute the weights of criteria, while the other MCDM techniques are used to rank the alternatives. The outcome of these combinations is compared to the results of other MCDM approaches such as TOPSIS, VIKOR, PROMETHEE-II, WSM, WPM, and WASPAS. The consequence of these combinations, on the other hand, is validated by calculating Spearman's and Karl Pearson's correlation coefficients. Finally, solar energy has been selected as India's most sustainable energy, followed by wind, hydro, biomass, gas, nuclear, and thermal energy.

In addition, the study created 14 scenarios based on the top five sustainable energy sources in order to determine the optimal energy mix scenario. Solar and wind energy are expected to rise in importance in these scenarios, with a phenomenal development rate. In contrast, the electricity consumption in India in 2030 is computed using the GOI's future vision. After making certain assumptions, the data was retrieved from CEA, NLDC, TERI, and Annual Statistical reports before being analyzed using the IESS 2047 tool and the MCDM technique. Finally, the optimal energy mix scenario carries the share of coal (49%), solar (14%), wind (13%), hydro (9%), gas (4%), nuclear (4%), biomass (2%), small hydro (2%), and foreign imports (2%).

Firstly, the technique devised for an implication of MCDM approaches, comparison of outcomes, and validation of results will be useful to researchers, academicians, and analysts in future studies. The report contains a wealth of information on energy sector generation and demand, power project costs, GDP growth rates in various sectors, GOI international targets, and so on, all of which will be useful in future studies and research. Furthermore, it would assist the GOI in meeting international commitments such as reducing emission intensity per unit of GDP by 30 to 35 percent by 2030 from 2005 levels. It will also assist policymakers and decision-makers in formulating strategies to attain the optimal energy mix scenario determined. Overall, it will assist the country in achieving sustainable development.

CHAPTER – 5

ASSESSMENT OF SOLAR AND WIND FARM LOCATIONS IN INDIA USING MCDM AND GIS TECHNIQUES

The present chapter developed a geographical information system (GIS) and MCDM model to create a site suitability map for India. The suitability map is divided into five categories: highly suitable, suitable, moderately suitable, less suitable, and not suitable. The suitability map also determines the highly suitable land area for states and union territories on the basis of technical, economic, and socio-environmental aspects. Finally, a sensitivity analysis is used to assess the analysis' robustness.

5.1 INTRODUCTION

Solar and wind energy are also helpful in improving the quality of rural life, minimizing the economic burden, increasing energy security, reducing foreign dependency, creating jobs at the local level, and finally, reducing the emission of pollutants in the environment. The rapidly growing solar and wind energy resources have led to new challenges related to their dependency on climatic and weather conditions [167]. These have also created new issues like habitat loss, land degradation, noise generation, and visual intrusion [323,324]. Nevertheless, to maximize the utilization of commercial resources and to minimize the impact of various issues, there is a clear need for a proper assessment of suitable locations for the installation of solar and wind farms [325]. Site selection for solar and wind energy resources is a complex and difficult task. In addition to issues like meteorological requirements, environmental concerns, and economic profitability, one also has to consider the societal challenges as well as the risks associated with plant construction and operations [326,327]. Sites with the highest availability of resources like solar radiation and wind velocity are not always the most feasible ones for the installation of solar and wind power plants as a number of other factors play a significant role in the assessment of suitable locations which can be categorized into climatic, ecological, economic factors [202,328]. Before investing capital in the infrastructure, a systematic analysis of the various factors affecting the performance and operational economy of renewable energy-based power plants is indispensable. In the current work, employing the GIS and MCDM based approaches for selecting the optimal locations of solar and wind power plants in India. These approaches have been widely used for the selection of suitable sites worldwide. GIS is a valuable tool in the multi-context decision-making problems in which geo-referenced information plays a significant role. The GIS approach has the capabilities of data storage, data management, calculations, analysis, and visualization of georeferenced data [218]. Mainly, GIS visualizes raw, unrelated data in a meaningful manner when combined with an expert's perception [329]. Similarly, the MCDM approach is a well-known decision support approach for solutions to complex problems where multiple factors affect a single goal [330,331]. The MCDM approach provides a suitable option through the evaluation and comparison of the characteristic properties of the alternatives [43]. Thus, by combining the two different approaches of GIS and MCDM, a unique and cohesive framework is possible that can handle complex spatial planning problems.

This identifies the objectives of the current research work which are as follows:

- To investigate suitable sites for the installation of solar and wind farms in India using GIS and MCDM approaches.
- To explore the potential area in different states and union territories of India.
- To perform the sensitivity analysis based on the aspects of equal weight, economic, technical, and socio-environment.

The next sections of the chapter, such as the research methods, results and discussion section, and so on, have a full discussion of achieving the aforementioned objectives. Which are covered in greater depth later on.

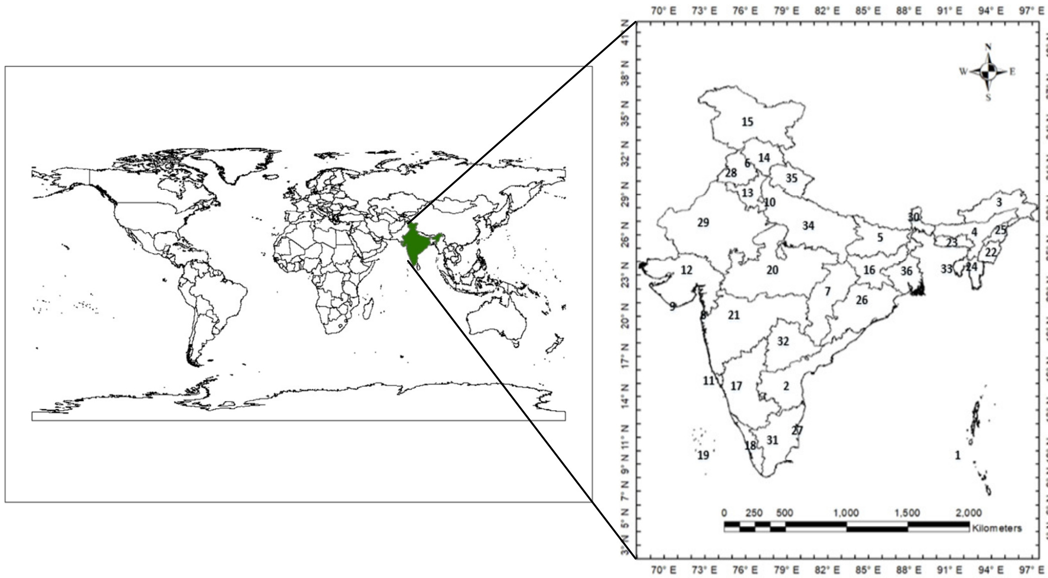
5.2 RESEARCH METHODOLOGY

This section briefly presents the research methodology adopted for achieving the set objectives.

5.2.1 Study Area

The aim of the study is to perform an identification study of the suitable solar and wind farm locations in India which is the 7th largest country in the world with an area of 3.29 million square kilometers. India is geographically situated between 8°4’ to 37°6’ North latitude and 68°7’ to 97°25' East longitude, the location in the world map is shown in Fig. 5.1. India has thirty states and six union territories and it shares borders with Pakistan, Nepal, Bhutan, China, and Myanmar [332,333]. India comprises six different physiographic zones, namely, the northern mountains (Himalayas), the Indo-Gangetic plains, the Thar desert, the peninsular plateaus (plateaus, mountain ranges, Ghats, and Deccan plateau), the coastal plains, and finally, the islands (Lakshadweep, Andaman, and Nicobar) [334]. In terms of climate, the Indian Meteorological Department (IMD) designates India into four climatological seasons winter, summer, monsoon or rainy season, and post-monsoon or autumn season. India has a comparatively higher annual average temperature ranging from 25°C to 27.5°C. Generally, the north-western part of the country records the lowest monthly mean temperature between 10-15°C in the month of December while the northern region records the highest monthly mean temperature between 32-40°C in the month of May. Normally, investigations related to the renewable energy generation are justified for countries with high average temperatures.

The Indian energy sector predominantly depends on fossil fuel resources which creates the challenges of energy security, climate change, fuel scarcity, and import dependence [335,336]. Among the fossil fuels, coal is widely used due to its cheap and easy availability. In 2013-14, the domestic coal demand stands at 516 million tons which is approx. 64 million tons higher than the previous year. The power utilities of India are advised to import 50 million tons of coal from Australia, Indonesia, and South Africa. This created an economic burden of 6550 USD on the nation. These fossil fuels also accounted for 58% (1047 million ton) of CO_2 emission in electricity generation application [294,295,333,337]. Recently, the Indian government has endorsed renewable energy resources to overcome the above-mentioned challenges. India has a wide potential for renewable energy resources, for example, it has a potential of 6000 million GWh of solar energy per year with approximately 4 to 7 kWh/m^2 daily incidence of solar radiation [291]. Similarly, India has a total potential of 49.13 GW of wind energy which can be increased up to 100 GW with proper utilization of resources, greater land availability, and with larger capacity wind turbines [291]. The Indian government also provides policy support to make renewable energy sources economically viable. The currently offered federal policies for solar and wind energy are as follows: (i) 80% accelerated depreciation on the solar projects, (ii) 0.5 Rs./kWh (USD 0.0068/kWh) generation-based incentives on the wind energy projects, and (iii) 30% viability gap funding on the solar project installation cost [338]. Considering the challenges, the huge solar, and wind energy potential, and the various government incentives, a systematic analysis of the potential solar and wind power plant locations is the need of the hour for India to become self-reliant on renewable energy.



1. Andaman and Nicobar
2. Andhra Pradesh
3. Arunachal Pradesh
4. Assam
5. Bihar
6. Chandigarh
7. Chattisgarh
8. Dadra & Nagar Haveli
9. Daman & Diu
10. Delhi
11. Goa
12. Gujarat
13. Haryana
14. Himachal Pradesh
15. Jammu & Kashmir
16. Jharkhand
17. Karnataka
18. Kerala
19. Lakshdweep
20. Madhya Pradesh
21. Maharashtra
22. Manipur
23. Meghalaya
24. Mizoram
25. Nagaland
26. Orissa
27. Pondicherry
28. Punjab
29. Rajasthan
30. Sikkim
31. Tamil Nadu
32. Telangana
33. Tripura
34. Uttar Pradesh
35. Uttarakhand
36. West Bengal

Fig. 5.1: The geographical position of the study area

5.2.2 Methodology

In this study, the MCDM approach is combined with a GIS tool to identify suitable locations for solar PV and wind power installations in India. This study is structured into five steps that are shown in Fig. 5.2. In step (I) the aim and objective of the research work are defined, step II includes an extensive literature review, selection of evaluation criteria, and data collection from open sources, and government agencies. In steps (III) and (IV), the MCDM (F-AHP) approach is used for weights and ranking of the energy alternatives. The commercial computer software ArcGIS 10.7 from the Environmental System Research Institute (ESRI) is then used for the digitization, conversion, analysis, and visualization of the spatial data. In Step (V), the available land area is categorized into five suitability scales ‘highly suitable’, ‘suitable’, ‘moderately suitable’, ‘less suitable’, and ‘not suitable’. Finally, in step (VI), explored the potential areas from different states and union territories of India.

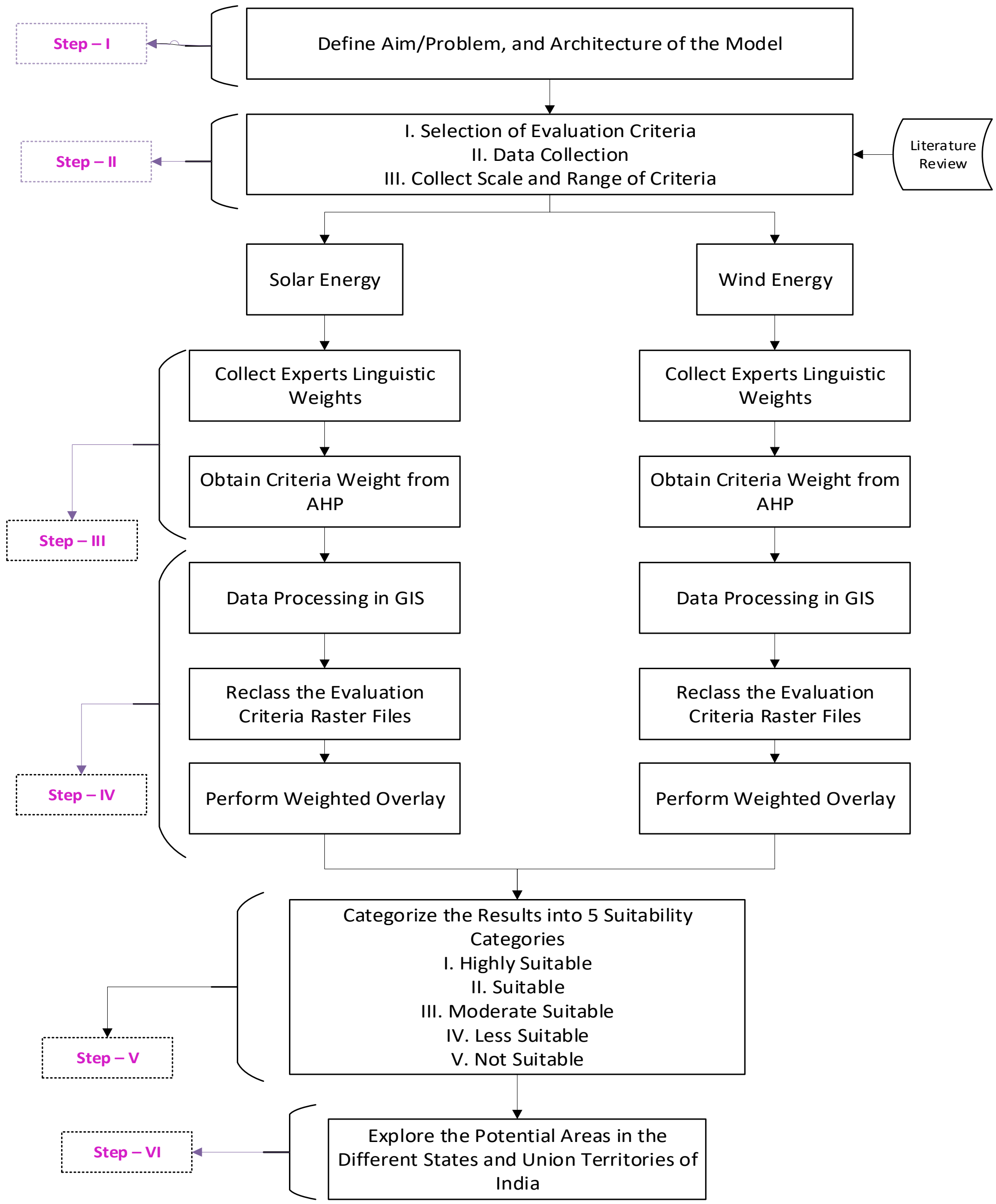


Fig. 5.2: Flow chart of research methodology

5.2.3 Sources of Data

Spatial and attribute data used in the present study are obtained from secondary sources. Data sources for various criteria used for the identification and evaluation of solar and wind power potential sites in India are different, hence discussed in detail in the proceeding lines. Solar radiation data are collected from the National Renewable Energy Laboratory, USA. These data are developed in a joint venture of the Ministry of New and

Renewable Energy (MNRE), India, and NREL, USA from 2000 to 2014. Wind speed at an altitude of 100 meters above ground level for a spatial resolution of 1000 meter × 1000 m is obtained from DTU wind energy global wind atlas. Wind speed data are in the form of wind speed frequency distribution for 12 direction sectors. Ground elevation and slope of land data (terrain data) on 900 m × 900 m spatial resolution are obtained from the GTOPO30 global digital elevation model (DEM) produced by the United States Geological Survey (USGS). Roads and inland water bodies' data are obtained from a digital chart of the world (DIVA-GIS). Airport location data are obtained from a dataset created by Addy & Lasma (2017). Wildlife designations are compiled from multi-sources like the world database on protected areas, consortium, IUCN, and UNEP-WCMC (2005). Source of land-use and land-cover data are obtained from USGS land-use/land-cover dataset (1993). Urban agglomerations data are obtained from CIESIN, Columbia University, 2017, and NASA-SEDAC. Electric power transmission lines of India data are obtained from the Power and Gas Grid map of south Asia (2006) prepared by US AID. Existing power plant locations in India are obtained from CARMA power plant dataset as discussed in Table 5.1. During the analysis, the spatial resolution of each factor was converted into a common spatial resolution of 1000 m ×1000 m.

Table 5.1: GIS data sets to identify suitable sites for solar and wind farm installation

Subject	Description	File Type	Geometry	Spatial Resolution	References
Solar radiations	Global solar radiations ($kWh/m^2/day$)	Raster file		1000 m	[339]
Wind Speed	The subject contains the wind speed at a height of 100 m above surface level.	Raster file		1000 m	[340]
Terrain Data	Elevation	Raster file		900 m	[341]
Inland Water	It contains the rivers, canals, and lakes.	Vector	Polygon		[342]
Airports	It covers the national and international aerodromes or airports	Shape file	Point		[343]
Wildlife designations	Wildlife designations cover the national parks, biological corridors, Strict nature reserves, and sanctuary.	Vector	Polygon	Varied, compiled from multiple sources	[344]
Land use	Land use and land covered by forest, water bodies, wet lands, snow, and ice.	Raster		1000 m	[345]
Urban agglomerations	Covers the rural and urban locations of the	Shapefile	Point		[346]

Subject	Description	File Type	Geometry	Spatial Resolution	References
	India				
Roads	Different state highways and national highways	Shapefile	Polyline		[342]
Transmission Lines	Electric power transmission lines of India.	Shapefile	Polyline		[347]
Power Plants	Locating the existing power plants in India	Shape file	Point		[348]

5.2.4 Evaluation Criteria

The various evaluation criteria are considered based on the defined goal, study area, accessibility of data sets, spatial scale, and operational techniques. The criteria selected are based on the rigorous literature review as summarized in Table 5.2. The current research work is carried out based on the established criteria.

Table 5.2: Decision criteria considered in the previous studies

Criteria	Hofer et al. [160]	Giamalaki and Tsoutsos [169]	Sanchez-Lozani et al. [142]	Ali et al. [45]	Noorollahi et al. [165]	Azizi et al. [204]	Aly et al. [113]	Sanchez-Lozani et al. [188]	Tahri et al. [162]	Merrouni et al. [118]
Solar resources	×	√	√	√	√	×	√	√	√	√
Wind resources	√	×	×	√	×	√	×	×	×	×
Slope	√	√	√	√	√	√	×	√	√	√
Aspect	×	√	×	×	×	×	×	√	√	×
Elevation	×	√	×	√	√	√	×	×	×	×
Distance from Coastline	×	√	×	×	×	×	×	×	×	×
Distance from Water bodies	×	√	×	√	×	√	×	×	×	√
Distance from Airports	×	×	×	√	×	√	×	×	×	×
Distance from Wildlife Designations	√	×	×	√	×	√	×	×	×	×
Land use	√	√	√	√	√	√	×	×	√	×
Distance from Urban areas	√	×	√	√	√	√	√	√	√	√
Distance from Roads	√	√	√	√	√	√	√	√	√	√
Distance from Transmission lines	√	√	√	√	√	√	√	√	×	√
Distance from Power plants	×	×	×	×	×	×	×	√	×	×

From the above Table 5.2 it is clear that studies are based on a min-max number of evaluation criteria, whereas, in the present study, we have considered 14 evaluation criteria comprise of three main categories, namely, technical, socio-environmental, and economic. The sub-factors falling into these main categories is shown in Fig. 5.3. The following section discusses and elaborates on the considered criteria with their importance.

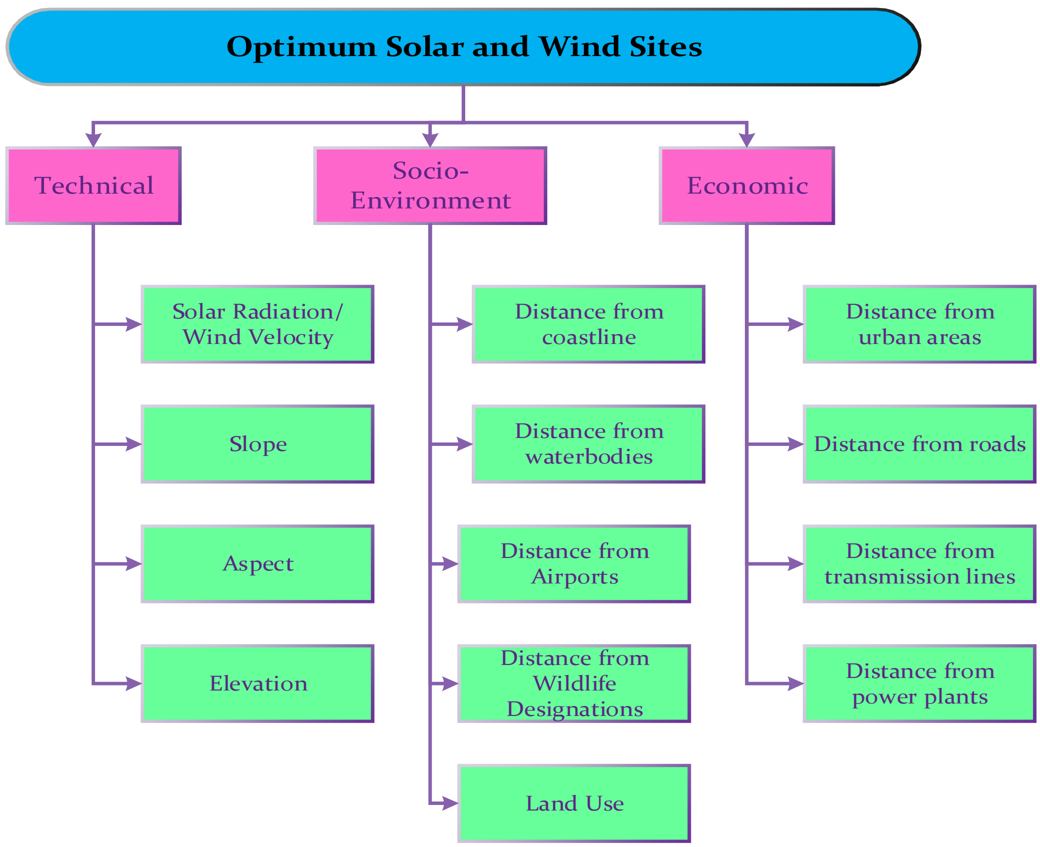


Fig. 5.3: Decision criteria considered for the evaluation of suitable sites

5.2.4.1 Technical factors

This section briefly discussed the various technical factors like solar radiation, wind speed, elevation, aspect, etc. which affect the decision-making process.

Solar radiation

Solar radiation is the incoming energy from the sun at a particular point on the earth's surface. Its visible spectrum is responsible for the electrical energy output from solar farms. Therefore, it is a very important factor in the site selection of solar farms [182,190,349]. The National Renewable Energy Laboratory (NREL), USA classifies solar radiation into four categories, namely, moderate (<4 kWh/m^2/day), good (4-5 kWh/m^2/day), very good (5-6 kWh/m^2/day), and finally, excellent (>6 kWh/m^2/day) radiation [350]. Also, various authors adopt different scales according to their country-specific norms. For example, Ali et al. [45] neglected areas with radiation of less than 3.5 kWh/m^2/day in their analysis for Thailand, Aly et al. [113] considered areas with at least 4.66 kWh/m^2/day of solar radiation as essential in Tanzania while Sanchez-Lozano et al. [142] considered areas with 5 kWh/m^2/day as essential in the south-east of Spain. India is among the best-suited countries for solar energy, the irradiance for which is shown in Fig. 4. Following the previous studies, this study considers the areas with a global horizontal irradiance value less than 3.8 kWh/m^2/day as 'not suitable' for solar plants [334,351]. Further, 3.8 to 4.4 kWh/m^2/day as 'less suitable', 4.4-5.0 kWh/m^2/day as 'moderately suitable', 5.0-5.6 kWh/m^2/day as 'suitable', and higher than 5.6 kWh/m^2/day GHI categorized as the 'highly suitable' for installation of solar power plants. Following the discussed classification, the final raster file of Indian solar radiation intensity was prepared in the ArcMap, which is shown in Fig. 5.4.

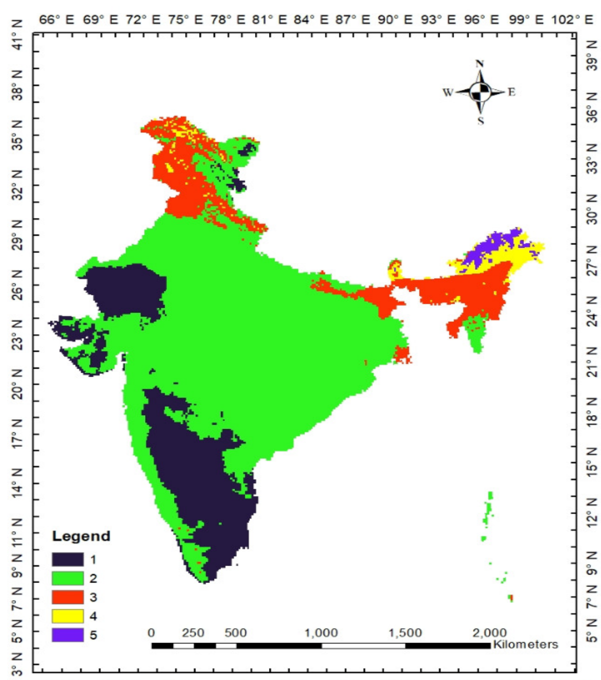


Fig. 5.4: Spatial distribution of global horizontal irradiance in India, where legend 1 shows the highly suitable while legends 2, 3, 4, and 5 respectively show the suitable, moderately suitable, less suitable, and not suitable areas

Wind speed

The average wind speed is also a key criterion for the determination of the economic feasibility and technical viability of wind farm installation sites. Hence, the wind speed criterion is incorporated in almost every study [122,160]. As summarized in Table 5.3, investigators have considered different wind speeds in their analysis. For example, Gorsevski et al. [173] considered wind speeds ranging from zero to 7.5 m/s, Ayodele et al. [178] excluded areas having wind velocity lower than 4.4 m/s, Ali et al. [45] considered a minimum wind velocity of 4 m/s for wind farms at different locations. Following the literature, the current research work considers a minimum wind speed of 3 m/s at a height of 100 m [122]. Accordingly, areas with a wind velocity of less than 3 m/s are classified as 'not suitable', 3 to 4 m/s as 'less suitable', 4 to 5 m/s as 'moderately suitable', 5 to 6 m/s as 'suitable', and finally, areas with more than 6 m/s of wind velocity are considered as 'highly suitable.' Following the discussed classification, the final raster file of wind speed variation was prepared in the ArcMap, which is shown in Fig. 5.5.

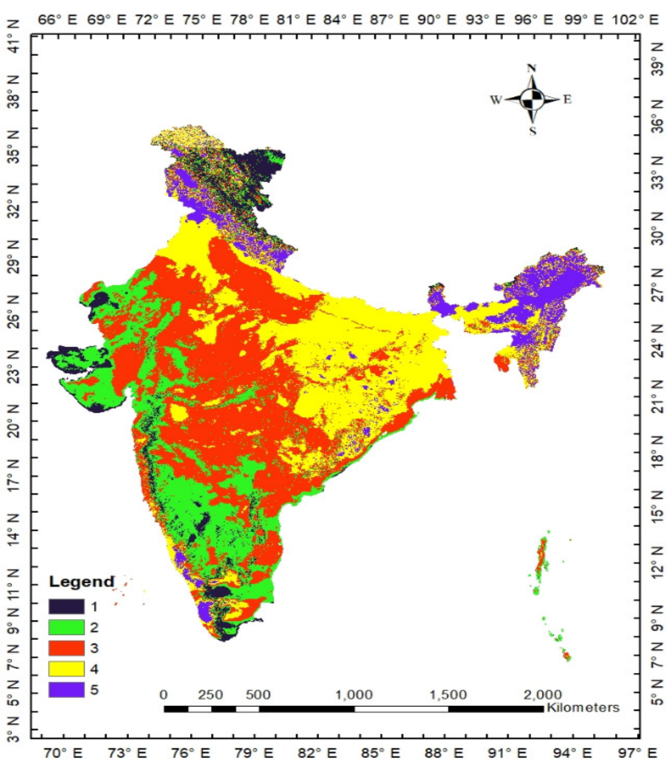


Fig. 5.5: Spatial distribution of average wind velocity in India at a hub height of 100m. Here legend 1 shows the highly suitable areas while legends 2, 3, 4, and 5 respectively show the suitable, moderately suitable, less suitable, and not suitable areas

Table 5.3: Summary of decision criteria values considered in previous studies

Criteria	**Tahri et al.** [162]	**Giamalaki and Tsoutsos** [169]	**Gorsevski et al.** [173]	**Ayodele et al.** [178]	**Ali et al.** [45]	**Ali et al.** [45]	**M Uyan** [110,180]	**Noorollahi et al.** [165]	**Aly et al.** [113]	**Baseer et al.** [111]	**Aydin et al.** [167]
Solar irradiation (GHI)	741 to 1967 kWh/m^2/year	1000 to 1800 and higher, kWh/m^2/year	–	–	–	3.5 to 5, kW/m^2/day	–	1300 to 2100 and higher, kWh/m^2/year	1700 to 2300, kWh/m^2/year	–	Higher than 4.5, kWh/m^2/day
Wind velocity	–	–	0 to 7.5 m/s	4.4 to 7.0 m/s	4 to 6 and higher, m/s	–	–	–	–	5 to 6 and higher, m/s	–
Slope	0 to 24%	0 to 28%	–	0 to 15%	0 to 15%	0 to 5%	0 to 3%	3 to 100%	–	–	0 to 7%
Orientation (Aspect)	South, and flat	South, southeast, southwest	–	–	–	–	–	South and flat	–	–	–
Elevation	–	0 to 1500 m	–	0 to 2000 m	0 to 200 m	0 to 200 m	–	0 to 4500 m	–	–	–
Distance from Coastline	–	50 to 200 and higher, m	–	–	–	–	–	–	–	–	–
Distance from Water bodies	–	100 to 400 and higher, m	–	–	0.4 to 1 and higher, km	0.4 to 1 and higher, km	–	–	0 to 9 km	–	Higher than 2500 m
Distance from Airports	–	–	–	–	–	–	–	–	–	Higher than 2500 m	Higher than 3000 m
Distance to Wildlife Designations	–	–	5000 to 30,000 m	–	3 to 4 and higher, km	1 to 2 and higher, km	–	–	–	–	Higher than 1000 m
Land use	Area without vegetation	A barren area with little or no vegetation	Shrub, barren, pasture, cropland	–	Barren grassland	Barren grassland	Barren and rocky	–	–	–	–
Distance to Urban areas	0 to 10 and higher, km	–	–	2000 to 20,000 and higher, m	1 to 3 and higher, km	0.5 to 1.5 and higher, km	500 to 5000 m	15 to 350 km	8 to 45 km	2000 to 10,000 m	–
Distance to Road network	1.4 to 10 km	100 to 4000 m	1000 to 10,000 m	500 to 20,000 m	0.5 to 10 km	0.5 to 10 km	100 to 5000 m	20 to 200 km	0 to 20 km	0 to 10,000 m	0 to 10 km
Distance to Transmission lines	–	0 to 10,000 m	1000 to 20,000 m	250 to 20,000	0 to 10 km	0 to 10 km	0 to 10,000 m	500 m to 60 km	0 to 50 km	0 to 10,000 m	1 to 45 km

Slope

The terrain slope is another influential factor in the selection of optimum locations for solar and wind power plants. The landscape slope influences the electrical output and construction cost of solar and wind farms [160,190]. Due to the lack of a clear consensus regarding the optimal value of terrain slope, various authors have adopted different values. For example, Finn and McKenzie [352] accepted a maximum of 5% terrain slope, Uyan [180] excluded more than a 3% slope for solar power plants while Garni et al. [353] considered less than 5% terrain slope for the solar farms. For wind farms, Ayodele et al. [178], Elkadeem et al. [354], and Ali et al. [45] accepted a maximum slope of 15%. Based on the data from the literature, the current research work considers a maximum 5-degree slope for solar energy and a 15-degree slope for wind energy.

Elevation

The elevation is yet another factor in the effective selection of optimum sites for solar and wind farms. Its importance is highlighted by various authors such as Giamalaki et al. [169] who argue that high altitude locations have fewer flora and fauna species while Zoghi et al. [182] mention that high altitude locations receive more solar energy due to a thinner atmosphere. Following the literature summarized in Table 5.3, the current work adopts a maximum of 2000 m elevation for wind energy while a maximum of 1500 m elevation for solar energy.

Aspect

The aspect is an important factor for solar farms because it enhances the efficiency of solar farms by receiving the maximum amount of solar radiation. As India is located in the northern hemisphere, this means that the solar panels should be oriented towards the geographical south to receive the maximum amount of solar radiation from the sun.

5.2.4.2 Socio-environmental factors

This section briefly discussed the various socio-environmental factors which affect the decision-making related to solar and wind power site selection.

Distance from the coastlines

It is an important factor from the technical, aesthetic, and environmental points of view. The distance from the coastline creates issues like visual impacts on tourist activities, pressure on the marine ecosystem, the effect of salt on the life and efficiency of the equipment, and pollution-related incidents [169]. Following the previous literature and expert's advice, the current research work considers a 10 km area from the shoreline in the 'not suitable zone' including the buffer and exclusion zone. The complete details of classifications are provided in Tables 5.4 & 5.5.

Table 5.4: Solar farms decision criteria values for different land suitability classes

Factors	Suitability Ranking				
	Highly Suitable	**Suitable**	**Moderately Suitable**	**Less Suitable**	**Not Suitable**
	1	2	3	4	5
Solar radiation ($kWh/m^2/day$)	>5.6	5.0-5.6	4.4-5.0	3.8-4.4	<3.8
Slope (degree)	0-2	2-3	3-4	4-5	>5
Orientation (facing direction)	South, Flat	Southeast and Southwest	East and West	Northeast and Northwest	North
Elevation (m)	<300	300-700	700-1100	1100-1500	>1500
Distance from Coastlines (km)	>40	30-40	20-30	10-20	<10
Distance from Waterbodies (km)	>28	21-28	14-21	7-14	<7
Distance from Airports (km)	>28	21-28	14-21	7-14	<7
Distance to Wildlife Designations (km)	>40	30-40	20-30	10-20	<10
Land use	Barren or Sparsely Vegetated	Mixed Shrubland/ grassland	Irrigated cropland and pasture	Herbaceous wetlands	Mixed forest
Distance to Urban Areas (km)	>40	30-40	20-30	10-20	<10
Distance to Road Network (km)	<10	10-20	20-30	30-40	>40
Distance to Transmission lines (km)	<10	10-20	20-30	30-40	>40
Distance from Power plants (km)	<10	10-20	20-30	30-40	>40

Table 5.5: Wind farms decision criteria values for different land suitability classes

Factors	Suitability Ranking				
	Highly Suitable	**Suitable**	**Moderately Suitable**	**Less Suitable**	**Not Suitable**
	1	**2**	**3**	**4**	**5**
Wind Velocity (m/s)	>6	5-6	4-5	3-4	<3
Slope (degree)	0-6	6-9	9-12	12-15	>15
Elevation (m)	<500	500-1000	1000-1500	1500-2000	>2000
Distance from Coastlines (km)	>40	30-40	20-30	10-20	<10
Distance from Waterbodies (km)	>28	21-28	14-21	7-14	<7
Distance from Airports (km)	>28	21-28	14-21	7-14	<7
Distance to Wildlife Designations (km)	>40	30-40	20-30	10-20	<10
Land use	Barren or Sparsely Vegetated	Mixed Shrubland/ grassland	Irrigated cropland and pasture	Herbaceous wetlands	Mixed forest
Distance to Urban Areas (km)	>40	30-40	20-30	10-20	<10
Distance to Road Network (km)	<10	10-20	20-30	30-40	>40
Distance to Transmission lines (km)	<10	10-20	20-30	30-40	>40
Distance from Power plants (km)	<10	10-20	20-30	30-40	>40

Distance from waterbodies

Solar PV and wind farms may contaminate or pollute the aquifers like permanent water bodies, reservoirs, dams, lakes, rivers, etc. To protect the natural water resources, the current research work considers the land within a 7 km distance from the water resources as 'not suitable' for the installation of solar and wind farms. Further details on the classification are given in Tables 5.4 & 5.5.

Distance from airports

It is also an important factor due to the adverse effects of solar and wind farms on aviation activities including interference to the aviation radar's signals, distractions to the pilot's vision, etc. Therefore, solar and wind farms need to be located at a significant distance from the airports. Following the regulations of the Indian aviation department, the current study considers land within a 7 km distance from the airports to be in the 'not suitable' category.

Distance to wildlife designations

To preserve the natural wildlife and biodiversity, solar and wind farms should be installed at a significant distance from wildlife sanctuaries, national parks, etc. The current research work includes wetlands, national parks, wildlife sanctuaries, biological corridors, strict nature reserves, game reserves, and world heritage sites in the category of wildlife designations. In the previous studies, Gorsevski et al. [173] considered a minimum distance of 5 km while Aydin et al. [167] considered a distance of 1 km from the wildlife designations. However, based on the discussion with regional and local experts, a minimum distance of 10 km is considered in the current work to be in the 'not suitable' category. More details of the classification are provided in Table 5.4 and Table 5.5.

Land use

The installation of an energy project requires a careful assessment of the available lands. Following the literature survey in Table 5.3, the barren or sparsely vegetated, cropland/grassland mosaic, dryland pasture, grassland, and shrubland are considered in the 'highly suitable' category [355]. Similarly, deciduous broadleaf forest, evergreen broadleaf & needle leaf forest, mixed forest, snow or ice, wooded wetlands, and urban and built-up lands are considered in the 'not suitable' category.

5.2.4.3 Economic factors

Here, discuss the various factors related to the economics of solar and wind farms which mainly include the distance from urban areas, road network, electrical transmission network, and existing power plants.

Distance to urban areas

The distance to the urban areas is specifically relevant for solar and wind power studies. A significant distance is necessary to avoid inconvenience, visual intrusion in daylight, noise nuisance to human life, and for the future development of cities [45,204]. The current research work considers the land within a 10 km distance from urban areas as belonging to the 'not suitable' category based on the expert's viewpoint, public opinions, and relying on the gathered information from the previous studies [356].

Distance to road network

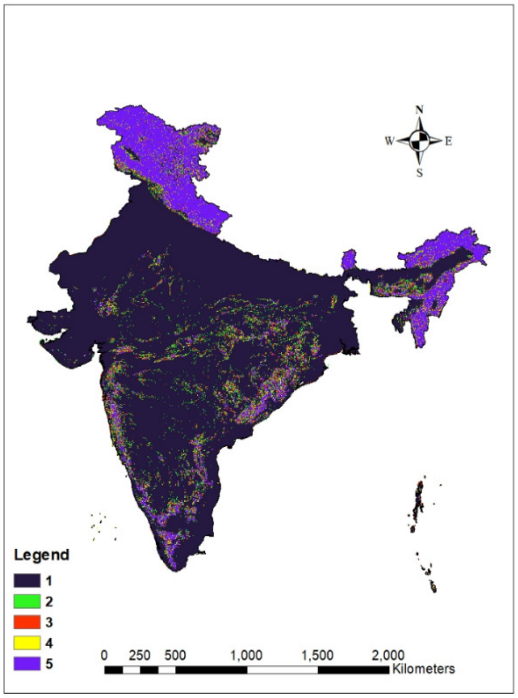
It is another important factor from an economic and environmental point of view. Suitable locations should be near the road/transportation network that avoids unnecessary environmental damage and road construction costs. Literature suggests a range of suitable distance for power plants such as 500 m - 10 km [45], 1.4 - 10 km [162], 1-10 km [173], less than 10 km [357], and 20 - 200 km [182]. The current research work considers a distance of 10 km from the road network as belonging to the 'highly suitable' category. The complete classification and descriptions are provided in Tables 5.4 and 5.5.

Distance to transmission lines

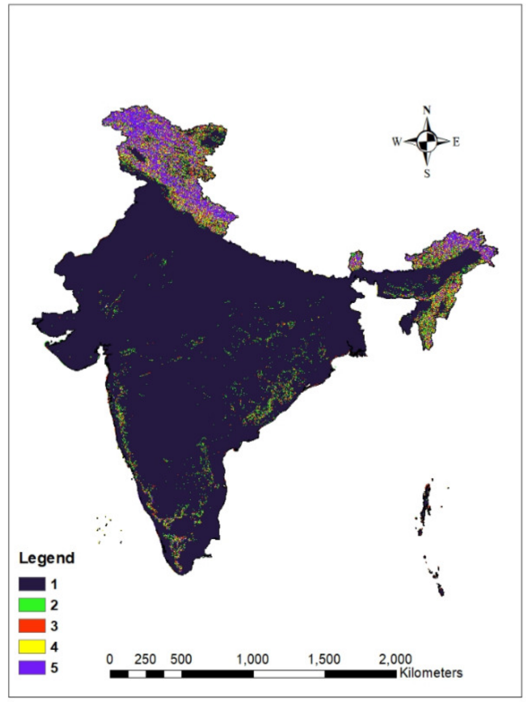
Similar to previous factors, it is also an important factor from economic and environmental aspects. An already existing transmission network minimizes the construction cost, ecological damage, and energy losses. Following the Indian Ministry of Power guidelines and expert suggestions, a 10 km area around the high voltage lines is considered 'highly suitable'.

Distance from power plants

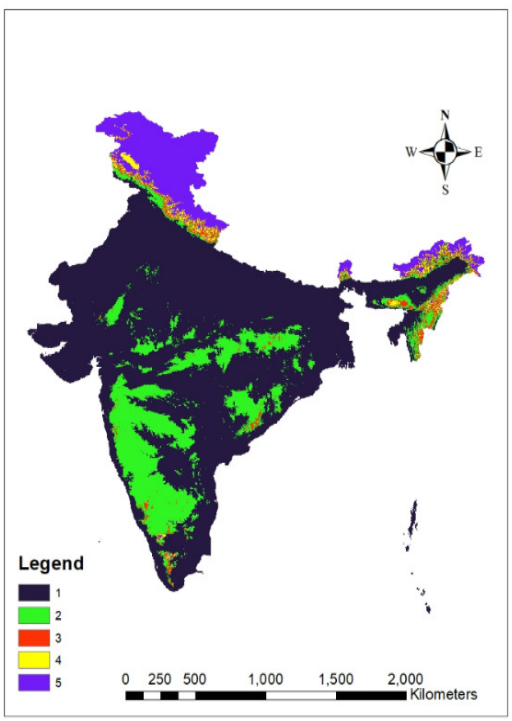
Minimum distance from already existing power plants will provide necessary things like road networks, transmission facilities, and water resources. Thus, it will provide higher economic viability and environmental stability. Based on the expert's advice, the land within a 10 km distance from the existing power plants is considered 'highly suitable'. Fig. 5.6 graphically represents the availability of land area in each of the suitability classes. These suitability charts are further used in the analysis of weighted overlay operation. In the current research work, adopted a common legend nomenclature where legend 1 implies the 'highly suitable' land while legends 2, 3, 4, and 5 respectively imply the 'suitable', 'moderately suitable', 'less suitable' and 'not suitable' lands.



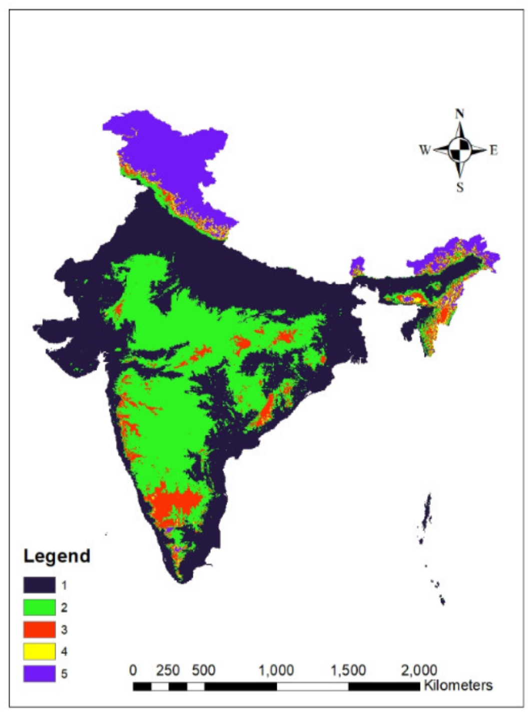
6.1: Slope for solar farms



6.2: Slope for wind farms

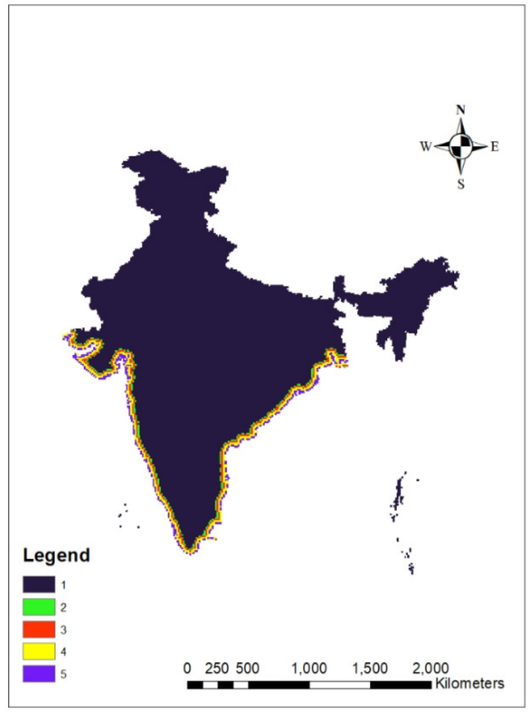


6.3: Elevation for solar farms

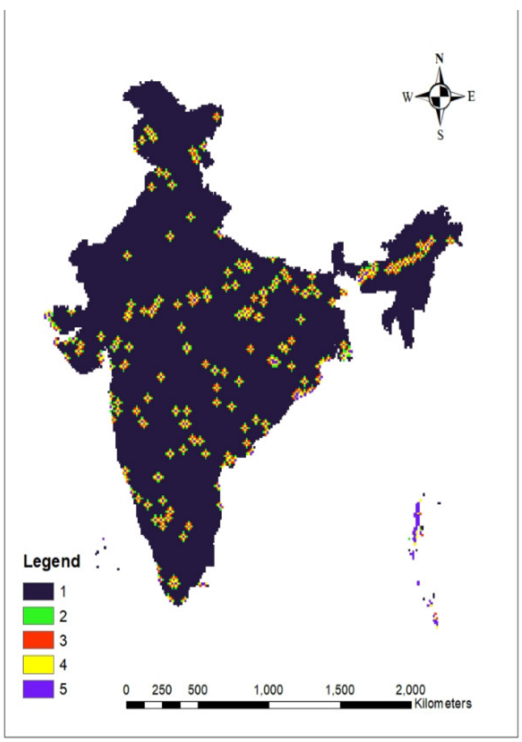


6.4: Elevation for wind farms

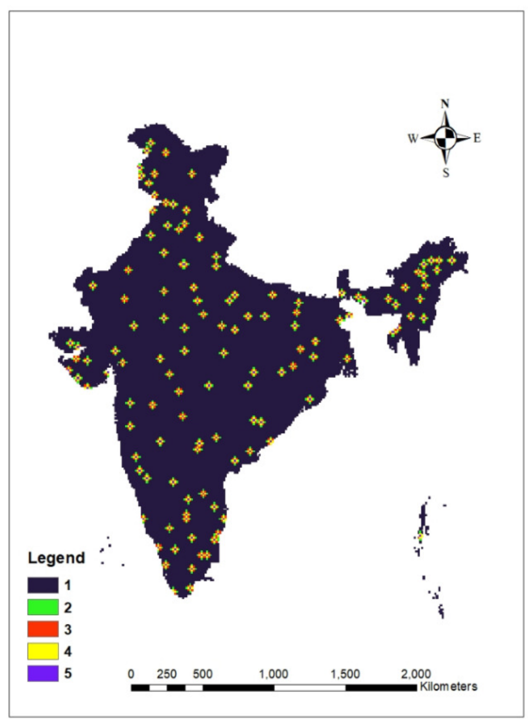
6.5: Aspect for solar farms



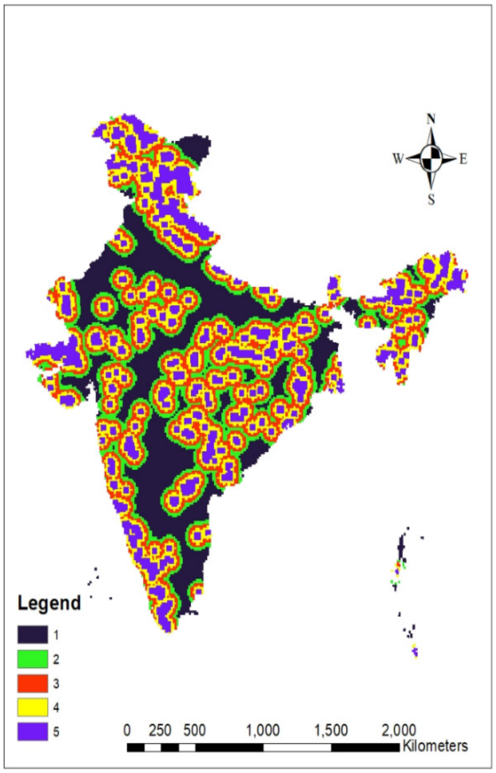
6.6: Coastline



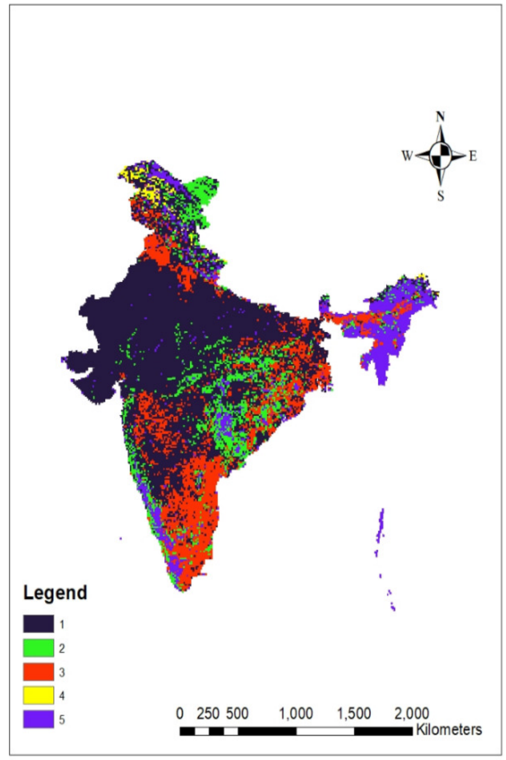
6.7: Waterbodies



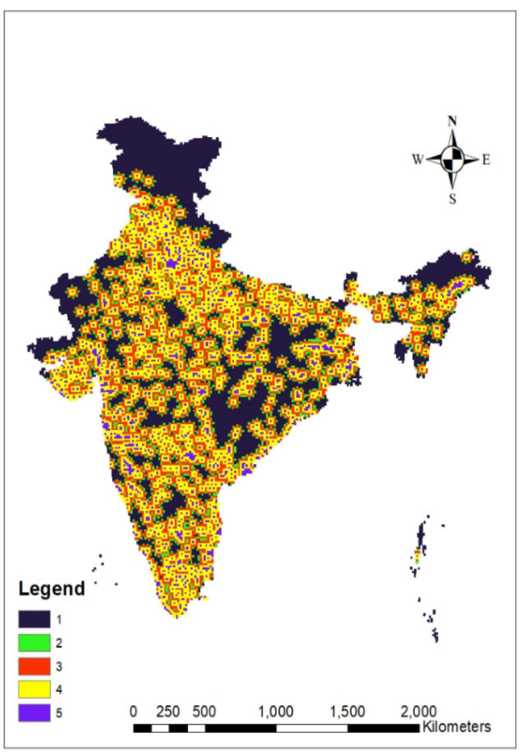
6.8: Airports



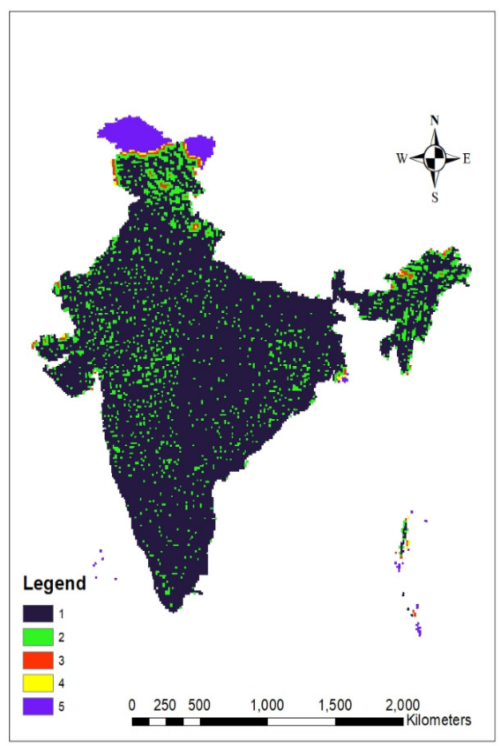
6.9: Wildlife



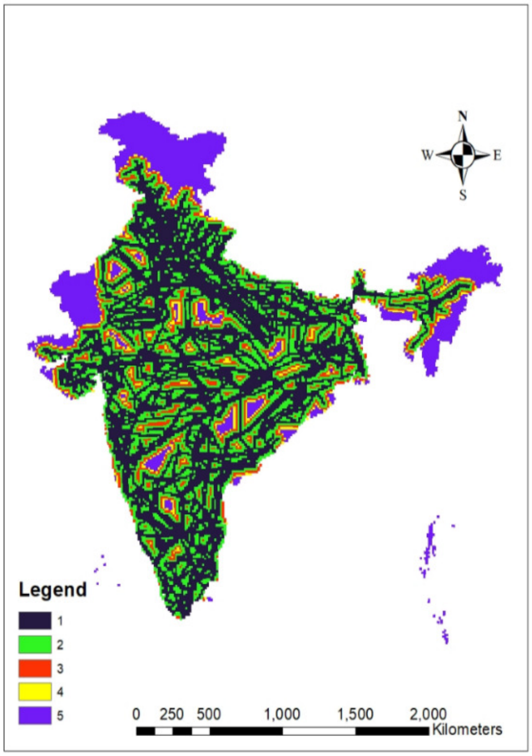
6.10: Land use



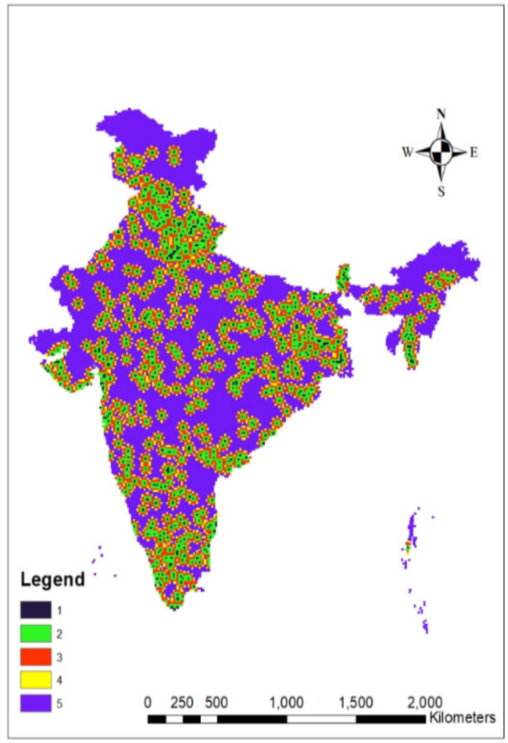
6.11: Urban areas



6.12: Roads



6.13: Transmission lines



6.14: Power plants

Fig. 5.6: Physical characteristics of the study area. Here, legend 1 shows the 'highly suitable' while legends 2, 3, 4, and 5 respectively show the 'suitable', the 'moderately suitable', the 'less suitable', and the 'not suitable' land

5.2.5 Hierarchical Model Development

Assessment of suitable sites for solar and wind farms involves conflicting issues and certain complexities that necessarily require an advanced decision-making approach. Among the available alternatives, the Analytical Hierarchy Process (AHP) decision-making approach has a strong ability to deal with complex and conflicting problems with different criteria [117]. The AHP approach was developed by Prof. Satty in 1979 [118,358]. It is quite popular in the MCDM research domain because of the use of a hierarchical or network-based structure in which, the topmost level contains the goal of the research work, the middle level contains the criteria and sub-criteria used for the analysis, and finally, the bottom-most level contains the different alternatives for evaluation. It also decomposes the problem into many sub-problems that are analyzed or solved separately [359].

The pair-wise comparison among the criteria and sub-criteria is done using the 9-point Satty fundamental linguistic scale. To make the pair-wise comparison, five experts are selected and asked to share their opinions using the provided linguistic scale. These linguistic weights were converted into the fuzzy geometric mean (GM) value using Buckley's GM approach. These fuzzy geometric mean values were converted into fuzzy weights, and further aggregated values of these fuzzy weights were given the weights or performance score of the criteria.

The AHP approach provided a good factor to check the consistency of the expert's weight called the Consistency Ratio (CR) which is defined as

$$CR = \frac{CI}{RI} \tag{5.1}$$

Where, RI is the random index while CI is the consistency index defined as

$$CI = \frac{(\lambda_{max} - n)}{n-1} \tag{5.2}$$

In the above equation, λ_{max} is the maximum eigenvalue and n is the number of elements.

The CR values less than or equal to 10% imply that the obtained AHP results are significant, otherwise, the pairwise comparisons will have to be performed again to improve the consistency of the analysis.

5.2.6 Geographic Information System (GIS)

Geographic Information System (GIS) is a tool used for digitization, conversion, analysis, and visualization of the spatial data [162] and is widely used for the planning of renewable energy-related projects which involve a variety of aspects such as economic, environmental, social and territorial. GIS easily manages these different aspects because of its in-built capabilities of investigating the territories, generation and sorting of data, capturing the geographic information, managing the commands, and visualization the output [119]. GIS has multiple in-built tools, the current research mainly uses data management, conversion, and spatial analysis tools. Generally, the graphical output of the GIS approach belongs to the following five categories: 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'. Table 5.6 provides the details of the classification scale along with the suitability score, various definitions, and explanations.

Table 5.6: Land suitability scale [45,180]

Suitability Score	Definitions	Explanations	Color Code
1	Highly suitable	Perfectly suitable in all considered aspects	Purple
2	Suitable	Suitable to a great extent	Green
3	Moderate suitable	A compromising or moderately suitable	Red
4	Less suitable	Lowest suitability	Yellow
5	Not suitable	Completely constrained or unsuitable for installation	Blue

5.3 RESULTS

Here, the results obtained from the analysis are summarized. This study aimed to evaluate the suitable sites for solar and wind farms in India using the GIS and MCDM approaches. Thirteen factors under the technical, socio-environment and economic aspects were selected based on the previous literature and according to the requirements of the study. The weights of the factors were obtained from the F-AHP approach and based on the experts' judgment. The technical, socio-environment and economic aspects are initially compared pair-wise to obtain the importance of each aspect. Table 5.7 shows that the technical aspect is the most important aspect with a preference score of 0.447 followed by the economic and socio-environment aspects. For solar farms, solar radiation is the most dominant factor with a weight of 0.170. With a weight of 0.116, the 'aspect' is the second most prominent factor while the distance to the transmission lines is the third important factor with a weight of 0.106. Distance to road network becomes the fourth choice followed by elevation and land-use factors. Distance from the coastlines is the least preferred criterion as shown in Fig. 5.7.

Table 5.7: Priority weights of decision criteria for solar and wind farms

Categories/ Criteria	Weights	Sub-Criteria	Solar sub-criteria	Solar Normalized Weights	Wind sub-criteria	Wind Normalized Weights
Technical	0.447	Solar irradiation/wind velocity	0.381	0.170	0.485	0.217
		Slope	0.171	0.076	0.211	0.094
		Orientation (Aspect)	0.260	0.116	---	---
		Elevation	0.188	0.084	0.303	0.135
Socio-Environment	0.255	Distance from coastlines	0.123	0.031	0.123	0.031
		Distance from	0.175	0.045	0.175	0.045

Categories/ Criteria	Weights	Sub-Criteria	Solar sub-criteria	Solar Normalized Weights	Wind sub-criteria	Wind Normalized Weights
		waterbodies				
		Distance from airports	0.142	0.036	0.142	0.036
		Distance to wildlife designations	0.229	0.058	0.229	0.058
		Land use	0.331	0.084	0.331	0.084
Economic	0.298	Distance to urban areas	0.197	0.059	0.197	0.059
		Distance to road network	0.288	0.086	0.288	0.086
		Distance to transmission lines	0.356	0.106	0.356	0.106
		Distance from power plants	0.159	0.047	0.159	0.047

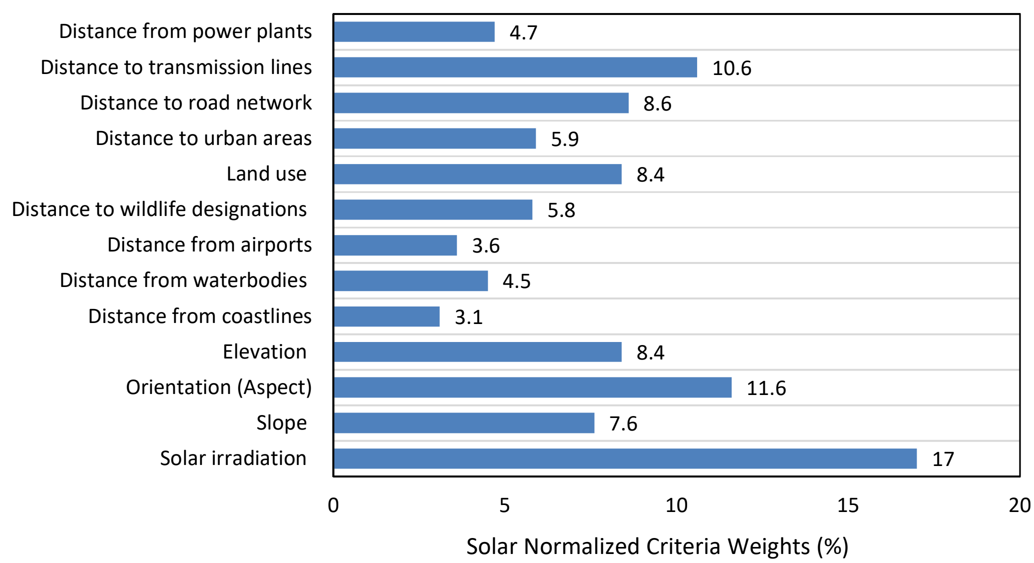


Fig. 5.7: Priority weights of the solar decision criteria

For wind farms, wind speed is the most dominant factor with a weight share of 0.217. The second preference is given to elevation with a weight of 0.135 while the distance to transmission lines is the third critical factor with a weight of 0.106. The slope becomes the fourth choice with a weight of 0.094 followed by the distance to the road network (weight 0.086) and land use (weight 0.084). Similar to solar farms, distance to the coastlines is the least preferred factor in the site selection for wind farms with a weight of 0.031. Fig. 5.8 shows the weights of criteria used for the evaluation of suitable sites for wind farm installation.

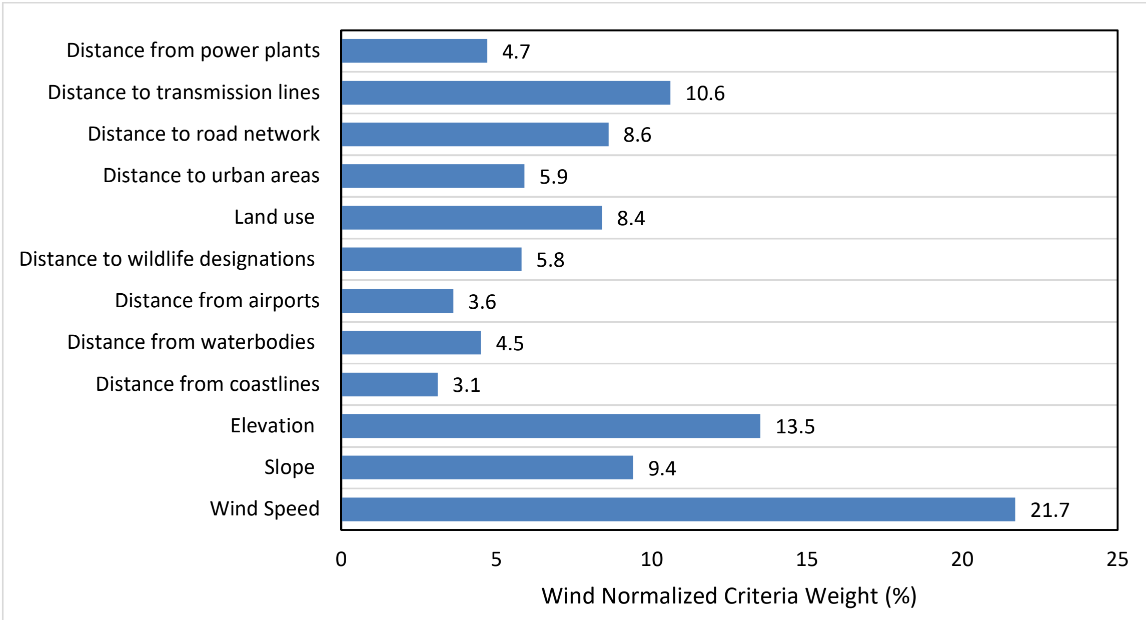
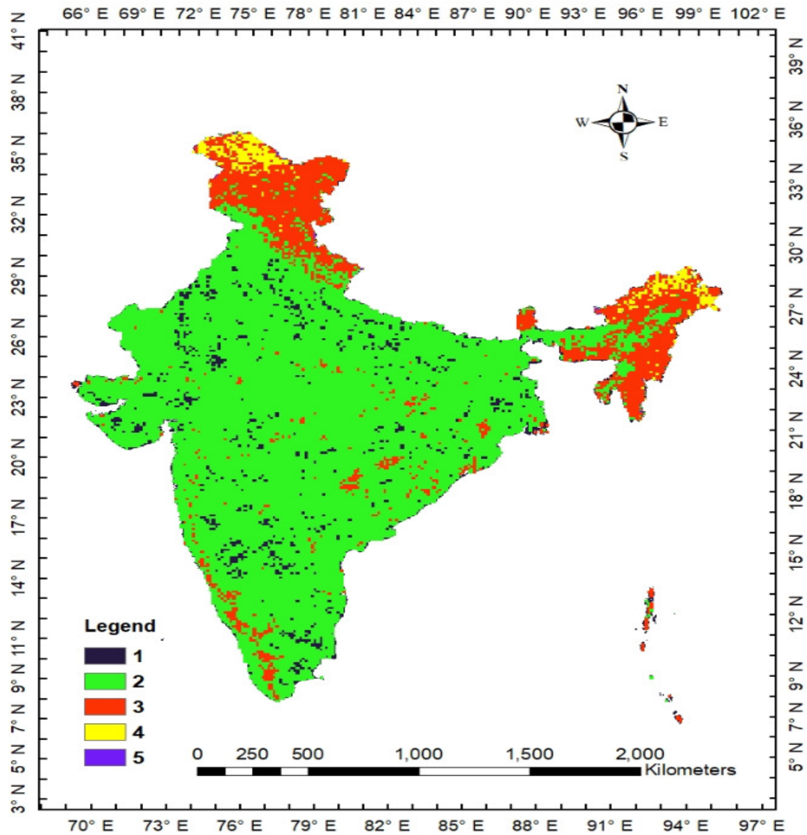
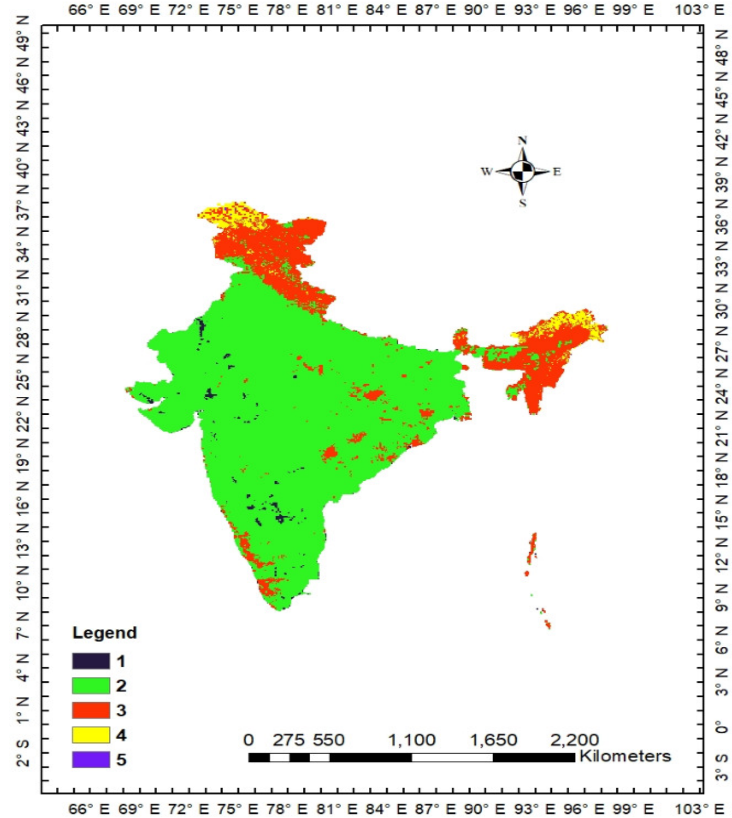


Fig. 5.8: Priority weights of the wind decision criteria

Suitable lands for solar and wind energy resources were assessed by combining all the GIS suitability maps (Fig. 5.6) and F-AHP weights using the weighted overlay technique in ArcGIS software. The final maps (Fig. 5.9) for both solar and wind energy resources were grouped into the five categories namely 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'. Results indicate that the highly suitable lands for solar and wind farms have respective areas equal to 133874 km^2 and 29457 km^2 representing a respective share of 4.13% and 0.91% of the total land area. Around 2567836 km^2 or 79.26% of the total land area is designated as the 'suitable' land for solar farms while around 2602763 km^2 or 80.43% of the total land area lies in the 'suitable' category for wind farms. The 'not suitable' category was not detected in the current analysis for both solar as well as wind power. Table 5.8 shows the statistical distribution of the remaining land suitability classes while Fig. 5.10 compares the assessment results of the solar plants and the wind farms.



(i). Solar farms suitability map of India



(ii) Wind farms suitability map of India

Fig. 5.9: The solar and the wind farms suitability map of India. Here, legend 1 shows the highly suitable land while legends 2, 3, 4, and 5 respectively show the suitable, moderately suitable, less suitable, and the not suitable lands

Table 5.8: Statistical information on land suitability area for solar, and wind farms

	1 (highly suitable)		2 (suitable)		3 (moderate suitable)		4 (less suitable)		5 (not suitable)	
	Area (km^2)	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**	**Area (km^2)**	**Area (%)**
Solar	133874	4.13	2567836	79.26	473309	14.61	64904	2.00	---	---
Wind	29457	0.91	2602763	80.43	546636	16.89	57044	1.77	---	---

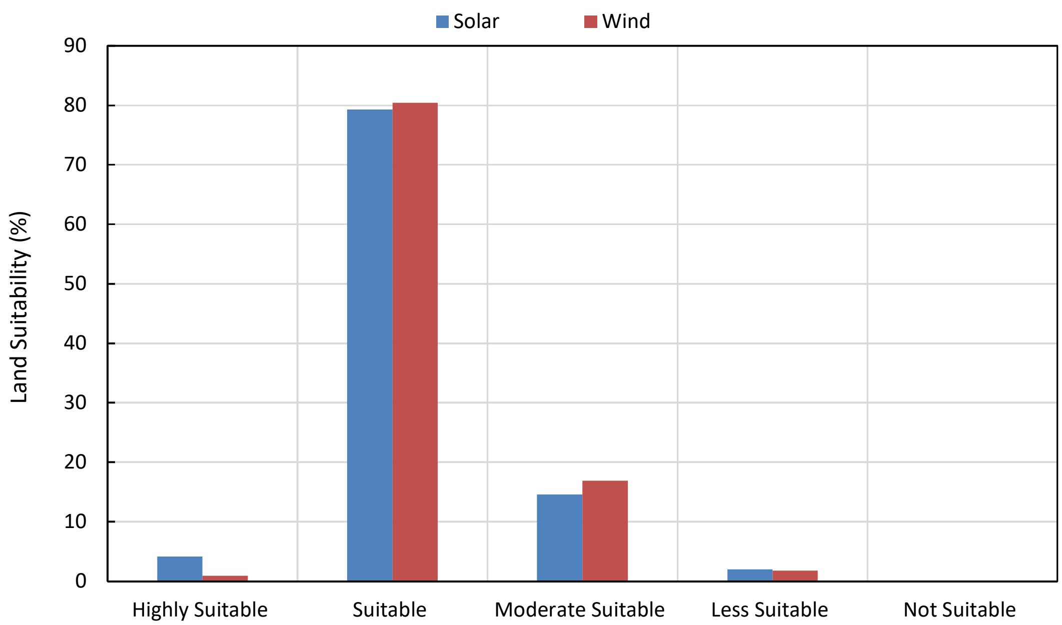


Fig. 5.10: Graphical interpretation of results of land suitability classes for solar, and wind farms

As explained in the introduction, India has thirty states and six union territories. Among all the states and union territories, the Rajasthan state has the highest 'highly suitable' land for both solar and wind energy. Rajasthan state has a 20881 km^2 area as 'highly suitable' for solar energy while 6323 km^2 is 'highly suitable' for wind energy. Table 5.9 provides the complete statistical land suitability description for solar and wind energy in the union territories and different states of India. Uttar Pradesh has the second-highest 'highly suitable' land for solar farms while Andhra Pradesh has the second-highest 'highly suitable' land for wind farms. Fig. 5.11 shows the 'highly suitable' land in the top ten states of India for solar and wind farm installations.

Table 5.9: Statistical information of land suitability area for different states and union territories of India

States	Highly Suitable (km^2)		Suitable (km^2)		Moderate Suitable (km^2)		Less Suitable (km^2)		Total Area (km^2)	
	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind	Solar	Wind
Andaman and Nicobar	---	---	976	350	3375	6063	---	---	4351	6413
Andhra Pradesh	6722	5821	147591	151361	3777	2691	---	---	158090	159873
Arunachal	---	---	1225	317	53696	47816	25727	35791	80648	83924
Assam	---	---	50053	22851	30269	58347	2	---	80324	81198
Bihar	3953	---	88739	91523	212	2395	---	---	92904	93918
Chandigarh	---	---	127	127	---		---	---	127	127
Chhattisgarh	4681	---	120250	117803	10940	18068	---	---	135871	135871
Dadra and Nagar Haveli	---	---	507	507	---	---	---	---	507	507
Daman and Diu	---	---	499	516	---	---	---	---	499	516
Delhi	150	---	1399	1549	---	---	---	---	1549	1549
Goa	---	---	2670	2411	672	918	---	---	3342	3329
Gujarat	13748	5360	162717	177095	3320	837	---	---	179785	183292
Haryana	4871	---	39443	44324	19	09	---	---	44333	44333
Himachal	---	---	16511	11415	38019	43158	520	1228	55050	55801
Jammu and Kashmir	---	---	18722	12374	160927	154964	36793	16911	216442	184249
Jharkhand	1751		77566	78701	1268	1884	---	---	80585	80585
Karnataka	12941	5407	167512	177004	12173	10305	---	---	192626	192716
Kerala	---	---	27614	20261	8846	17126	---	---	36460	37387
Lakshadweep	---	---	---	32	---	---	---	---	0	32
Maharashtra	11360	1093	285953	301124	9565	4310	---	---	306878	306527
Manipur	---	---	106	---	20950	22766	1027	193	22083	22959
Meghalaya	---	---	5708	2205	16348	20435	---	---	22056	22640
Mizoram	---	---	1533	342	18677	20546	169	63	20379	20951
Madhya Pradesh	5427	1971	298437	301599	5423	5717	---	---	309287	309287
Nagaland	---	---	1265	521	14510	14778	666	1653	16441	16952
Orissa	4687	---	138680	137307	11325	18240	---	---	154692	155547
Puducherry	---	---	441	537	---	15	---	---	441	552
Punjab	1443	---	48229	48119	215	2251	---	---	49887	50370
Rajasthan	20881	6323	322151	338926	1501	488	---	---	344533	345737
Sikkim	---	---	1162	1122	5183	4985	---	710	6345	6817
Tamil Nadu	11976	2172	108315	122588	7454	4922	---	---	127745	129682
Telangana	4005	567	110123	113902	854	513	---	---	114982	114982
Tripura	---	---	3871	4848	5374	4890	---	---	9245	9738
Uttar Pradesh	20306	743	218213	234602	1547	5328	---	---	240066	240673
Uttarakhand	171	---	28851	12079	23157	40766	---	495	52179	53340
West Bengal	4801	---	70677	72421	3713	11105	---	---	79191	83526
Total	**133874**	**29457**	**2567836**	**2602763**	**2602763**	**546636**	**64904**	**57044**	**3239923**	**3235900**

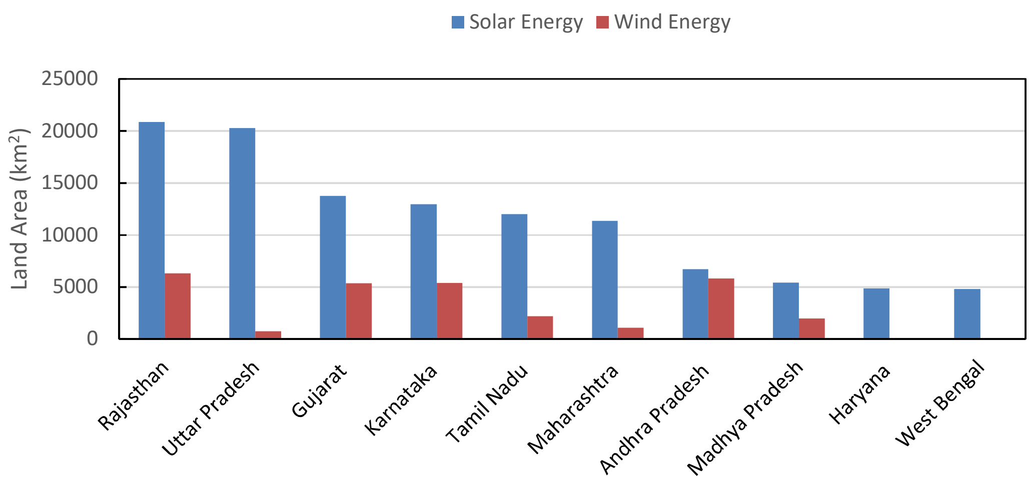


Fig. 5.11: Graphical representation of suitable land areas for solar, and wind farms in various states of India

5.3.1 Sensitivity Analysis

Sensitivity analysis was carried out to understand the influence of each factor and to confirm the robustness of the analysis. In the previous sub-sections, suitable land for solar and wind farms was evaluated based on the weight assigned to the factors using the F-AHP approach. The sensitivity analysis here was performed by changing the criteria weights for four different cases, the details of which are provided in Table 5.10.

Table 5.10: Sensitivity analysis cases for technical, socio-environment, and economic aspects

	Case – I (Equal-weight aspect)	Case – II (Technical aspect)	Case – III (Socio-environment aspect)	Case – IV (Economic aspect)
Technical	0.34	0.8	0.1	0.1
Socio-environment	0.33	0.1	0.8	0.1
Economic	0.33	0.1	0.1	0.8

In equal weight criterion, an increment from 4.13% to 4.83% for the solar farms 'highly suitable land' area and from 0.91% to 1.87% for the wind farms 'highly suitable land' area show that the results are quite sensitive to the criterion weights. From a technical perspective (Case-II), factors like solar radiation, wind velocity, slope, elevation, aspect contribute significantly to the increase of the 'highly suitable land' area from 4.13 to 10.67% for solar farms and from 0.91 to 8.99% for the wind farms. In case III, there is a significant increase in the 'highly suitable land' area from 4.13% to 27.45% for the solar farms while an increase from 0.91% to 26.28% for wind energy. The reason behind this huge increase may be due to the fact that India has a large area outside the protected areas and constraints. Thus, minimizing the importance of resource factors (solar radiation, and wind velocity) leads to an increase in a suitable area. The economic aspect shows the least ‘highly suitable land’ area because of the poor availability of the infrastructure and transmission facilities. Table 5.11 provides the complete statistical classification of the suitability of lands. The sensitivity analysis results indicate that the output results are sensitive to the criteria weights and each considered criteria is influential in the evaluation of the study region.

Table 5.11: Statistical information of land suitability areas for four sensitivity cases

		Highly suitable		**Suitable**		**Moderate suitable**		**Less suitable**		**Not Suitable**	
		Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)	Area (km^2)	Area (%)
Equal weight	Solar	156985	4.83	2636149	81.06	447970	13.78	10660	0.33	---	---
	Wind	61055	1.87	2750085	84.31	446861	13.70	3983	0.12	---	---
Technical weights	Solar	350216	10.67	2300255	70.10	391793	11.94	237287	7.23	1600	0.06
	Wind	290406	8.99	2512075	77.77	261740	8.10	155304	4.82	10443	0.32
Socio-environment weights	Solar	900861	27.45	2056219	62.67	318999	9.73	5072	0.15	---	---
	Wind	848766	26.28	2092195	64.77	284556	8.81	4451	0.14	---	---
Economic weights	Solar	45437	1.38	2032560	61.95	1099510	33.51	103644	3.16	---	---
	Wind	44350	1.37	1987161	61.52	1127706	34.92	70751	2.19	---	---

5.4 DISCUSSION

Even though India has built an ambitious renewable energy installation target especially expanding solar and wind energy resources. But still, very slow progress has been observed in the installation of renewable energy sources compare to their targets. The possible reasons may be due to unavailability of evidence of energy resources, poor infrastructure, limited planning, and lack of political motivation. For all these reasons, the outcome of the study could facilitate the different government organizations, policy and decision-makers, researchers, and investors to bring more renewable energy into the national energy system. This study developed and applied a GIS-MCDM model to evaluate suitable sites for the development of two prominent onshore renewable energy sources i.e., solar and wind energy. This research study would provide valuable information to the research community as well as potential investors pertaining to the most suitable locations for installing solar and wind farms. On the basis of publically available data from different reliable sources, the present study evaluates the highly suitable locations for solar and wind farms. The outcome of the study will help to achieve future renewable energy targets.

In addition, the Government of India (GOI) is highly intended to achieve its goals of (i) to achieve 175 GW of renewable power capacity by 2022, (ii) to produce about 40% of its electricity from "non-fossil fuel resources" by 2030, and (iii) to reduce emission intensity per unit of GDP by 30 to 35% by 2030 from the level of 2005 [20,319]. Therefore, the outcome of the study will help in achieving these goals by properly exploring the existing energy resources as well as assessing the new energy resources. It will be helpful in developing local and national infrastructure, preparing a sufficient market base, developing grid and transmission systems, and establishing weather monitoring stations. Development of local and national infrastructure such as roads, and railways would also be beneficial for rural development and flexible transportation servicing. Whereas, identification of suitable sites will also provide an opportunity to develop a sufficient and strong market base near facilities such as manufacturing industries, the construction sector, transportation facilities, and educational and training institutes. The output would also be beneficial in terms of the development of the grid and transmission system by minimizing the transmission and distribution losses and harnessing the untapped renewable energy potential. Following the research output, GOI may directly install the weather monitoring stations to validate the outcome, otherwise, the assessment of suitable locations is a crucial and costly process. GOI may also plan to develop an attractive investment environment and open international trade and investment in highly suitable locations.

The results of the study will also enlighten and guide the policy and decision-makers. They may formulate adequate government policies to support and increase the installed power capacity of India. Other than this, they could disseminate awareness about the technology's benefits which will increase the chances of the adoption of renewable technologies. Finally and importantly, they may also plan about the subsidies according to the availability and suitability of the renewable sites. The identification of highly suitable sites will also motivate and encourage investors and stakeholders to invest in green and renewable energy sources.

The implementation of the research outcomes will highly affect the rural and backward communities, especially due to the availability of renewable energy sources in rural remote areas. Due to the development of power plants in remote areas, more jobs will be created at the local and regional levels. Moreover, to increase the social acceptance of projects, some social benefits will also be given to them such as health care, electricity, and education. Further, the social welfare and living standards of the society will also increase with the development of infrastructure and earnings at the local level. Whereas from an industrialist's perspective, huge human resources will be available at a low cost, and the development of infrastructure will be cheap as compared to urban areas.

5.5 SUMMARY

The purpose of this research is to create an Indian site suitability map for the development of solar and wind power projects. To obtain supporting data, required factors, and sufficient understanding, a thorough literature review has been conducted. As a result, it has been determined that a solar site suitability analysis should be conducted using 13 parameters, while a wind energy analysis should be conducted using 12 parameters. These parameters correspond to the three economic, technological, and socio-environmental categories. To investigate these parameters analytically and graphically, two well-known technologies, fuzzy AHP and GIS, are used. Here, fuzzy AHP is used to determine the weights of criteria, and a GIS technique is used to analyze the data and illustrate the results. As a result of these methodologies, an India site suitability map is created, with five categories: highly suitable, suitable, moderately suitable, less suitable, and not suitable. Among all of these classes, the highly suitable land area has 133874 km^2 and 29457 km^2 respectively for the implementation of solar and wind power projects, respectively. In addition, the land suitability analysis is further carried out for the states and union territories of India. Rajasthan leads all states in terms of highly suitable land area for solar and wind power development, with 20881 km^2 and 6323 km^2 respectively. In the case of solar energy, Uttar Pradesh, Gujarat, Karnataka, Tamil Nadu, Maharashtra, Andhra Pradesh, Madhya Pradesh, Haryana, and West Bengal follow Rajasthan respectively. Whereas in the case of wind power, Andhra Pradesh, Karnataka, Gujarat, Tamil Nadu, and Madhya Pradesh are followed by Rajasthan.

To begin with, it would assist the Government of India in meeting its long-term targets of generating 175 GW of renewable power capacity by 2022 and producing 40% of its electricity from non-fossil fuel resources. It would also assist in the proper utilization of renewable energy potential and infrastructure. It would also aid in the preparation of the investment environment and in attracting investors to participate in green or renewable energy technology. Finally, it would aid in the development of vast solar zones in the country, which would have the potential to build manufacturing enterprises, transportation infrastructure, educational and training research institutes, and so on. As a result of all of this, jobs will be created at the local level, the living standard of rural and remote region residents will improve, transportation facilities will be expanded, and necessary services such as health and medical facilities will be accessible to them.

CHAPTER – 6

A MULTI CONSTRAINT-BASED ASSESSMENT OF SOLAR AND WIND ENERGY POTENTIAL IN INDIA

The present chapter calculates the exploitable power potential at previously determined highly suitable sites using multiple constraints. The exploitable power potential is measured in theoretical, technical, economic, and environmental categories by applying certain actual and environmental limits and constraints.

6.1 INTRODUCTION

It is observed that solar and wind energy are the two most promising renewable energy resources on which nations, including India, are relying for future energy needs. For properly utilizing the vast solar and wind power resources, an optimal site selection is essential for ensuring the cost-effectiveness of the project, proper exploitation of resources, and sustainable development [42,360]. After examining the promising solar and wind power sites, it is essential to estimate the actual solar and wind power potential (SWPP) available at these sites [334].

The assessment of SWPP depends on multi-dimensional factors such as the local solar radiation intensity, average wind velocity, land use, land cover, available technology, its limitations, the economics of resources, and finally, the government policies. All these factors have a tangible impact on the development of solar and wind energy resources, but the local solar radiation intensity and the average wind speed are the most important [361]. Afterward, the land use and land cover are the next dominant factors for the elimination of unsuitable or restricted land areas [362]. Finally, technological innovations directly or indirectly influence the economic feasibility of the system. In addition, government policies already have been endorsed to play a vital role in solar and wind power development [363]. Due to these factors, a comprehensive SWPP estimation should include technical innovation, land use constraints, economic viability, and other factors apart from resource availability. Therefore, a successful estimation of SWPP should consider the local resources, technology availability, economic feasibility, as well as the elimination of unsuitable land using land-use constraints.

Therefore, the primary objectives of the present chapter are as follows:

(i) To estimate the exploitable SWPP based on the theoretical, technical, economic, and environmental aspects at these potential sites.

(ii) To assess the robustness of the results by performing sensitivity analysis and demand-potential scenario for different Indian states and at the country level.

6.2 MATERIALS AND METHODS

This section describes the methodology used, criteria incorporated, data collection, research approaches used, and the different energy potentials investigated, etc. They are briefly described in the sub-sections.

6.2.1 Methodology

The present study aims to estimate the exploitable power potential of solar and wind resources at highly suitable locations in India. Initially, the theoretical power potential at these highly suitable sites is calculated, taking into account essential factors such as solar radiation and wind velocity. Further, by taking into account technological considerations and restrictions, theoretical power potential is narrowed down to technical potential. In the end, a validation of the exploitable power potential is performed by estimating the economic feasibility/potential and environmental sustainability (environmental potential). The detailed flow chart of methodology is shown in Fig. 6.1.

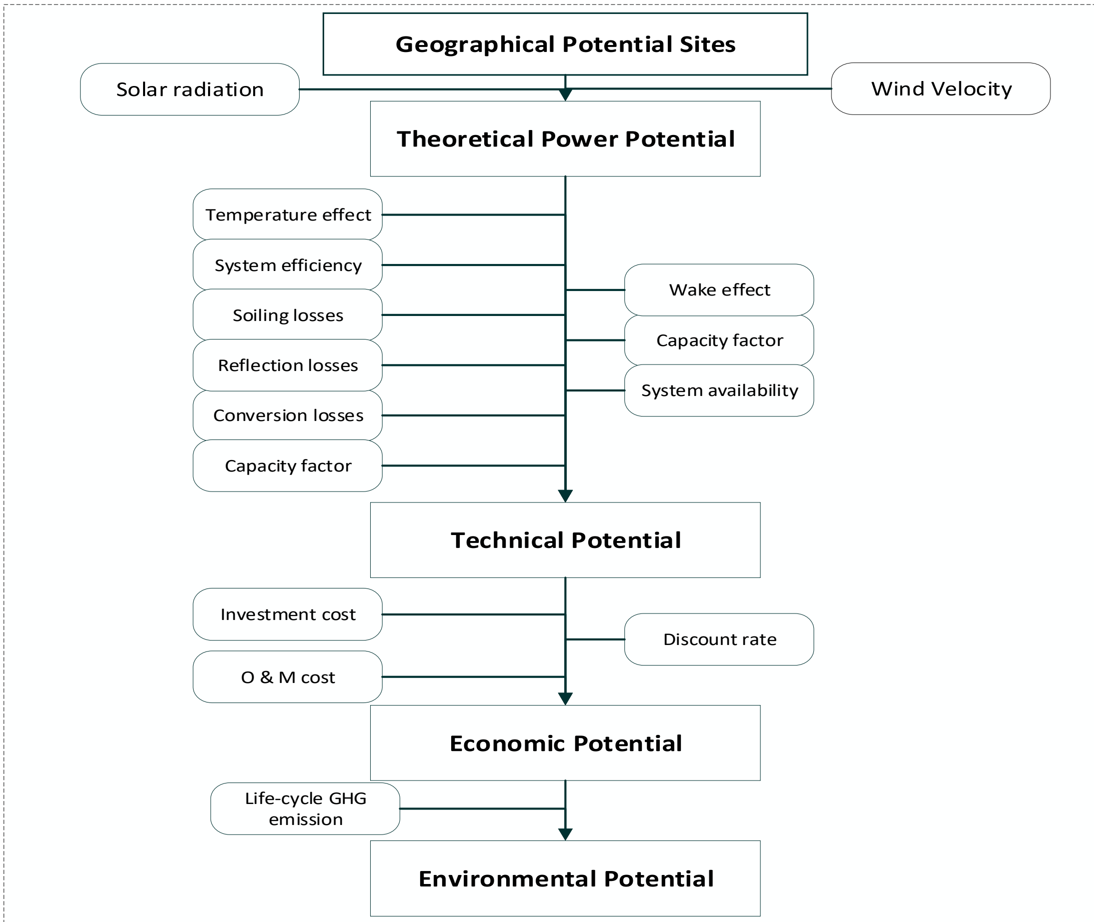


Fig. 6.1: Research process flow-chart

6.2.2 Assessment Tools

The current study incorporates two well-known research tools, viz., fuzzy AHP, and the GIS approach. Here, fuzzy AHP is employed for the evaluation of criteria weights while the GIS approach is used for land suitability, overlay, and graphical analysis. These tools are briefly addressed in the preceding chapters.

6.2.3 Energy Potentials

The present study aims to estimate the exploitable SWPP in India. A distinctive top-down approach has been employed in which each potential narrows down the previous potential by considering certain limits, obstacles, and losses [47,49,364]. Based on the earlier literature, the current study considers five different potentials, namely, geographical, theoretical, technical, economic, and environmental as shown in Fig. 6.2.

A brief discussion about the considered potentials is given in the following sub-sections.

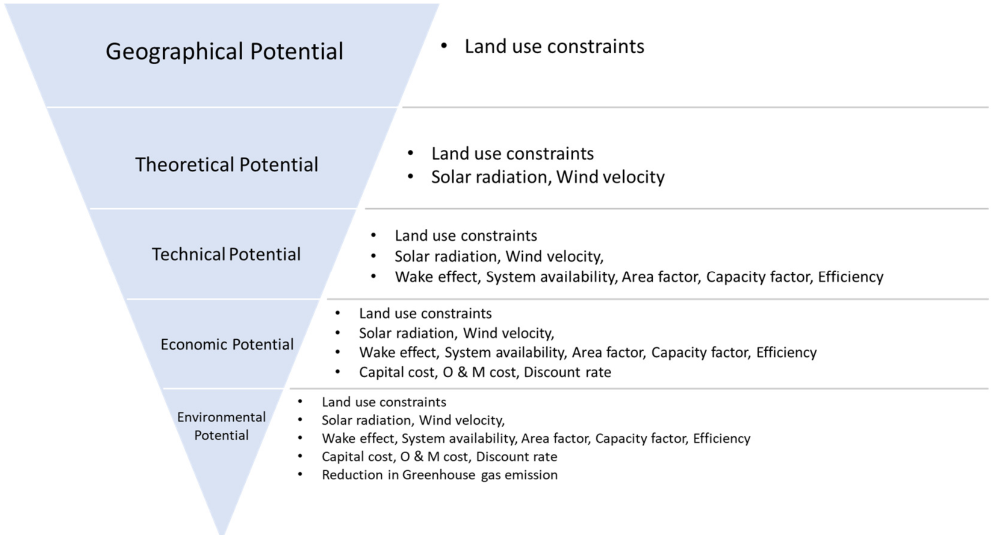


Fig. 6.2: Diverse potentials and their determinants encompassed in the evaluation of SWPP

The geographical potential is estimated in terms of highly suitable land areas by incorporating resource availability, geographical feasibility, and economic viability. Therefore, the geographical potential is the availability of highly suitable land areas in km^2 for the deployment of solar and wind power projects. The theoretical power potential at geographically suitable locations is estimated by considering the magnitude of solar radiation intensity and average wind velocity. Therefore, the theoretical power potential is the highest level of SWPP that can be extracted from nature without considering any restrictions or limits.

For geographically potential sites, the theoretical solar power potential (*TSPP*) is calculated based on the product of solar radiation intensity ($kWh/m^2/day$), area factor, the available potential land area, and the solar module efficiency. That is, the *TSPP* can be calculated using Eq. (6.1) [44,46,112,247],

$$TSPP = SR \times CA \times AF \times \eta \tag{6.1}$$

In the above equation, SR is the mean solar radiation intensity ($kWh/m^2/day$), *CA* is the geographical potential area (km^2), *AF* is the area factor (%), and η is the solar module efficiency (%). In this study, we take the area factor as 70% which means 70% of land area from a highly suitable category can be used for *PV* panels installation without any shading effect [46,189]. The solar radiation intensity was considered to be 5.61

($kWh/m^2/day$) in the study, which is the lowest figure for the 'highly suitable' land area group.

Similarly, the theoretical wind power potential (TWPP) for geographical potential sites can be determined on the basis of the capacity of the wind turbine generator, wind turbine rotor diameter, and the identified potential areas. *TWPP* can be calculated based on Eq. 6.2 [187,248],

$$TWPP = TA \times AF \tag{6.2}$$

In the above equation, *TA* is the total available 'highly suitable' land area (km^2), and *AF* is the area factor (MW/km^2). In this study, wind turbines are assumed to be arranged in a grid of $7D \times 5D$, where D is the rotor diameter [365].

The theoretical potential finally narrows down into technical potential by considering the factors such as technical limitations, generation losses, device efficiency, etc. For the technical potential of solar energy, the study took temperature, installation angle, dust or soiling, inverter, reflector, and capacity factor into consideration. The values for technical factors are taken from an extensive literature survey. A 10% performance loss is considered for solar *PV* panels where approx. 2% loss is attributed to the dusting/soiling effect, a 5% loss is assumed in the converter/inverter, and a 3% loss is assigned to irradiance reflection [112,366–369]. In addition, the study considers 10% system loss due to the module quality, array mismatch, installation angle efficiency, wiring/cabling, terrain shading of solar panels. Like solar energy, the wind power technical potential can be calculated by considering the losses due to the wake effect, grid availability, machine availability, and capacity factor. Following the previous literature, the current study assumes a 10% loss due to the wake effects [370]. Further, the present study incorporates the values of grid availability and machine availability as 95% and 90% respectively. The product of grid availability and machine availability are known as system availability. Finally, the study assumed a capacity factor (*CF*) as 19% and 27% for solar and wind power projects, respectively [368,370,371].

The economic potential is the amount of technical potential that can be achieved at a favorable per unit power cost. The economic potential is assessed in terms of Levelized cost of energy (LCOE), capital cost, operation & maintenance cost, discount rate, etc.

Here, in terms of electrical energy production, the LCOE is defined as the current price of the produced electrical energy (per kWh), taking into account the operational life of the plant and costs incurred during its construction, operation, maintenance, and fuel supply [372]. Because of its simplicity and easy computability, the LCOE is the most widely used economic indicator all over the world to assess the financial viability of energy projects [373]. The lower value of LCOE for a new technology compared to the existing ones represents competitiveness which encourages the capitalists. The LCOE also represents a single number that would be easier to comprehend while comparing and interpreting energy policies. In the current study, solar and wind energy are considered as energy resources, therefore there is no concern about the fuel price. In the current study, the LCOE is calculated using Eq. (6.3), which is adopted from the previous studies [292,374],

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + O\ \&\ M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \quad (6.3)$$

Here, n is the operational life of the technology in years, I_t is the investment cost of technology, $O\ \&\ M_t$ is the operation and maintenance cost per year, F_t represents the expenditure on the fuel, r shows the discount rate, and E_t is the amount of electricity generated per year. This study considers an investment cost of 618 USD/kW and 1054 USD/kW respectively for solar and wind power in India [375,376]. Similarly, the study adopts 9.5 USD/kW-year of O & M cost for solar power while 0.015 USD/kWh of O & M cost on electricity generation from wind power [374,376]. The study assumes 25 years of operational life for both solar and wind power plants. Further, the discount rate is taken as 4.25% [377]. [Note: 1 USD is considered equal to ₹ 72.99].

Finally, the environmental potential is the amount of technical potential that can reduce the emission of greenhouse gases compared to conventional energy sources. The current study assumes a reduction in the emission of the main greenhouse gas (CO_2) compared to the coal-fired thermal power plants and gas power plants. The current study considers a life-cycle emission from the different power plants including that during the various phases of construction, operation, fuel combustion, and decommissioning. Following the numerous studies and the inter-governmental panel on climate change (IPCC) guidelines, the current study assumes 820 g-CO_2/kWh life-cycle greenhouse gas emission from a coal-fired thermal power plant while 607 g-CO_2/kWh emission is assumed from a gas power plant. The solar PV (utility-scale) and onshore wind power plants have the life cycle greenhouse gas emission of 48 g-CO_2/kWh and 11 g-CO_2/kWh respectively [307,378–380].

6.3 RESULTS

This section discusses the various results obtained based on the current study. First, discuss the results on the evaluation of geographical potential sites and later discusses the calculation of exploitable SWPP in India. These are briefly discussed in the following sections.

6.3.1 Estimation of Exploitable Power Potential

Once the geographically potential sites are qualitatively shortlisted, the exploitable SWPP are quantitatively estimated. Hereafter, further analysis will be carried out only for the geographical potential sites of 133874 km^2 and 29457 km^2 for solar and wind energy respectively. First, a theoretical power potential is estimated which depends on the technology for solar PV modules and wind turbines, geographically potential areas, and plant facilities.

In the context of solar energy, the study investigates the mono-and poly-crystalline types of four solar photovoltaic panels, some manufacturers which are TATA solar power (TP-300), WAAREE (WS-320), EMMVEE (E320P72), and Canadian solar (CS6X-320P). Following Eq. (3), this study calculates the TSPP by incorporating the solar radiation intensity at geographically potential areas, area factors, and the efficiency of solar modules. The CS6X-320P PV power modules have the highest TSPP generation potential of 3653 GW. The other solar PV modules such as TP-300, WS-320, E320P72 have the respective TSPP potentials of 3592 GW, 3612 GW, and 3594 GW. The details regarding the estimation of TSPP are summarized in Table 6.1.

Table 6.1: Calculation of theoretical solar power potential in India

Manufacturers	Photovoltaic Module	Description	Solar Radiation (SR) (kWh/m^2/day)	Geographical potential area (km^2)	Area Factor (%)	Efficiency (%)	Theoretical Power Potential (GW)
TATA Solar Power	TP-300	Poly-crystalline	5.61	133874	70	16.4	3592
WAAREE	WS-320	Mono-crystalline				16.49	3612
EMMVEE	E320P72	Poly-crystalline				16.41	3594
Canadian Solar	CS6X-320P	Mono-crystalline				16.68	3653

To calculate the TWPP, the study considers the International Electrotechnical Commission (IEC) standardized wind turbine models available in the Indian market which are manufactured by multi-national companies such as Vestas, Suzlon, General Electric (GE), Inox Wind, and ReGen Powertech. Among all the available wind turbine models, the ReGen Powertech model (VENSYS-77) could tap the highest TWPP of 213.44 GW, followed by the GE model (1.6-82.5 WT), and the Inox wind model (93 RD + 80 HH). The complete details about the generation of TWPP by different wind turbine models are summarized in Table 6.2.

Table 6.2: Calculation of theoretical wind power potential in India

Manufacturers	Wind Turbine Model	IEC Class	Rotor Diameter (m)	Capacity (MW)	7D × 5D Area (km^2)	Area Factor (MW/km^2)	Theoretical Wind Power Potential (GW)
Vestas	V120-2.2	IEC IIB / IEC S	120	2.2	0.504	4.365	128.58
Vestas	V110-2.0	IEC IIIA	110	2.0	0.4235	4.722	139.09
Suzlon	S-111	IEC IIIA	112	2.1	0.439	4.783	140.89
Suzlon	S-120	IEC S	120	2.1	0.504	4.167	122.75
Suzlon	S-128	IEC S	129	2.7	0.582	4.639	136.65
GE	1.6-82.5 WT	IEC IIIB	82.5	1.6	0.238	6.723	198.04
Inox Wind	93 RD + 80 HH	IEC IIIB	93	2.0	0.303	6.601	194.44
ReGen Powertech	VENSYS-77	IEC IIIA	77	1.5	0.207	7.246	213.44

The technical potential is further refined by narrowing the theoretical potential with certain technological limitations and generation losses. For the case of solar energy, the study took temperature level, system efficiency, dusting or soiling level, inverter efficiency, reflector performance, and the capacity factor into consideration. By incorporating all the factors, the study estimates the highest technical power potential of 507.18 GW (4442.94 TWh/year) by the CS6X-320P PV module. The alternative modules such as TP-300, WS-320, and E320P72 have a generation potential of 498.72 GW, 501.49 GW, and 498.99 GW, respectively. Finally, the study concludes that India has vast solar power potential ranging from 4368.75 TWh to 4442.94 TWh. The described details about the calculation of technical solar power potential are summarized in Table 6.3.

Table 6.3: Calculation of technical solar power potential in India

PV Module's	Potential (GW)	Temperature losses (%)	System efficiency (%)	Dusting or soiling losses (%)	Conversion losses (inverter/ converter)	Reflection losses (%)	CF (%)	Technical power potential (GW)	Electricity (TWh)
TP-300	3592	10 %	90%	2.1 %	5 %	3 %	19 %	498.72	4368.75
WS-320	3612							501.49	4393.07
E320P72	3594							498.99	4371.18
CS6X-320P	3653							507.18	4442.94

For estimating the technical wind power potential, the current study incorporates several factors such as capacity factor, losses due to wake effect, and system availability. As an outcome, the study calculates the highest technical wind power potential of 44.34 GW by the ReGen Powertech wind turbine followed by GE wind turbine (41.15 GW), and Inox wind (40.40 GW). Finally, it concludes that India has a gigantic wind power potential ranging from 223.38 TWh to 388.42 TWh at the geographically potential sites (Rank 1). Table 6.4 below compiles the estimation of technical wind power potential by different wind turbine generator models.

Table 6.4: Calculation of technical wind power potential in India

Wind Turbine Models	Theoretical Wind Power Potential (GW)	Wake Effect losses (%)	System Availability (%)	Capacity Factor (%)	Technical Power Potential (GW)	Electricity (TWh)
V120-2.2	128.58	10 %	85.5 %	27 %	26.71	233.98
V110-2.0	139.09				28.90	253.16
S-111	140.89				29.27	256.41
S-120	122.75				25.50	223.38
S-128	136.65				28.39	248.70
1.6-82.5 WT	198.04				41.15	360.47
93 RD + 80 HH	194.44				40.40	353.90
VENSYS-77	213.44				44.34	388.42

The present study anticipates the technical power potential ranging from 498.72 to 507.18 GW, and 25.50 to 44.34 GW for solar and wind energy respectively. At this stage, it is essential to assess the economic viability and environmental sustainability of the technical power potentials. Therefore, the present study incorporates factors such as investment cost, O & M cost, discount rate, operational life, and electricity potential to assess the feasibility of the project. An economic analysis indicates LCOE of 40 USD/MWh (4 US₵/kWh, and ₹ 2.91/kWh) for solar energy and 51 USD/MWh (5.1 US₵/kWh, and ₹ 3.76/kWh) for the wind energy. A lower value of LCOE indicates that the solar and wind energy resources are a competitor to conventional power plants and attract investors/stakeholders for investment. It also indicates the easy availability of affordable electricity to non-electrified areas and helps in combating environmental degradation.

From an environmental point of view, the study further estimates the reduction in life-cycle emissions of greenhouse gas. Solar energy has an enormous potential of reducing around 3429.9 million tons of greenhouse gas emissions per year from thermal power plants. It also has an extensive potential to reduce 2483.6 million tons of greenhouse gas emissions per year from gas power plants. Similarly, wind energy also has a huge potential to reduce 314.23 and 231.53 million tons of greenhouse gas emissions per year from thermal and gas power plants respectively. Fig. 6.3 shows the various calculated potentials following the top-down approaches.

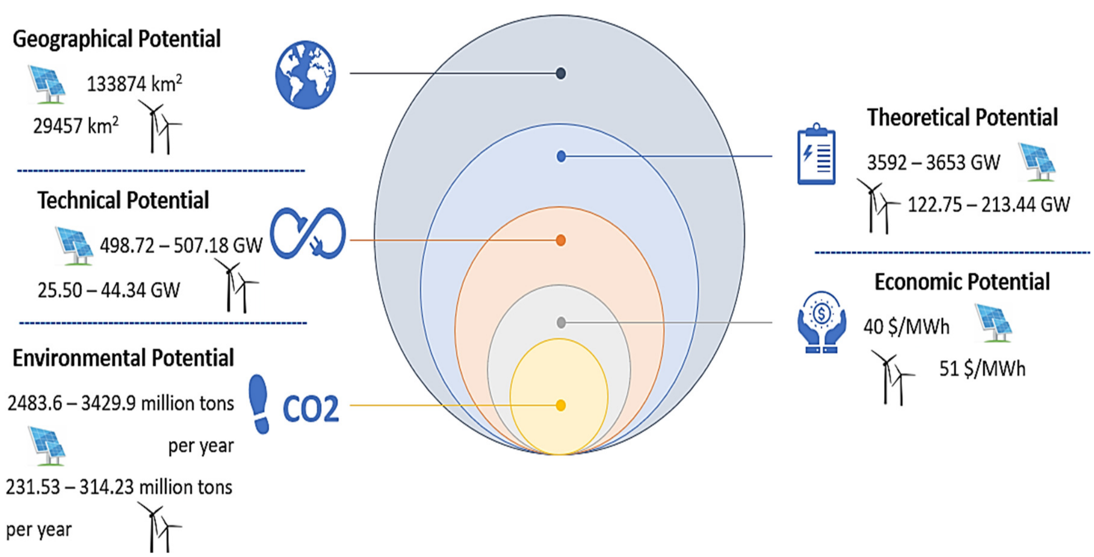


Fig. 6.3: Estimated calculation of available SWPP in India

After assessing the various possibilities at the country level, the research work assesses the solar and wind energy potentials at the states level. Among all the states, Rajasthan is the leading state with respective potentials of 693.13 TWh and 83.40 TWh for solar and wind energy. Uttar Pradesh is the second-highest state in solar power with a potential of 674.05 TWh but the state is lagging in wind power potential with a capacity of only 9.80 TWh. The third position is held by the Gujarat state with a potential of 456.36 TWh in solar power potential. Besides solar energy, Gujarat is also the leading state in wind power potential (70.70 TWh). In addition, Andhra Pradesh (solar 223.13 TWh, and wind 76.78 TWh), Karnataka (429.57 TWh & 71.32 TWh), Maharashtra (377.09 TWh & 14.42 TWh), Madhya Pradesh (180.15 TWh & 26 TWh), Tamil Nadu (397.54 TWh & 28.65 TWh), and Telangana (132.94 TWh & 7.48 TWh) are the other states in India blessed with considerable solar and wind power potentials. The SWPP for the different states of India is represented in Fig. 6.4.

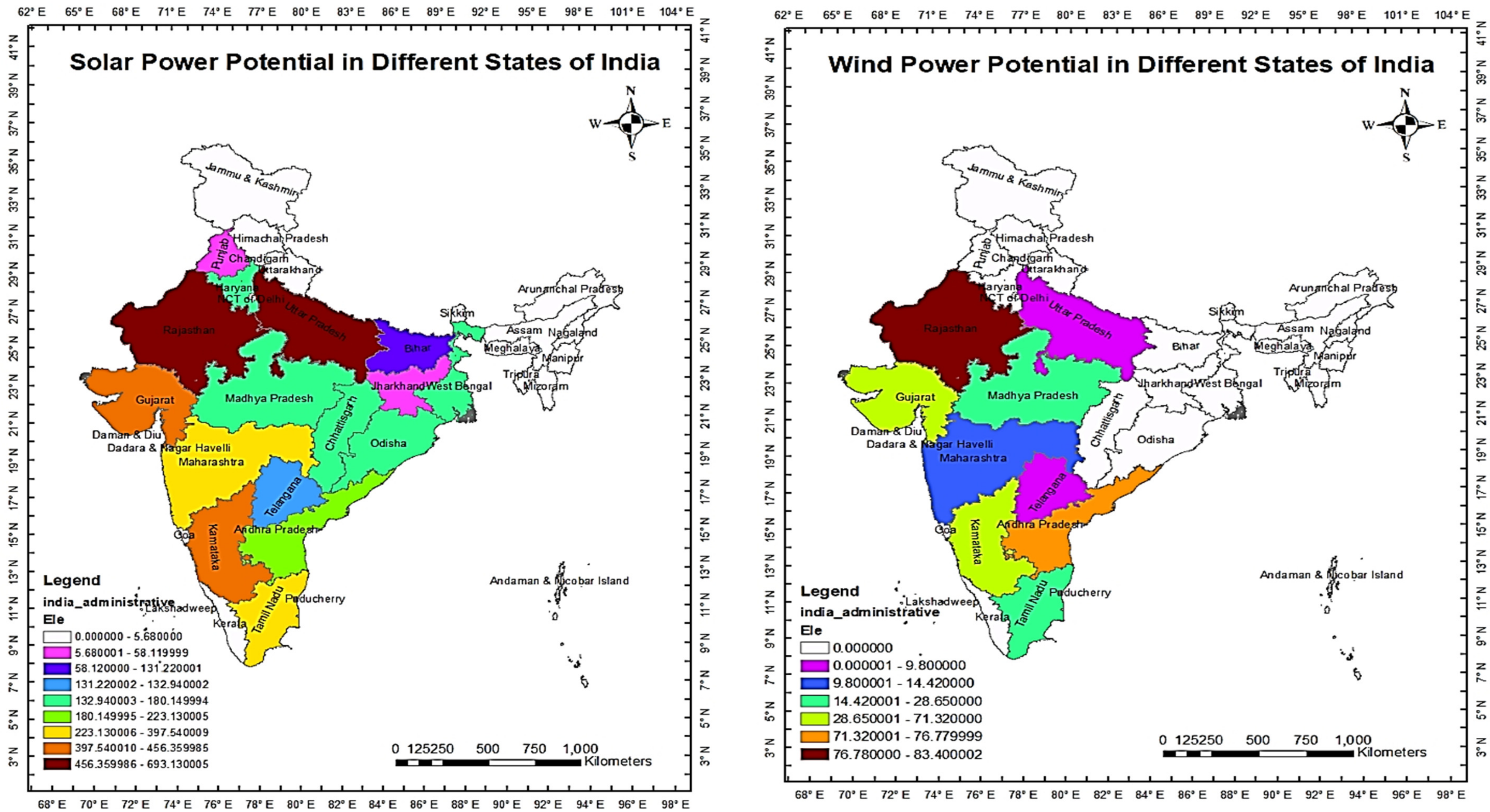


Fig. 6.4: Solar and wind technical power potentials (TWh) in different states of India

6.3.2 Demand-Potential Scenario

Here, the demand-potential scenario of the country is assessed as it is well known that the electricity demand of India is continuously increasing due to rapid industrialization, urbanization, and population growth. Further, It is expected that the electricity demand will reach up to 2143 TWh by the year 2030, as calculated in the previous chapter – 4. This poses a great challenge for the government of India to meet the ever-increasing electricity demand from conventional resources. Therefore, the present study enlightens the path of government agencies, and decision/policymakers by assessing the solar and wind power potentials. Table 6.5 below summarizes the total electricity consumption (TWh), technical solar power potential (TWh), and technical wind power potential (TWh) available in India. The study finds that India has an abundant solar power potential of 4443.88 TWh which is three times more than India's total electricity demand during 2020-21. Wind energy also has enough potential to meet about 30% of the existing electricity demand. In terms of the state-wise demand-potential scenario, the solar power potential in the state of Rajasthan is more than 10 times the current demand while the wind energy potential also exceeds the current power consumption. In addition, sixteen states in India have more potential than the current demand. Finally, it is concluded that India has huge solar and wind power potential. However, there is only a need for proper exploitation of the existing resources and infrastructure.

Table 6.5: Total electricity consumption and available solar and wind technical power potential in India [381]

States	Total electricity consumption (TWh), 2020-21	Technical solar power potential (TWh)	Technical wind power potential (TWh)
Northern region			
Delhi	5.829	4.98	---
Haryana	23.898	161.69	---
Himachal Pradesh	36.786	---	---
Jammu and Kashmir	16.935	---	---
Punjab	33.351	47.90	---
Rajasthan	64.416	693.13	83.40
Uttar Pradesh	135.402	674.05	9.80
Uttarakhand	14.527	5.68	---
Ladakh	0.270	---	---
Western region			

States	Total electricity consumption (TWh), 2020-21	Technical solar power potential (TWh)	Technical wind power potential (TWh)
Chhattisgarh	119.535	155.38	---
Goa	0	---	---
Gujarat	110.260	456.36	70.70
Madhya Pradesh	123.662	180.15	26
Maharashtra	141.567	377.09	14.42
Southern region			
Andhra Pradesh	69.174	223.13	76.78
Karnataka	52.138	429.57	71.32
Kerala	5.910	---	---
Puducherry	0.225	---	---
Tamil Nadu	91.358	397.54	28.65
Telangana	50.301	132.94	7.48
Eastern region			
Andaman & Nicobar	0.150	---	---
Bihar	37.260	131.22	---
Jharkhand	28.715	58.12	---
Odisha	52.872	155.58	---
Sikkim	10.156	---	---
West Bengal	78.476	159.37	---
North Eastern region			
Arunachal Pradesh	3.865	---	---
Assam	7.221	---	---
Manipur	0.600	---	---
Meghalaya	0.920	---	---
Mizoram	0.210	---	---
Nagaland	0.218	---	---
Tripura	6.563	---	---
Total	**1322.77**	**4443.88**	**388.55**

6.4 DISCUSSION

The objectives of the current research study are to evaluate the suitable sites for utility-scale solar and wind farms and to assess the different potentials for solar and wind power at geographically suitable sites. As a result, the study evaluated 133874 km^2 and 29457 km^2 areas as the geographical potential areas (Rank 1) for the installation of solar and wind power projects. Subsequently, different potentials such as geographical, theoretical, technical, economic, and environmental have been calculated on these highly suitable land areas. Further, to compare and validate the research results, the current section comprises sensitivity analysis, comparison with existing studies, the implications of the research outcome, research limitations, and future scope which are briefly discussed in the following sections.

6.4.1 Sensitivity Analysis

A sensitivity analysis is performed to examine the importance of the considered technical and non-technical factors and their impacts on energy production and associated costs. To perform a robust analysis, the present study incorporates the analysis with multiple factors which are as follows: investment cost, capacity factor, soiling effect, temperature, discount rate, area factor, installation pattern, etc. A detailed impact of these parameters is discussed in the following sections.

For solar energy, the study carried out a sensitivity analysis for the investment cost because it is very important for the project development and installation. In addition, it covers a large share of the overall investment of the project. A recently published report [376] discussed the sharp decrease in installation cost of solar projects (18% less than that in 2018). In this scenario, India leads the world with the lowest installation cost of 618 USD/kW. Therefore, the present study performs the sensitivity analysis from 500 to 700 USD/kW with a constant step size of 50 USD/kW. Sensitivity analysis results indicate a continuous decrease in LCOE with a decrease in investment cost. The LCOE are 0.044 USD/kWh (₹ 3.22/kWh), 0.041 USD/kWh (₹ 3.03/kWh), 0.039 USD/kWh (₹ 2.84/kWh), 0.036 USD/kWh (₹ 2.65/kWh), and 0.034 USD/kWh (₹ 2.46/kWh) at the investment costs of 700 USD/kW, 650 USD/kW, 600 USD/kW, 550 USD/kW, and 500 USD/kW respectively.

Further, the sensitivity analysis is carried out for the discount rate from 3 to 10% with an interval of 1%. The least LCOE of 0.0399 USD/kWh (₹ 2.91/kWh) was obtained at the discount rate of 3%. The LCOE increases with an increase of approximately 7% for each discount rate and reaches up to 0.065 USD/kWh (₹ 4.78/kWh) for a 10% discount rate. Subsequently, the sensitivity analysis is performed for one more important factor, i.e., capacity factor. The study calculated the LCOE and electricity generation at four values of capacity factor (13%, 19%, 25%, and 30%). The electricity generation linearly (R^2 = 0.9992) increases with the capacity factor while LCOE decreases exponentially (R^2 = 0.9891) with the increase in capacity factor. A similar trend in LCOE and electricity generation has been observed for the area factor (from 60 to 70%). Finally, sensitivity analysis is performed for the temperature (from 0 to 10%) and soiling effect (from 0 to 2%), and it is observed that these highly influence the electricity output and LCOE. Their impacts may be minimized by adopting recent technologies, proper cooling, and cleaning.

In the end, sensitivity analysis is performed for wind energy, along with the aspects of capacity factor, and installation pattern. With an increase in capacity factor, the electricity generation also increases proportionally whereas the LCOE decreases exponentially. The sensitivity analysis is then carried out for the three installation patterns of 3D × 5D, 5D × 7D, and 7D × 10D. The electricity output obtained for these is 903.37 TWh, 388.42 TWh, and 193.54 TWh respectively.

6.4.2 Comparison and Validation of Findings

The present study aims to estimate the exploitable solar and wind power potentials at the relevant sites in India. To fulfill this aim, the primary objective is to evaluate the geographically potential sites in India for utility-scale solar and wind power projects. Through an in-depth and rigorous literature review, the authors could not find studies similar to the primary objective. However, the authors found very few studies in which the investigators calculate the solar and wind power potentials. The brief details about these studies including the assumptions about land suitability, the estimated SWPP, etc. are discussed in the following sections.

For solar power, a study estimated the solar power potential on the country's barren land, with a minimum GHI of 4 kWh/m^2/day and a maximum terrain slope of 2.1%. They calculated the vast potential of 6000 GW and 2500 GW for the solar photovoltaic and concentrated solar power respectively [334]. Another study estimated a large-scale solar PV power potential in the range of 1300 to 5200 GW by employing the land-use factor of 7.5 MW/km^2 and 30 MW/km^2 [382]. Following the assumptions of the preceding studies, the outcome of the current research study is comparable.

For wind power, comparatively more case studies are available in the literature. A research study estimated the wind power potential by incorporating wind velocities of magnitude more than 5.5 m/s and land cover factors of 2.25 MW/km^2 and 9 MW/km^2. By involving these parameters, the study calculated a total wind power potential in India between 800 GW and 3400 GW [382]. Mentis et al. [383] extrapolated the wind velocity at 10 m height in Rajasthan and Gujarat to that at the wind turbine's hub height and estimated a total wind power potential of 486.6 GW. In another study, the authors calculated the wind power potential over a footprint area of 2094036.27 km^2 in India (excluding urban and Himalayan regions). The study estimated a total wind power potential of 4250.64 GW for a plant load factor between 15 and 45% [384]. Afterward, a technical report assessed the wind power potential for two sensitivity scenarios of (i) no farmland included, and (ii) with all farmlands. They estimated the respective potentials of 253 GW and 306 GW with a minimum capacity factor of 25% at a hub height of 80 m [213]. Finally, a study from the National Institute of Wind Energy (NIWE) classified the available land area into three categories of rank 1, rank 2, and rank 3 for which the available wind power potential (at 100 m hub height) was calculated as 153 GW, 146 GW, and 3 GW respectively [320]. Finally, we conclude that the outcome of the present research study is in-line with the previously published studies. However, the present study systemically analyses the geographical, theoretical, technical, economic, and environmental potentials. In addition, the study also discussed the demand-potential scenarios in different states of India.

6.5 SUMMARY

The goal of this research is to calculate the different solar and wind power potentials on previously determined highly suitable sites. Firstly, to gain a better understanding of the notion of distinct level potentials, inter-relationships, and mathematical expressions, the study first conducted a comprehensive literature survey. The study selected geographical, theoretical, technical, economic, and environmental potentials, which are connected to each other in a top-down approach. Firstly, the geographical potential is estimated in terms of highly suitable land area by incorporating resource availability, geographical feasibility, and economic viability. Here, the geographical potential is 133874 km^2 and 29457 km^2 for solar and wind power, respectively. Further, theoretical power potential is the maximum amount of power potential available in these highly suitable areas. The study estimates the maximum theoretical power potential of 3653 GW and 213 GW for solar and wind power respectively. Furthermore, taking into account certain technical restrictions, efficiency, and losses, the theoretical potential is narrowed-down in technical potential. In the form of technical potential, the study calculated the maximum solar and wind power potential of 507 GW and 44 GW, respectively. Then there's the matter of determining the technical power potential's commercial viability as well as its environmental sustainability. According to the analysis, solar and wind power potential may be obtained at the least LCOEs of 40 \$/MWh and 51 \$/MWh, respectively. From an environmental standpoint, the technical potential of solar and wind power has the ability to save maximum life cycle GHG emissions of 3429 and 314 million tons per year, respectively.

Finally, the study also assessed the demand potential scenario for the country as well as for states. It is concluded that solar energy has three times more potential than the current energy demand of the country. while, in terms of states, 16 states are power-rich states, which means they are having potential higher than their current demand. The study's findings will aid in accomplishing and meeting objectives of GOI, such as 450 GW of installed renewable energy capacity by 2030, 24 × 7 power for all, and the Deendayal Upadhyaya Gram Jyoti Yojana for rural and distant electrification. It will also contribute to the country's GDP growth through expanding economic trade, property revenue, capital investment, and other factors. It will also aid in the better management of power between power-rich and power-scarce states.

CHAPTER – 7

ASSESSMENT OF TECHNO-ECONOMIC FEASIBILITY OF THE POWER PROJECTS: A CASE STUDY

The objective of the chapter is to assess and prioritize the physical characteristics of highly suitable sites. In addition, to validate the techno-economic feasibility of the project at the conspicuous site.

7.1 INTRODUCTION

In previous chapters, the study developed a site suitability map of India, which was split into five categories: highly suitable, suitable, moderately suitable, less suitable, and not suitable. Further, at these highly suitable sites, analytical theoretical, technological, economic, and environmental potentials were calculated using multi-constraints. As a result, the present study aimed to conduct a case study in order to analyze the project's techno-economic viability. Prior to that, examine and prioritize the physical characteristics of the highly suitable land locations. Furthermore, the conspicuous site among the highly suitable sites is selected to perform the case study and validate the economic feasibility, technical viability, and environmental sustainability. The detailed analysis is summarized in the following sections.

7.2 RESEARCH METHODOLOGY

The objectives of the research work will be achieved in eight consecutive phases which are as follows. In the first phase, the objectives of the research work will be discussed while in the second phase the necessary details and numerical values of the considered criteria will be compiled. In next step three, the geographical features of the alternatives such as latitude, longitude, district, state, and region will be discussed in detail. In addition, a brief description of the research approaches to be used will be summarized in section 4. Section 5 will compile the calculation of the weights of the criteria while section 6 will rank the alternatives using the weights of the criteria. In the subsequent section 7, the results will be displayed chronologically in the order of priority. Finally, a feasibility analysis on specific potential site alternatives for solar and wind power will be carried out in Section 8. The discussed research methodology is graphically represented in Fig. 7.1.

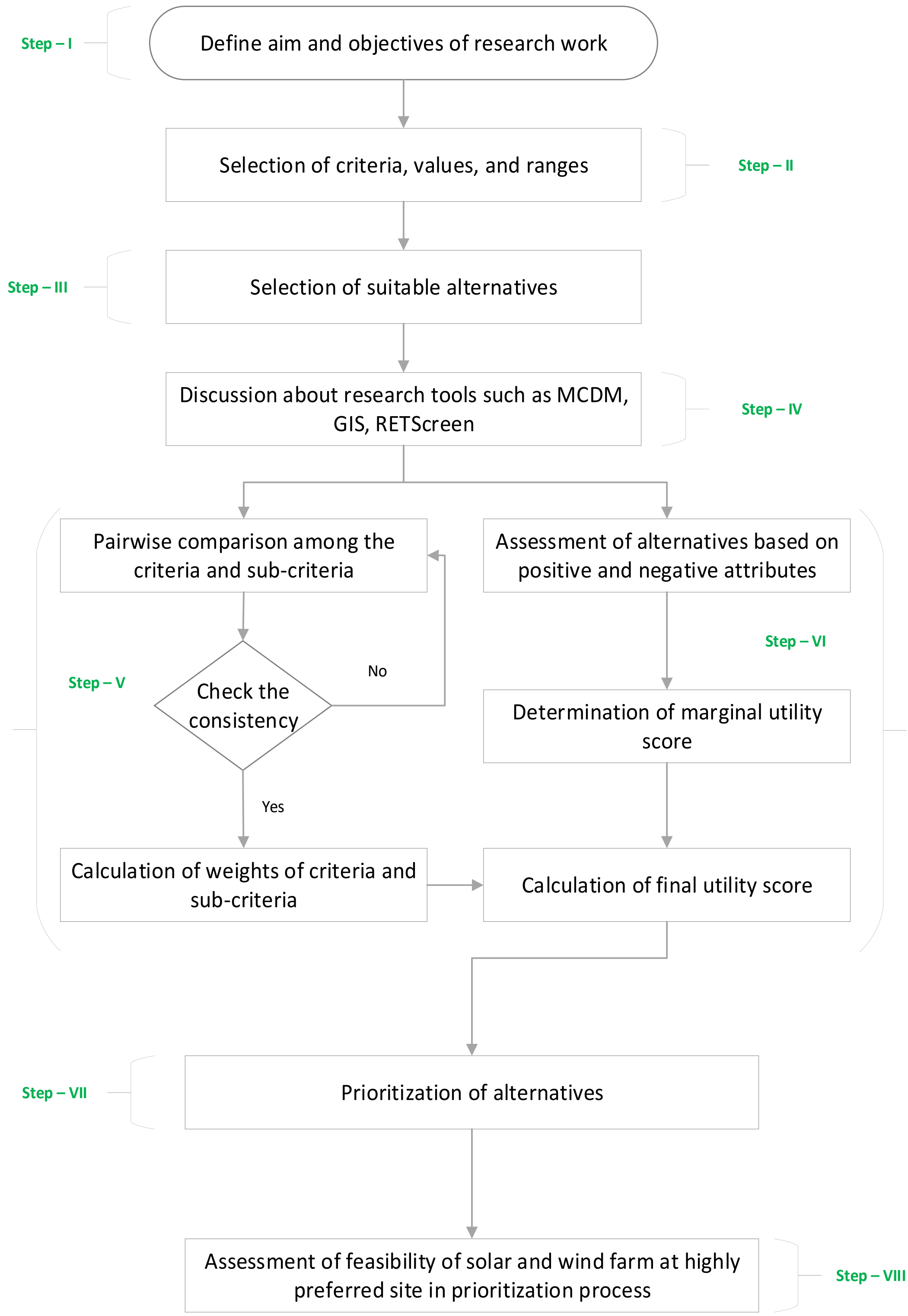


Fig. 7.1: Proposed research methodology

7.2.1 Selection of Criteria

To evaluate the solar and wind power potential site alternatives, the study incorporates the thirteen sub-factors under the categories of technical, socio-environment, and economic. These sub-factors participate in the evaluation process in two ways: (i) to estimate the weight of the sub-criteria using the fuzzy AHP approach and (ii) to identify and analyze the numerical weights of the respective alternatives. In a first way, a committee of experts provides linguistic judgments about the importance of the sub-factors which will be further converted into crisp numeric values. These steps are briefly discussed in the subsequent sections. Whereas, in a second way, numeric values of these sub-criteria are obtained from ArcGIS tools to evaluate the alternatives. Therefore, the shapefiles were critically analyzed in an ArcGIS tool to assess the available information and data. For this purpose, the study exclusively used tools from the Arc toolbox tool such as data management tools, conversion tools, and spatial analyst tools. Furthermore, this available information is used to graphically represent the variable scale of sub-criteria with potential alternatives. These graphical figures will be helpful in the visualization of the geographical presence of these sites and also in estimating the numerical values of the associated factors.

Through an in-depth and extensive analysis of GIS shapefiles, obtained the numeric performance values of indicators for their respective alternatives. The numeric values are considered in their respective measuring units such as solar radiation in $kWh/m^2/day$, slope and orientation in degree, distance indicators in meter or kilometer. Apart from this, the land use data is in linguistic terminology which will be further converted into numerical values. These numeric and linguistic performance data of indicators for the solar and wind alternatives are summarized in Table 7.1 and Table 7.2.

Table 7.1: Qualitative and Quantitative characteristics of solar potential alternatives

Alter natives	Solar radiation (kWh/m^2/day)	Slope (degree)	Orientation (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
S1	5.117	0.1362	349	203	872	132	34	32	Dryland cropland and pasture	14032	2334	5185	2581
S2	5.483	0.0504	225	159	631	146	62	177	Barren or sparsely vegetated	54411	792	3390	4891
S3	5.421	0.0629	8	205	715	170	123	112	Barren or sparsely vegetated	53984	3080	17	56001
S4	5.452	0.1015	255	192	685	149	91	107	Barren or sparsely vegetated	63268	2601	2044	72812
S5	5.529	0.2085	340	158	593	131	54	178	Shrubland	52773	2630	2951	62530
S6	5.638	0.1754	293	34	513	797	86	177	Shrubland	42682	6666	1898	72187
S7	5.686	0.1469	284	270	434	124	68	64	Shrubland	30814	2265	18535	11952
S8	5.69	0.2899	137	255	443	102	40	29	Dryland cropland and pasture	3883	5048	3261	7102
S9	5.684	0.0629	278	164	387	160	36	42	Shrubland	23101	7356	18535	35699
S10	5.687	0.3250	189	170	385	158	30	31	Dryland cropland and pasture	13203	4856	4464	32677
S11	5.609	0.6539	299	446	397	102	106	104	Cropland grassland mosaic	1489	1216	5121	8091
S12	5.589	0.1578	286	11	110	83	103	16	Shrubland	51401	6975	2665	26244
S13	5.654	0.4143	205	33	13	52	46	85	Dryland cropland and pasture	34193	5987	6923	9765

Alter natives	Solar radiation (kWh/m^2/ day)	Slope (degree)	Orientation (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
S14	5.556	0.5346	50	135	131	79	76	90	Cropland grassland mosaic	58031	8095	4121	46756
S15	5.620	0.1038	59	175	57	47	48	52	Cropland grassland mosaic	37822	2923	2579	6457
S16	5.619	0.050	135	139	88	70	81	61	Cropland grassland mosaic	41193	2247	2665	77552
S17	5.421	1.268	167	432	278	102	103	25	Cropland grassland mosaic	38702	3577	2745	8920
S18	5.524	0.486	185	267	382	47	58	44	Dryland cropland and pasture	27787	9511	8924	8653
S19	5.456	0.7232	260	317	337	118	36	46	Dryland cropland and pasture	54426	5436	6577	32865
S20	5.642	1.7260	119	707	108	130	65	15	Cropland grassland mosaic	6605	5200	720	25138
S21	5.632	0.8955	289	659	147	129	62	36	Irrigated cropland and pasture	13306	10649	5388	25520
S22	5.707	0.6421	19	546	229	124	116	108	Dryland cropland and pasture	19417	3498	930	6006
S23	5.690	0.2312	74	637	134	121	39	84	Dryland cropland and pasture	24823	137	5935	28774
S24	5.735	0.8244	100	723	168	54	60	98	Dryland cropland and pasture	52437	1232	5600	14961
S25	5.785	0.0890	270	552	154	71	123	15	Irrigated cropland	7370	2984	698	7507

Alter natives	Solar radiation (kWh/m²/ day)	Slope (degree)	Orientation (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
									and pasture				
S26	5.883	0.2096	192	85	745	100	25	59	Irrigated cropland and pasture	20134	4212	479	31211
S27	5.886	0.214	253	97	70	102	34	51	Dryland cropland and pasture	20300	4809	114	9684
S28	5.818	0.0377	135	28	64	184	31	68	Cropland woodland mosaic	18086	1625	6723	21053
S29	5.733	0.3529	100	189	152	102	56	131	Irrigated cropland and pasture	25310	4018	7160	31855
S30	5.910	0.8048	155	279	200	54	37	68	Cropland grassland mosaic	22284	2149	468	27689
S31	5.845	2.4656	109	265	246	172	86	45	Shrubland	26957	7124	2631	24311
S32	5.784	0.3218	194	394	316	95	60	64	Dryland cropland and pasture	24880	484	8104	27506
S33	5.619	0.4102	152	424	379	79	115	199	Dryland cropland and pasture	16019	2182	2044	22032
S34	5.420	0.1927	146	240	519	29	70	44	Cropland grassland mosaic	23428	1311	1483	22819
S35	5.385	0.2077	30	235	385	47	55	64	Cropland grassland mosaic	27527	1749	1739	8496
S36	5.190	0.3284	49	117	180	153	87	31	Dryland cropland and pasture	44332	3300	323	15181
S37	5.063	0.0454	348	93	741	52	110	171	Dryland cropland and pasture	5851	1895	2897	12805

Alter natives	Solar radiation (kWh/m^2/ day)	Slope (degree)	Orientation (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
S38	5.103	0.0282	108	120	901	59	91	58	Dryland cropland and pasture	34992	683	251	55927
S39	5.184	0.0252	135	171	832	213	24	62	Dryland cropland and pasture	7766	7406	1958	19005
S40	5.084	0.0454	168	196	863	149	88	149	Dryland cropland and pasture	22712	3272	1089	28044
S41	5.068	0.1069	180	204	884	106	36	106	Irrigated cropland and pasture	1359	2968	1464	12507
S42	5.083	0.0178	0	223	902	70	67	70	Dryland cropland and pasture	18886	5611	2480	23779
S43	5.063	0.0378	225	223	945	118	86	118	Dryland cropland and pasture	46213	2276	892	54719
S44	5.089	0.0378	315	62	584	29	72	29	Dryland cropland and pasture	30723	2371	8854	11055
S45	5.243	1.041	10	129	752	157	48	157	Dryland cropland and pasture	14919	8773	1255	11773

Table 7.2: Qualitative and Quantitative characteristics of wind potential alternatives

Alter natives	Wind velocity (m/s)	Slope (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
W1	4.914	0.1315	132	639	142	64	182	Barren or sparsely vegetated	27117	1202	75	6483
W2	5.624	0.1015	239	513	73	97	106	Shrubland	36165	6478	173	66910
W3	5.032	0.2877	280	521	10	101	79	Shrubland	28056	6460	662	68310
W4	5.148	0.7669	296	478	41	86	77	Shrubland	29806	3225	22535	27032
W5	5.293	0.6651	284	431	35	61	60	Shrubland	16441	8301	18909	19217
W6	5.274	0.8076	458	487	22	123	90	Dryland cropland and pasture	750	859	1640	5366
W7	4.424	0.5749	441	462	2	103	99	Dryland cropland and pasture	6360	1250	3799	14202
W8	5.103	0.255	311	408	26	99	78	Dryland cropland and pasture	11097	6131	9900	41535
W9	6.116	0.8287	131	51	47	64	29	Dryland cropland and pasture	36320	2215	729	93001
W10	5.824	1.011	175	51	42	40	52	Dryland cropland and pasture	19192	4426	7471	58566
W11	6.230	0.4796	33	10	26	45	46	Dryland cropland and pasture	25723	6243	3919	27068
W12	6.311	0	08	71	40	14	0	Barren or sparsely vegetated	36976	3710	3836	58566

Alter natives	Wind velocity (m/s)	Slope (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
W13	5.360	0.6467	275	148	8	83	78	Dryland cropland and pasture	13567	746	5750	27068
W14	5.036	0.1889	485	281	61	76	107	Dryland cropland and pasture	12763	11518	6747	15350
W15	6.147	0.709	251	71	23	103	33	Dryland cropland and pasture	16277	8211	1718	17335
W16	5.353	0.971	396	232	29	14	67	Dryland cropland and pasture	7519	6800	19153	17629
W17	5.184	0.7583	631	287	44	91	11	Savanna	25771	3677	4345	22490
W18	5.427	0.6916	573	343	44	35	77	Dryland cropland and pasture	15865	2855	1932	2983
W19	4.578	0.5667	291	344	35	24	59	Dryland cropland and pasture	14617	1683	7320	21344
W20	4.576	0.9532	370	336	58	38	30	Dryland cropland and pasture	20322	5346	3431	16149
W21	7.418	3.651	673	66	109	62	38	Cropland grassland mosaic	45089	5820	4990	59600
W22	6.372	1.8176	380	38	63	73	68	Cropland grassland mosaic	20123	454	8703	31452
W23	6.417	1.2355	719	85	39	29	36	Cropland grassland mosaic	14937	3939	11417	26654
W24	6.451	1.4078	781	59	10	54	11	Cropland grassland mosaic	23200	5775	1373	31723
W25	5.761	3.811	713	156	108	86	50	Shrubland	37387	871	6382	26400

Alter natives	Wind velocity (m/s)	Slope (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
W26	5.292	0.6031	558	227	73	109	91	Dryland cropland and pasture	4206	965	930	11237
W27	5.760	0.4551	621	171	30	70	68	Shrubland	8050	2359	1114	14125
W28	6.206	0.7124	752	187	52	120	64	Irrigated cropland and pasture	14394	3284	4631	20123
W29	6.873	0.1689	317	150	62	22	72	Irrigated cropland and pasture	3476	3321	1314	12785
W30	7.764	0.1076	312	144	57	34	36	Irrigated cropland and pasture	25292	2610	4575	10519
W31	7.583	0.3922	387	138	53	53	19	Irrigated cropland and pasture	640	852	4406	3087
W32	6.149	0.2648	227	165	75	95	74	Irrigated cropland and pasture	5068	2251	4216	38011
W33	6.918	0.2593	71	47	41	37	48	Irrigated cropland and pasture	9706	1175	1911	5577
W34	7.938	0.3046	14	4.5	3	63	27	Dryland cropland and pasture	14849	3403	8881	6464
W35	5.280	0.0917	14	7.6	17	91	86	Dryland cropland and pasture	7100	3388	3911	18897
W36	5.716	0.1259	228	115	39	50	116	Irrigated cropland and pasture	6849	2759	6838	31630
W37	5.086	0.3088	144	90	22	74	39	Irrigated cropland and pasture	15516	6826	2393	18609
W38	5.37	0.3983	364	285	72	65	82	Shrubland	4211	971	1346	10687

Alter natives	Wind velocity (m/s)	Slope (degree)	Elevation (m)	Distance from Coastlines (km)	Distance from Waterbodies (km)	Distance from Airports (km)	Distance to Wildlife Designations (km)	Land use	Distance to Urban Areas (m)	Distance to Road Network (m)	Distance to Transmission lines (m)	Distance from Power plants (m)
W39	5.165	1.4274	237	218	145	59	91	Irrigated cropland and pasture	7548	2260	5636	39731
W40	5.347	0.5624	129	121	36	32	111	Irrigated cropland and pasture	8885	716	9544	30086
W41	5.133	1.2926	259	129	63	72	83	Dryland cropland and pasture	18856	3269	2393	68038
W42	5.501	0.3151	420	303	39	60	53	Dryland cropland and pasture	3135	214	2764	19358
W43	6.169	1.292	481	253	11	35	119	Dryland cropland and pasture	6681	3733	3527	9601
W44	5.344	0.3672	476	260	37	69	136	Dryland cropland and pasture	17066	7112	2400	35064
W45	5.073	0.3797	414	297	28	72	121	Dryland cropland and pasture	6459	1049	1541	52614
W46	5.08	0.3483	425	350	38	109	109	Shrubland	6332	216	2486	9141
W47	4.471	0.3955	421	360	66	122	120	Dryland cropland and pasture	580	1916	2709	5025
W48	5.382	0.3438	443	327	72	79	63	Dryland cropland and pasture	3639	3196	4384	39193
W49	4.424	0.2593	453	665	3	98	101	Dryland cropland and pasture	4297	565	3574	8311
W50	5.364	0.4822	165	52	38	51	59	Shrubland	10813	7556	3264	16036

7.2.2 Selection of Alternatives

The assessed total area of 133874 km^2 and 29457 km^2 is highly suitable for the installation of solar and wind power projects in India. The identified area is distributed over several smaller areas throughout the country. Therefore, especially for solar energy, the study considered areas over 500 km^2 as solar site alternatives. Whereas, for wind energy, the study considered almost all the available potential site alternatives in the entire country. Finally, the study marked 45 and 50 sites as an alternative for solar and wind farm installations. Brief details about the sites such as talukas, districts, states, areas, latitude, and longitude are provided in Tables 7.3 and 7.4.

Table 7.3: The geographical and physical positioning of solar potential alternatives

Alternative ID	Taluk	District	State	Latitude	Longitude	Area (Square km)
S1	Talwandi Sabo	Bathinda	Punjab	30.034476	74.985605	512
S2	Bikaner	Bikaner	Rajasthan	28.521031	72.843501	1377
S3	Lunkaransar	Bikaner	Rajasthan	28.841226	74.106256	673
S4	Lunkaransar	Bikaner	Rajasthan	28.658609	73.843224	539
S5	Bikaner	Bikaner	Rajasthan	28.184496	72.672095	513
S6	Phalodi	Jodhpur	Rajasthan	27.429317	72.717113	1040
S7	Shergarh	Jodhpur	Rajasthan	26.691937	72.581205	846
S8	Osiyan	Jodhpur	Rajasthan	26.593420	72.943410	681
S9	Jodhpur	Jodhpur	Rajasthan	26.130237	72.716840	518
S10	Jodhpur	Jodhpur	Rajasthan	25.995536	72.953353	678
S11	Bhilwara	Bhilwara	Rajasthan	25.356608	74.553655	2770
S12	Dasada	Surendranagar	Gujarat	23.470945	71.726936	710
S13	Mundra	Kachchh	Gujarat	22.884041	69.631444	2059
S14	Bayad	Sabar Kantha	Gujarat	23.329127	73.296493	1570
S15	Jam Jodhpur	Jamnagar	Gujarat	22.087135	70.219557	1756
S16	Amreli	Amreli	Gujarat	21.706918	71.201085	1743
S17	Sendhwa	Barwani	Madhya Pradesh	21.409285	75.481154	513
S18	Jalgaon	Buldana	Maharashtra	21.007496	76.605025	891
S19	Jhirnia	West Nimar	Madhya Pradesh	21.815130	76.016917	523
S20	Vite	Sangli	Maharashtra	17.251206	74.317323	840
S21	Tasgaon	Sangli	Maharashtra	17.057949	74.698122	1182

Alternative ID	Taluk	District	State	Latitude	Longitude	Area (Square km)
S22	Bagalkot	Bagalkot	Karnataka	16.184386	75.755963	1183
S23	Saundatti	Belgaum	Karnataka	15.710175	75.107220	693
S24	Gadag	Gadag	Karnataka	15.283264	75.637618	2898
S25	Harihar	Davanagere	Karnataka	14.550595	75.855505	1008
S26	Tiruchuli	Virudhunagar	Tamil Nadu	9.663464	78.243463	850
S27	Sivaganga	Sivaganga	Tamil Nadu	9.888356	78.397763	1044
S28	Papanasam	Thanjavur	Tamil Nadu	10.956077	79.265973	1721
S29	Turaiyur	Tiruchchirapp alli	Tamil Nadu	11.202860	78.456523	1375
S30	Sankari	Salem	Tamil Nadu	11.462041	77.959914	1171
S31	Tadpatri	Anantapur	Andhra Pradesh	14.923218	77.769359	1175
S32	Adoni	Kurnool	Andhra Pradesh	15.624526	77.173075	686
S33	Chitapur	Gulbarga	Karnataka	17.143103	76.893029	1352
S34	Pawni	Bhandara	Maharashtra	20.915902	79.690816	1212
S35	Champa	Janjgir-Champa	Chhattisgarh	22.060216	82.634442	1375
S36	Bankura	Bankura	West Bengal	23.201081	86.928783	1242
S37	Sultanpur	Sultanpur	Uttar Pradesh	26.359588	82.143007	1190
S38	Biswan	Sitapur	Uttar Pradesh	27.533590	81.190326	1017
S39	Etmadpur	Firozabad	Uttar Pradesh	27.298252	78.148831	1180
S40	Bulandshahr	Bulandshahr	Uttar Pradesh	28.170885	77.970874	1338
S41	Hapur	Ghaziabad	Uttar Pradesh	28.659389	77.560877	837
S42	Gohana	Sonepat	Haryana	29.119555	76.828531	858
S43	Kaithal	Kaithal	Haryana	29.628714	76.473640	1212
S44	Ghazipur	Ghazipur	Uttar Pradesh	25.598289	83.555913	677
S45	Morena	Morena	Madhya Pradesh	26.688279	78.017491	869

Table 7.4: Geographical and physical positioning of wind potential alternatives

Alternative ID	Taluk	District	State	Latitude (Decimal degree)	Longitude	Area (Square km)
W1	Bikaner	Bikaner	Rajasthan	28.471768	72.742573	2928
W2	Phalodi	Jodhpur	Rajasthan	27.296267	72.764916	316
W3	Nagaur	Nagaur	Rajasthan	27.148350	73.164549	280
W4	Phalodi	Jodhpur	Rajasthan	26.939849	72.663995	174
W5	Shergarh	Jodhpur	Rajasthan	26.581120	72.561623	182
W6	Beawar	Ajmer	Rajasthan	26.086985	74.258614	1036
W7	Mandal	Bhilwara	Rajasthan	25.366832	74.494129	742
W8	Kharchi	Pali	Rajasthan	25.565118	73.678970	153
W9	Nakhtarana	Kachchh	Gujarat	23.413589	69.071096	170
W10	Nakhtarana	Kachchh	Gujarat	23.295324	69.285790	161
W11	Mundra	Kachchh	Gujarat	22.887982	69.666440	1100
W12	Kachchh	Kachchh	Gujarat	23.442429	71.376559	201
W13	Modasa	Sabar Kantha	Gujarat	23.599420	73.213179	2796
W14	Khachrod	Ujjain	Madhya Pradesh	23.293864	75.394293	618
W15	Mangrol	Surat	Gujarat	21.453245	73.512921	202
W16	Pansemal	Barwani	Madhya Pradesh	21.733347	74.995183	262
W17	Bhagwanpur	West Nimar	Madhya Pradesh	21.420120	75.612515	520
W18	Dewas	Dewas	Madhya Pradesh	22.725712	76.141748	173
W19	Bhikangaon	West Nimar	Madhya Pradesh	21.909934	76.144413	195
W20	Jhirnia	West Nimar	Madhya Pradesh	21.663893	76.048147	187
W21	Surgana	Nashik	Maharashtra	20.474905	73.577117	152
W22	Dharampur	Valsad	Gujarat	20.341687	73.236059	100
W23	Dindori	Nashik	Maharashtra	20.180597	73.662185	50
W24	Rajgurunagar	Pune	Maharashtra	18.983214	73.627104	94
W25	Atpadi	Sangli	Maharashtra	17.262391	74.796039	559
W26	Bagalkot	Bagalkot	Karnataka	16.210526	75.599145	565
W27	Gadag	Gadag	Karnataka	15.355870	75.731825	1508
W28	Chitradurga	Chitradurga	Karnataka	14.289361	76.223127	1299
W29	Tiruppur	Coimbatore	Tamil Nadu	11.056264	77.241884	221
W30	Tiruppur	Coimbatore	Tamil Nadu	10.804212	77.252789	182

Alternative ID	Taluk	District	State	Latitude (Decimal degree)	Longitude	Area (Square km)
W31	Udumalaippettai	Coimbatore	Tamil Nadu	10.605685	77.266818	198
W32	Karur	Karur	Tamil Nadu	10.69996	77.845373	192
W33	Kovilpatti	Thoothukudi	Tamil Nadu	8.921324	77.758357	433
W34	Radhapuram	Tirunelveli Kattabo	Tamil Nadu	8.225440	77.752742	179
W35	Ramanathapuram	Ramanathapuram	Tamil Nadu	9.272721	78.702311	187
W36	Perambalur	Perambalur	Tamil Nadu	11.204756	78.796857	289
W37	Chengam	Tiruvannamalai	Tamil Nadu	12.055001	79.019503	103
W38	Anantapur	Anantapur	Andhra Pradesh	14.665322	77.502650	2899
W39	Pulivendla	Cuddapah	Andhra Pradesh	14.516874	78.184789	492
W40	Sidhout	Cuddapah	Andhra Pradesh	14.628883	79.040650	135
W41	Badvel	Cuddapah	Andhra Pradesh	15.149584	78.876436	251
W42	Alur	Kurnool	Andhra Pradesh	15.555555	77.263366	1963
W43	Hospet	Bellary	Karnataka	15.300270	76.588621	375
W44	Gangawati	Koppal	Karnataka	15.649225	76.478070	109
W45	Sindhnur	Raichur	Karnataka	15.770433	76.656725	122
W46	Manvi	Raichur	Karnataka	16.147309	76.950406	412
W47	Seram	Gulbarga	Karnataka	17.134770	77.283317	476
W48	Siddipet	Medak	Telangana	18.166485	78.906386	289
W49	Lalitpur	Lalitpur	Uttar Pradesh	24.611560	78.440479	744
W50	Kalavad	Jamnagar	Gujarat	22.10797	70.319500	535

The geographical locations of these sites are graphically represented in Fig. 7.2 and 7.3. In addition, the figures contain information about the alternatives id's and their corresponding states.

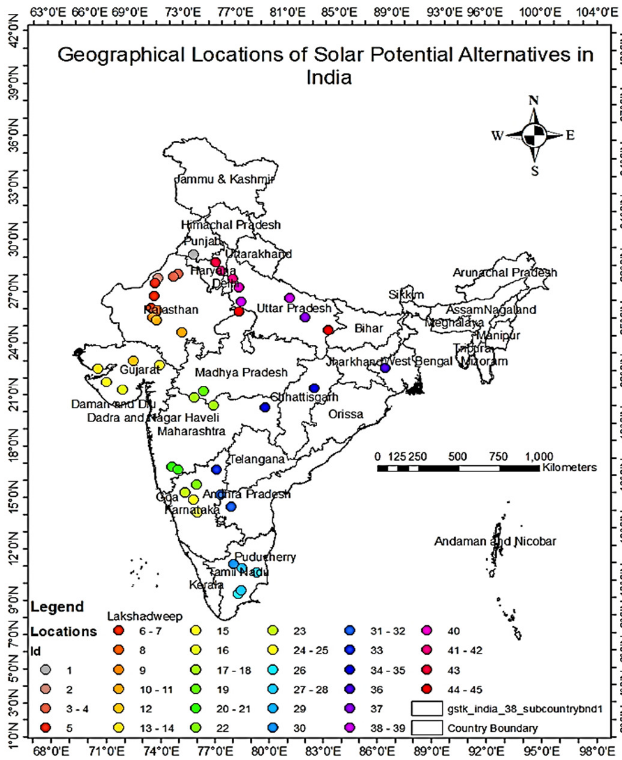


Fig. 7.2: The geographical positioning of solar suitable site alternatives in different states of India

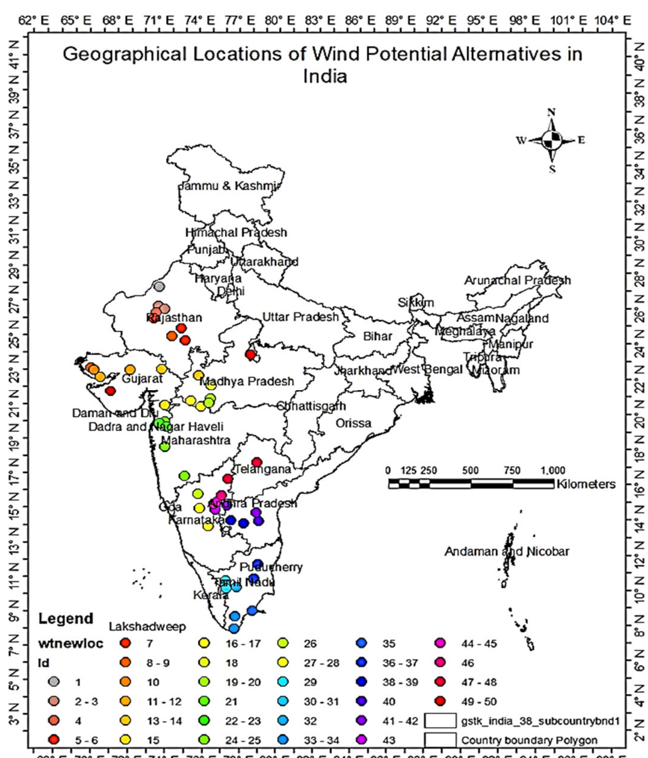


Fig. 7.3: The geographical positioning of wind suitable site alternatives in different states of India

7.2.3 Research Approaches

Primarily, three analytical and software research tools have been used in research work, which are the fuzzy AHP approach, GIS software, and RETScreen software. Whereas the fuzzy AHP and GIS approaches were covered briefly in the previous chapter, and the rest of the RETScreen approach will be discussed briefly in the following sections.

7.2.3.1 RETScreen overview

RETScreen International is a cutting-edge, one-of-a-kind renewable energy education, decision-making, and capacity-building tool. Natural Resource Canada is in charge of its development and upkeep. Except for the latest version of the software known as RETScreen Expert, all versions of the software are freely accessible for public usage with no cost implications [385,386]. The software allows users to assess the viability of new and retrofit power projects, as well as evaluate the performance of current projects and analyse clean or renewable energy initiatives. Each analysis procedure has to pursue a standard procedure consisting of the same seven steps: selection of facility and analysis type, location and weather conditions, energy modelling, cost analysis, emission analysis, financial analysis, and sensitivity and risk analysis [387]. These steps are briefly discussed in the following sections.

Firstly, the software provides the facility to choose the application type among the power generation, heating, and cooling applications and also to select the type of analysis for that particular selected application. In the second step, the geographical location of the facility is marked using the latitude and longitude, and it also facilitates receiving data from the nearest ground and NASA weather station. Further, in energy modelling, the essential resources such as technology adopted, specification of adopted technologies, losses incurred in the adopted technologies, electricity selling price, etc. are considered. Whereas in step IV, economic analysis requires initial cost, O & M cost, development cost, engineering cost, power system cost, and miscellaneous costs. Sequentially, the country and region of project, fuel type, GHG emission factor (tCO_2/MWh), and transmission and distribution losses are required to perform the emission analysis. As a result of emission analysis, the study calculates the total GHG emission in the base case or proposed case. In step VI successively, some essential financial parameters are required for financial analysis like inflation rate, discount rate, debt ratio, etc. As result, it will provide annual cash flow, equity payback period, etc. Finally, in step VII, sensitivity analysis is performed for a particular factor with a certain number of iterations and as results, impact and distribution graphs are provided. The discussed details of software tools are graphically shown in Fig. 7.4.

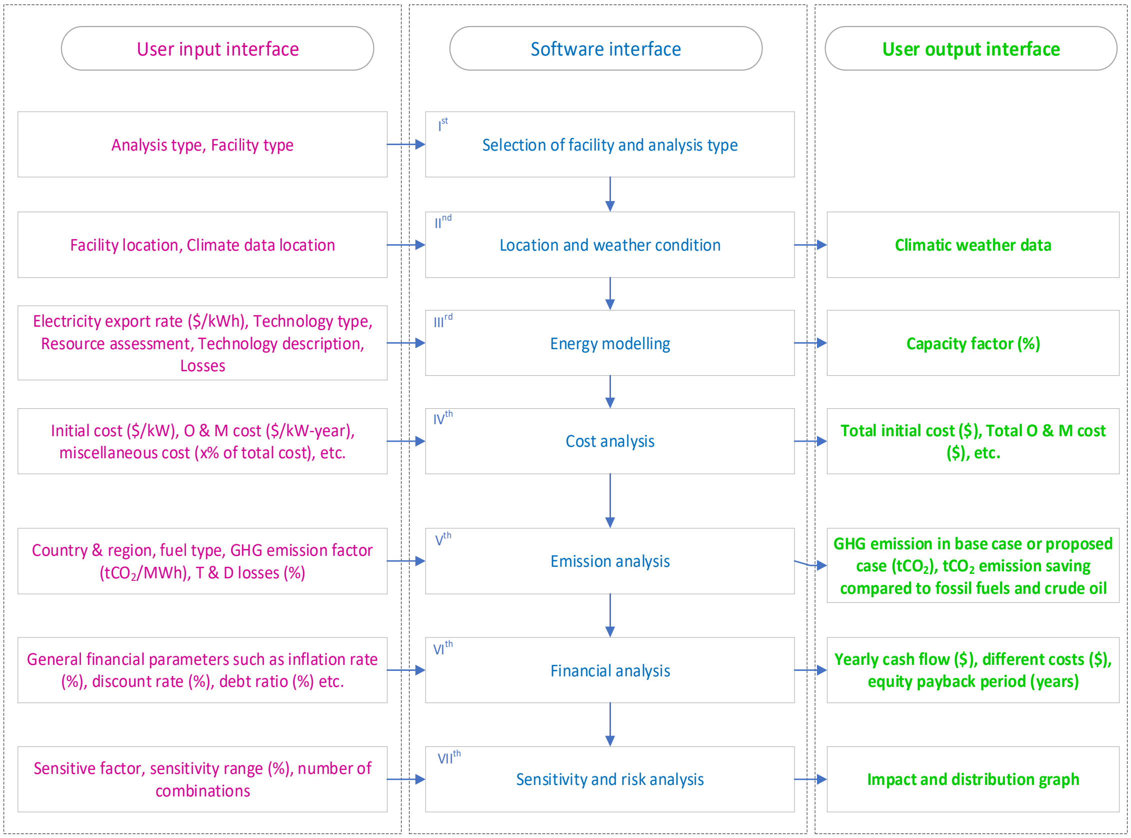


Fig. 7.4: RETScreen software model flowchart [386,388]

7.3 RESULTS

The results section is comprised of two sub-sections, namely "weights of decision criteria" and "Prioritization of potential alternatives." These sections discuss in detail the calculation of the weights of the decision criteria via the fuzzy AHP approach and the prioritization of potential alternatives through using the multi-attribute utility theory (MAUT) approach. These approaches are briefly discussed in the following sections.

7.3.1 Weights of Decision Criteria

In the earlier chapters, 13 decision factors for solar energy and 12 decision factors for wind energy are selected under the technical, economic, and socio-environment categories. Further, to assign weights to these criteria fuzzy AHP approach has been employed. The weights of these decision criteria, in brief, are given in Table 5.7.

7.3.2 Assessment of Potential Alternatives

At this stage, all the necessary data collected is used in the MAUT approach to developing the priority order of the alternatives. Firstly, the MAUT approach normalizes the cost and beneficial criteria. Subsequently, determine the marginal utility score for the solar and wind site alternatives. In the end, the final utility score is calculated involving the marginal utility score and weights of criteria. The alternatives are ranked based on the highest priority of the final utility score.

Next, in the overall ranking of solar alternatives, solar alternative 26 (S26) is selected as the first preference with the highest final utility score of 0.546. The alternative S26 is located in Tiruchuli taluka of Virudhunagar district of Tamil Nadu state. The geographical location (latitude and longitude) of the alternative is 9°39'48.5" N, and 78°14'36.5" E. In addition, the alternative location is close to 30 km from the 230/110 kV Savaspuram substation, which will reduce the power transmission and distribution losses as well as minimize the cost of new transmission lines. Furthermore, the alternative location would also benefit from being close to transmission lines, and road infrastructure. The second preference has been given to solar site alternative S2, which is situated in the Pugal taluka of Bikaner district of Rajasthan. It is geographically located at the latitude and longitude of 28°31'15.7" N, and 72°50'36.6" E. It covers a broader area of 1377 km^2 and is also blessed with closeness to roads, transmission infrastructure, and power plants. The subsequent order of preference is followed by solar site alternatives S27 (Sivaganga, Tamil Nadu), S30 (Sankari taluka of Salem district, Tamil Nadu), and S40 (Bulandshahr, Uttar Pradesh). The solar site alternative S21 is at the last order of preference, which is located in the Tasgaon taluka of Sangali district of Maharashtra.

Similar to solar energy, wind potential site alternatives were also assessed and obtained the highest preference score of 0.621 for wind site alternative 34 (W34). The potential site alternative W34 is located in Radhapuram taluka of Tirunelveli district of Tamil Nadu. The potential location is near 15 km from the 110/33/11 kV TNEB sub-station. Whereas, other beneficial factors, such as distance from power plants, transmission lines, and road networks are also near to less than 10 km. The second preference is given to wind site alternative W1, which is situated in the Bikaner region of Rajasthan state. The preference order is followed by W12 (Kachchh, Gujarat), W30 (Tiruppur taluka of Coimbatore district of Tamil Nadu), and W33 (Kovilpatti taluka, Thoothukudi district of Tamil Nadu) wind site alternatives. However, the least preference is given to two sites of Madhya Pradesh state located in the districts of West Nimar, and Barwani.

Further, in order to assess the robustness of the prioritization order, the sensitivity analysis has been performed for three different cases of FAHP-TOPSIS, FAHP-WASPAS, and Equal weight-MAUT. In the first case, the fuzzy AHP integrated TOPSIS approach has been employed. In the TOPSIS approach, firstly, the numeric values of the decision criterion were normalized. Further, these normalized values are multiplied with the weights of criterion, to calculate the weighted normalized index for alternatives. Sequentially, calculated the distance from the positive and negative ideal solution which will be further used for the assessment of the closeness coefficient. Finally, based on the higher values of closeness coefficient, solar and wind site alternatives are ranked. The highest values of closeness coefficients are 0.708 and 0.782 for solar (S6) and wind (W1) site alternatives. Whereas, the solar and wind potential site alternatives S21 and W21 are given the least preference, with minimum closeness coefficient of 0.479 and 0.439, respectively.

In the second case of sensitivity analysis, the hybrid fuzzy AHP-WASPAS approach is used in which fuzzy AHP is used for criterion weight assessment and WASPAS approach is employed for ranking of alternatives. The WASPAS approach sequentially performs multiple processes: (i) normalization of cost and benefit criteria, (ii) determination of additive and multiplicative relative importance, (iii) integration and generalization of additive and multiplicative relative importance, to obtain the joint generalized criterion (Q), and finally (iv) highest amount of joint generalized criterion (Q) has the highest rank. The highest joint generalized criterion is given to solar site alternative S3 (0.447) while the least is to solar site alternative S21 (0.195). Similar way the wind site alternatives W1 and W37 achieved the highest and lowest score of 0.422 and 0.180 respectively. Brief details about the ranking of potential site alternatives from different approaches are provided in Table 7.5 and Table 7.6.

Table 7.5: Ranking of solar potential alternatives from different MCDM approaches

Alternatives (Solar)	FAHP-MAUT		FAHP-TOPSIS		FAHP-WASPAS		Equal weight-MAUT	
	Results	Rank	Results	Results	Results	Rank	Results	Rank
S1	0.345	38	0.584	26	0.279	35	0.384	23
S2	0.543	2	0.690	2	0.402	2	0.556	1
S3	0.452	12	0.646	7	0.447	1	0.481	5
S4	0.441	15	0.652	6	0.331	9	0.452	9
S5	0.413	20	0.620	17	0.306	20	0.414	13
S6	0.506	6	0.708	1	0.368	5	0.509	2
S7	0.361	35	0.458	43	0.280	34	0.341	37
S8	0.409	22	0.597	24	0.263	37	0.362	31
S9	0.313	42	0.436	44	0.263	38	0.279	41
S10	0.448	14	0.605	23	0.296	23	0.368	30
S11	0.356	36	0.553	35	0.261	39	0.356	33
S12	0.440	16	0.612	21	0.336	7	0.425	12
S13	0.413	19	0.573	28	0.293	26	0.375	25
S14	0.380	31	0.579	27	0.291	27	0.354	34
S15	0.412	21	0.617	20	0.281	31	0.387	20
S16	0.450	13	0.632	11	0.316	12	0.399	15
S17	0.408	23	0.558	34	0.314	14	0.383	24
S18	0.371	34	0.505	40	0.298	22	0.336	38
S19	0.275	44	0.531	38	0.257	41	0.267	43
S20	0.331	39	0.491	41	0.242	43	0.269	42
S21	0.163	45	0.479	45	0.195	45	0.131	45
S22	0.403	26	0.572	31	0.284	30	0.389	19
S23	0.384	29	0.564	32	0.319	10	0.335	39
S24	0.389	27	0.526	39	0.280	33	0.353	35
S25	0.403	25	0.622	30	0.245	42	0.373	27
S26	0.546	1	0.684	14	0.317	11	0.430	11
S27	0.539	3	0.637	10	0.314	15	0.439	10
S28	0.452	11	0.646	19	0.309	19	0.374	26
S29	0.282	43	0.601	37	0.236	44	0.240	44
S30	0.524	4	0.610	22	0.289	29	0.398	16
S31	0.374	33	0.457	42	0.259	40	0.298	40
S32	0.499	7	0.573	29	0.332	8	0.410	14
S33	0.477	8	0.627	13	0.314	16	0.472	8
S34	0.424	18	0.637	9	0.296	24	0.395	18
S35	0.376	32	0.622	16	0.281	32	0.369	29
S36	0.388	28	0.641	8	0.298	21	0.387	21
S37	0.437	17	0.621	18	0.313	17	0.484	4

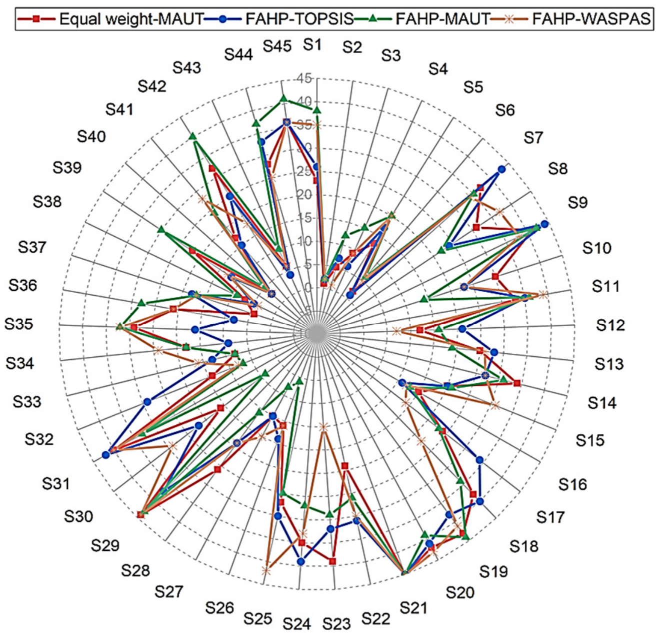
Alternatives (Solar)	FAHP-MAUT		FAHP-TOPSIS		FAHP-WASPAS		Equal weight-MAUT	
	Results	Rank	Results	Results	Results	Rank	Results	Rank
S38	0.462	9	0.656	5	0.382	4	0.474	7
S39	0.383	30	0.630	12	0.315	13	0.385	22
S40	0.509	5	0.682	3	0.391	3	0.506	3
S41	0.404	24	0.684	15	0.290	28	0.398	17
S42	0.330	40	0.591	25	0.309	18	0.360	32
S43	0.458	10	0.671	4	0.366	6	0.479	6
S44	0.349	37	0.562	33	0.294	25	0.371	28
S45	0.323	41	0.555	36	0.274	36	0.342	36

Table 7.6: Ranking of wind potential alternatives from different MCDM approaches

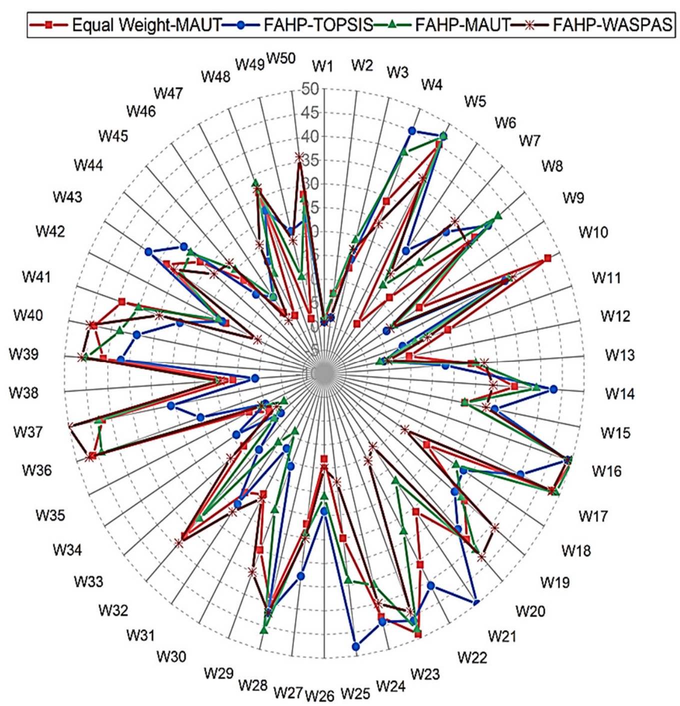
Alternatives (Wind)	FAHP-MAUT		FAHP-TOPSIS		FAHP-WASPAS		Equal weight-MAUT	
	Results	Rank	Results	Rank	Results	Rank	Results	Rank
W1	0.617	2	0.782	1	0.422	1	0.706	1
W2	0.440	7	0.703	2	0.321	2	0.460	7
W3	0.374	19	0.656	15	0.245	17	0.395	13
W4	0.285	40	0.485	45	0.229	24	0.320	29
W5	0.243	47	0.475	47	0.209	37	0.263	45
W6	0.416	13	0.640	22	0.246	16	0.483	3
W7	0.362	22	0.627	31	0.212	34	0.407	12
W8	0.284	42	0.584	39	0.214	33	0.305	35
W9	0.431	9	0.679	7	0.254	8	0.380	16
W10	0.289	37	0.603	36	0.209	38	0.251	47
W11	0.419	12	0.672	9	0.248	15	0.361	20
W12	0.489	3	0.696	4	0.282	5	0.416	10
W13	0.352	25	0.648	18	0.226	27	0.346	24
W14	0.285	39	0.558	43	0.221	29	0.312	34
W15	0.361	23	0.627	30	0.225	28	0.353	23
W16	0.205	50	0.439	49	0.186	49	0.212	50
W17	0.217	49	0.592	40	0.187	48	0.245	48
W18	0.343	26	0.627	28	0.248	12	0.363	18
W19	0.314	31	0.625	29	0.202	41	0.316	32
W20	0.284	41	0.607	35	0.201	43	0.296	38
W21	0.377	18	0.439	50	0.251	9	0.330	26
W22	0.322	28	0.565	41	0.251	11	0.302	36
W23	0.238	48	0.476	46	0.201	44	0.218	49

Alternatives (Wind)	FAHP-MAUT		FAHP-TOPSIS		FAHP-WASPAS		Equal weight-MAUT	
	Results	**Rank**	**Results**	**Rank**	**Results**	**Rank**	**Results**	**Rank**
W24	0.294	36	0.530	44	0.205	40	0.265	43
W25	0.307	34	0.445	48	0.248	13	0.338	25
W26	0.399	16	0.643	19	0.251	10	0.434	8
W27	0.357	24	0.623	33	0.227	25	0.356	22
W28	0.251	46	0.592	42	0.201	42	0.282	40
W29	0.365	21	0.712	11	0.211	35	0.319	30
W30	0.462	4	0.725	8	0.236	20	0.362	19
W31	0.433	8	0.675	24	0.226	26	0.357	21
W32	0.313	32	0.711	12	0.207	39	0.298	37
W33	0.462	5	0.749	3	0.243	18	0.393	14
W34	0.621	1	0.658	14	0.296	3	0.472	5
W35	0.457	6	0.688	5	0.278	6	0.428	9
W36	0.275	44	0.685	20	0.194	47	0.258	46
W37	0.281	43	0.672	26	0.180	50	0.269	42
W38	0.407	15	0.682	6	0.248	14	0.414	11
W39	0.251	45	0.643	37	0.196	46	0.275	41
W40	0.286	38	0.661	34	0.198	45	0.263	44
W41	0.307	35	0.629	25	0.221	30	0.289	39
W42	0.387	17	0.656	16	0.265	7	0.383	15
W43	0.318	29	0.594	38	0.221	31	0.315	33
W44	0.316	30	0.624	32	0.230	23	0.323	27
W45	0.370	20	0.658	13	0.232	22	0.363	17
W46	0.425	10	0.669	10	0.291	4	0.465	6
W47	0.408	14	0.653	17	0.236	21	0.476	4
W48	0.313	33	0.629	27	0.215	32	0.318	31
W49	0.423	11	0.642	21	0.237	19	0.504	2
W50	0.340	27	0.636	23	0.210	36	0.322	28

In the last case, the priority order of potential site alternatives is validated by assuming equal criterion weights instead of the weight assigned by the fuzzy AHP approach. Therefore, in the final case-III, the MAUT approach ranks the alternatives using equal criterion weights. Here, the first preference is given to site alternatives S2 and W1 with a utility score of 0.556 and 0.706 respectively. Similar to previous approaches, the last preference is assigned to S21 (0.131) and W16 (0.212) site alternatives. The ranking order of solar and wind potential site alternatives in different approaches is graphically represented in Fig. 7.5.



(a)



(b)

Fig. 7.5: Ranking order of (a) solar and (b) wind site alternatives in different approaches

Here, the results of the sensitivity analysis are discussed from another perspective, aimed at discovering some of the most conspicuous potential sites among these identified sites. Here, Table 7.7 presents the 10 leading potential alternatives for solar and wind power among all the methodologies studied.

Table 7.7: Foremost solar and wind potential alternatives in different MCDM approaches

Rank	Solar Energy				Wind Energy			
	FAHP-MAUT	FAHP-TOPSIS	FAHP-WASPAS	Equal weight-MAUT	FAHP-MAUT	FAHP-TOPSIS	FAHP-WASPAS	Equal weight-MAUT
1	S26	S6	S3	S2	W34	W1	W1	W1
2	S2	S2	S2	S6	W1	W2	W2	W49
3	S27	S40	S40	S40	W12	W33	W34	W6
4	S30	S43	S38	S37	W30	W12	W46	W47
5	S40	S38	S6	S3	W33	W35	W12	W34
6	S6	S4	S43	S43	W35	W38	W35	W46
7	S32	S3	S12	S38	W2	W9	W42	W2
8	S33	S36	S32	S33	W31	W30	W9	W26
9	S38	S34	S4	S4	W9	W11	W21	W35
10	S43	S27	S23	S27	W46	W46	W26	W12

From the above analysis, a few important conclusions may draw which are as follows.

- Rajasthan state is having the highest number of solar potential sites followed by Uttar Pradesh, Gujarat, and Andhra Pradesh. Similarly, in wind power potential sites, Tamil Nadu state carries the highest number of potential sites followed by Karnataka, Rajasthan, and Gujarat.
- Few conspicuous potential sites for solar energy are S2 (Bikaner, Rajasthan), S6 (Phalodi, Rajasthan), S40 (Bulandshahr, Uttar Pradesh), S43 (Kaithal, Haryana), S3 (Lunkaransar, Bikaner, Rajasthan), S38 (Biswan, Sitapur, Uttar Pradesh), S4 (Lunkaransar, Bikaner, Rajasthan), and S27 (Sivaganga, Tamil Nadu).
- Few conspicuous potential sites of wind energy installation are W1 (Bikaner, Rajasthan), W2 (Phalodi, Jodhpur, Rajasthan), W12 (Kachchh, Gujarat), W35 (Ramanathapuram, Tamil Nadu), W46 (Manvi, Raichur, Karnataka), W34 (Radhapuram, Tirunelveli, Tamil Nadu), and W9 (Nakhtarana, Kachchh, Gujarat).

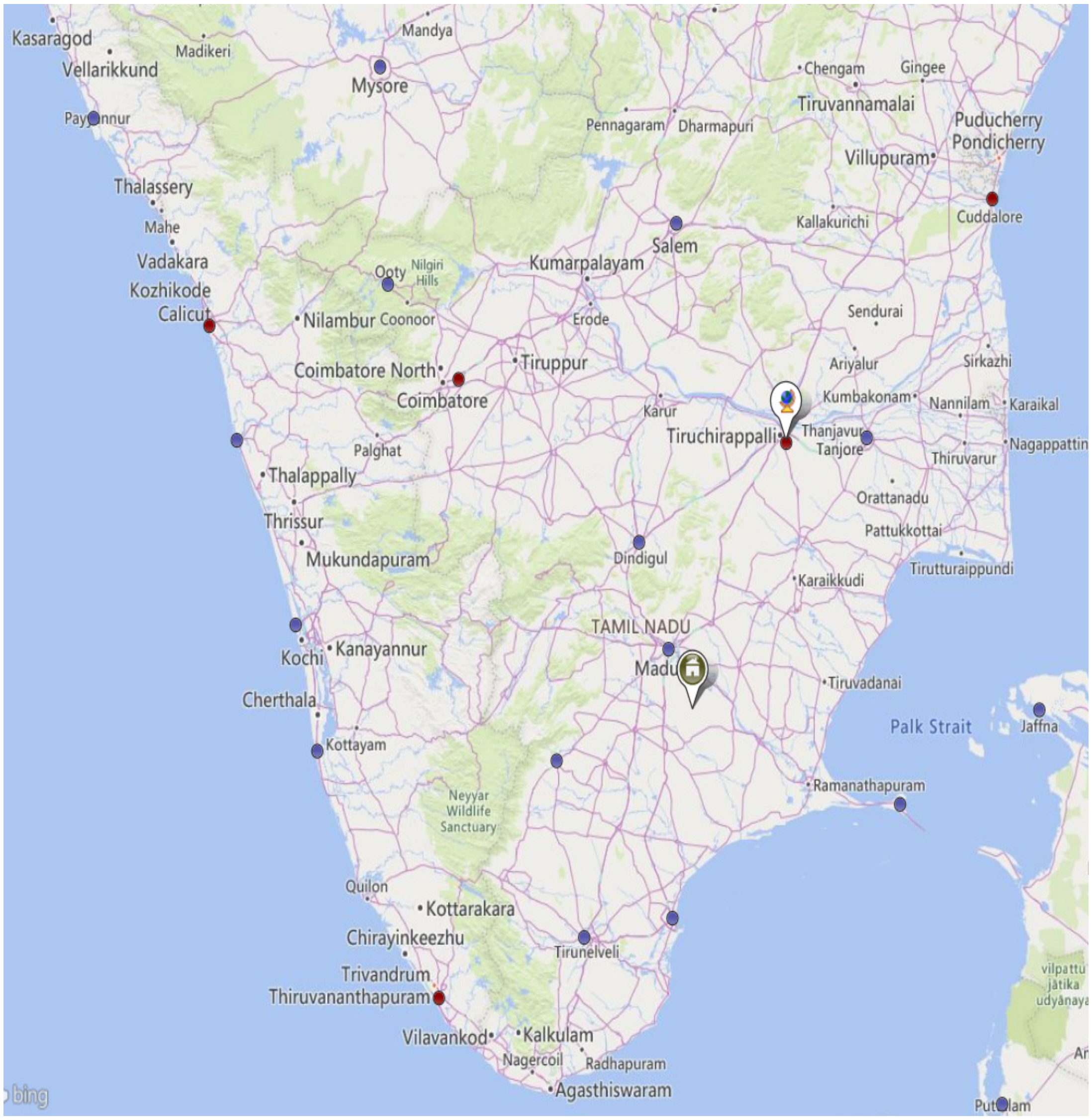
- Results of sensitivity analysis examine that the alternatives perform in-line and near about similar among all the considered approaches.

7.4 DISCUSSION

The present study prioritized the solar and wind potential site alternatives and highlighted some conspicuous potential sites. This prioritization order is determined based on the numeric values of indicators and the application of MCDM approaches. Therefore, there developed a need to perform a case study on these conspicuous sites to assess the technical viability and economic feasibility of the project. The case study is conducted at the conspicuous solar and wind potential alternative sites of S26 and W34, which are the first preference in the fuzzy AHP-MAUT approach. The case study is carried out using the RETScreen expert software tool. It covers economic, technical, environmental, financial, and risk aspects during the pre-feasibility analysis. Here, pre-feasibility assessment has been carried out in four consecutive steps: (i) Description of conspicuous potential sites, (ii) Modelling of system, (iii) Pre-feasibility analysis, and (iv) sensitivity and risk analysis. These steps are briefly discussed in the following sections.

7.4.1 Description of Conspicuous Sites

The conspicuous potential site S26 is situated in Tiruchuli taluka of Virudhunagar district, Tamil Nadu. Geographically the site is located at 9°39’48.5” N, and 78°14’36.5” E with an area of 850 km^2. At this site, a study is assessing the pre-feasibility of a 100 MW solar photovoltaic power plant. The data is jointly taken from the ground and NASA weather station. Madurai is the nearest NASA climate data center with a distance of 32 km, while the nearest ground weather station is located at Tiruchchirappalli with a distance of 134 km. In addition, the blue dots show the location of the NASA meteorological station and wine-red dots show the ground weather station. The geographical position of the study area, NASA meteorological center, ground weather is graphically shown in Fig. 7.6.



Facility location

Nearest ground measure weather station

Ground measure weather station

NASA climate data location

Fig. 7.6: Geographical location of conspicuous solar potential sites with availability of ground and satellite weather station

The study area is located in the extremely hot and humid climatic zone with an average solar radiation intensity of 5.20 kWh/m^2/day. In addition, monthly average air temperature of 27.3 $^{\circ}$C, relative humidity of 68.6%, and wind velocity of 4.5 m/s at a hub height of 10 m above the ground. Here, the monthly average solar radiation intensity and air temperature at the facility location are shown in Fig. 7.7.

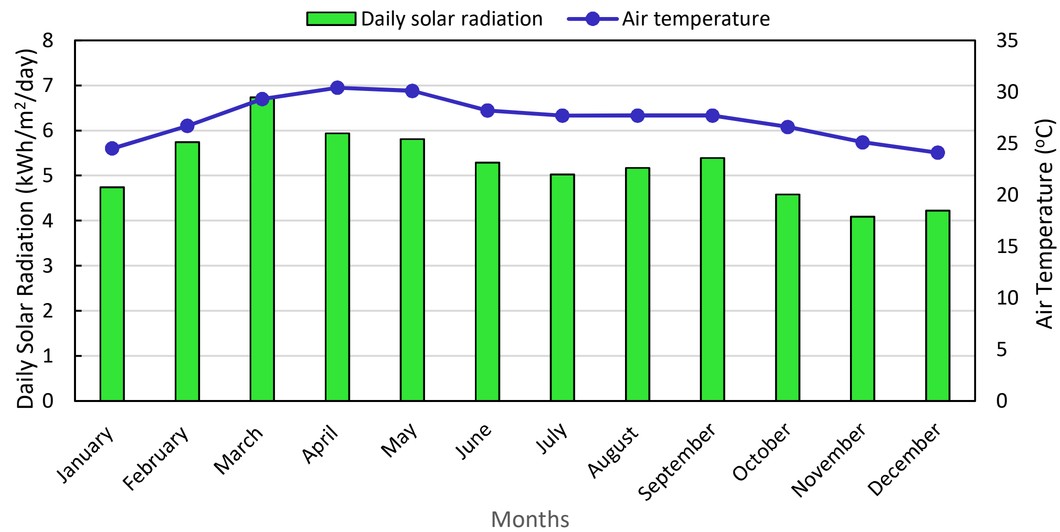


Fig. 7.7: Monthly average solar radiation intensity and air temperature at the study area

Secondly, for wind energy, the conspicuous potential site alternative W34 is considered for the pre-feasibility analysis. The alternative is situated in Radhapuram taluka of Tirunelveli district of Tamil Nadu state. Geographically, the site can be traced to latitude and longitude of 8°13'31.6" N, and 77°45'09.9" E with an overall available land area of 179 km^2. Similar to solar energy, a wind power project is also assessed for a 100 MW power capacity. The site is blessed with a monthly average wind speed of 4.2 m/s at an altitude of 10 m above ground level. Average wind speed and air temperature in the study area are graphically shown in Fig. 7.8.

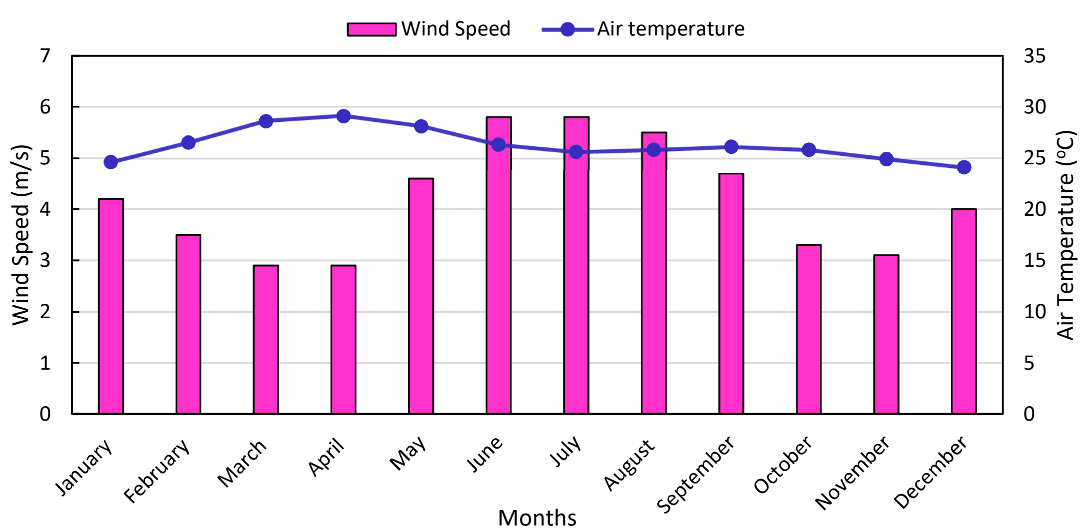


Fig. 7.8: Monthly average wind velocity and air temperature at the study area

In addition, the site has a temperature of 26.3 °C, relative humidity of 76.6%, global solar radiation intensity of 4.91 kWh/m^2/day, and an atmospheric pressure of 99.1 kPa. These data are combined and obtained from ground-mounted weather stations and NASA weather stations. The NASA weather station 57 km away in Tirunelveli district of Tamil Nadu is the nearest station to the site, while the ground measurement station is 93 km away, located in Thiruvananthapuram district of Kerala. The geographical position of the ground measurement station, NASA weather station, and closest weather station from the study area are shown in Fig. 7.9.

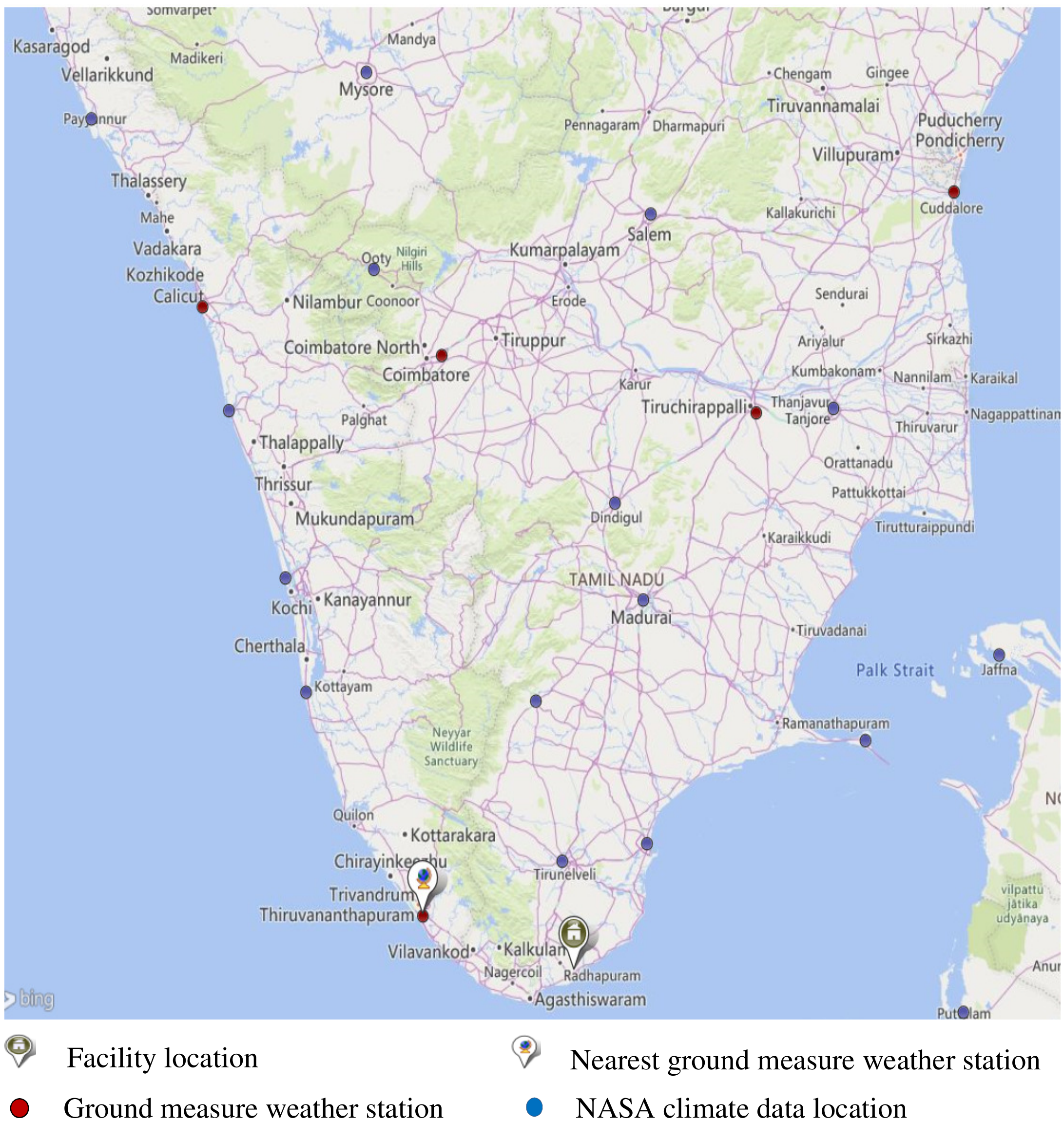


Fig. 7.9: Geographical location of conspicuous wind potential sites with availability of ground and satellite weather station

7.4.2 Techno-Economic-Environment Modelling

To assess the pre-feasibility of solar and wind power projects, it is essential to model the project by covering the aspects of technical, economic, and environmental. The technical modeling concerns the resource assessment, specification of photovoltaic cells, specification of an inverter, and capacity factor. Whereas, economic and environmental aspects include the initial cost, O & M cost, electricity export rate, greenhouse gas emission factor, and saving of fossil fuels. These steps are briefly discussed in the following sections.

7.4.2.1 Technical modeling

The technical modelling of the solar photovoltaic power project includes the assessment and specification of available resources, photovoltaic cells, inverters, and the capacity factor of the system. The system is assumed to be a fixed axis with a slope equal to the latitude of the location. In addition, a monocrystalline Canadian silicon solar cell (CS6X-320P) with an efficiency of 16.39% will be installed which also has the additional specifications of nominal operating cell temperature of 45 $^{\circ}$C, temperature coefficient of 0.4%/$^{\circ}$C. A total of 312500 solar photovoltaic panels will be used to build a capacity of 100 MW, covering an area of 610128 m^2. The system assumes a capacity factor of 16.8%, including 5% inverter losses and 10% miscellaneous losses.

To assess the pre-feasibility of a wind power project, the key factor is wind speed measured at a speed of 4.2 m/s at a height of 10 m above ground level. This wind speed (kinetic energy) is converted into power using Suzlon S97 wind turbine model. Some key specifications of the Suzlon S97 wind turbine model are as follows: power capacity-2.1 MW, rotor diameter-97 m, swept area-7386 m^{2,} and hub height-100 m. Therefore, a total of 48 wind turbines will be installed in the wind farm to achieve a power capacity of 100 MW. The system calculated the capacity factor of 26.3%, including 10% of an array and airfoil losses, and 85.5% of system availability (machine + grid availability).

7.4.2.2 Economic modeling

Economic modeling of the system includes key expenses such as capital cost in the installation of power plants, O & M cost, and electricity export rate to the grid. Here, the capital cost is considered as 618 $/kW which includes the equipment and installation cost of the system [376]. In addition, the installation cost of a solar plant generally decreases with an increase in the capacity of the plant. Over there, the study assumes 9.5 $/kW-year of O & M cost [374,376]. Ultimately, the government paid off 0.045 $/kWh (₹ 3.28/kWh) of the electricity export rate to the electric utilities or customers. In the case of wind power, the study assumes an initial cost and maintenance cost of $1054/kWh, and $ 0.015/kWh-year respectively [374–376]. Whereas, the study assumes 1600 hours as a wind turbine power generation hour in a year [389]. As a result, the government would pay $ 0.049 per unit of electricity (₹ 3.58/kWh) to local power generation utilities.

7.4.2.3 Environmental modeling

Environmental modeling is carried out to help the user estimate the greenhouse gas emission reduction potential. It will calculate the gross annual greenhouse gas emission reduction potential by computing the greenhouse gas emission potential for the base case and proposed case. The study assumes that India's thermal power plants (coal) emit 1.171 tonnes of CO_2 per MWh and also assumes transmission and distribution losses of 22% [390]. The study estimated CO_2 emissions of 221254 and 48676 tonnes per year for the base and proposed case respectively. Ultimately, incorporating the base and the proposed case, the study calculated the gross annual GHG emission reduction potential of 172578 tonnes of CO_2 emission per year. Similarly, in the case of wind power, the base case and the proposed case emit 348971 and 76773 tonnes of CO_2 per year respectively. In the end, the study calculated that there is a saving of 272198 tonnes per year in CO_2 emissions.

7.4.3 Pre-feasibility Analysis of System

The study primarily defines the feasibility of the project based on the energy production cost, payback period, gross GHG reduction, and barrels of crude oil not consumed. In the case of solar energy, a total of $ 61800000 will be invested in the installation of the pre-discussed capacity of the solar project. Whereas, a total of $ 950000 will be required in the O & M cost of the installed solar plant. The total capital cost of the solar project is paid in two ways, either equity or debt amount. It is always better to consider the debt amount as 40% or less than 40% of the total capital cost. Therefore, the present study assumes 30% of the total investment cost as debt amount and the remaining 70% as the equity amount. The overall installed capacity of the plant will export a total of 147328 MWh of electricity per year, which earns total revenue of $ 6629751 from electrical grids. Finally, incorporating multiple factors simultaneously such as capital cost, electricity exported to the grid, and total revenue earned to calculate the energy production cost per unit ($/kWh or ₹/kWh). The cost per unit of electricity generation is $0.04 (4 US₵/kWh, and ₹2.92/kWh) with 11.5 years of system equity payback period. The cumulative cash flow of the solar power project with an equity payback period is shown in Fig. 7.10. Environmental, the proposed solar power project will have the potential to save 74 million liters of gasoline per year and 0.4 million barrels of crude oil per year. In addition, it will also have the potential to reduce GHG emissions by 4.3 million tonnes over its operational life.

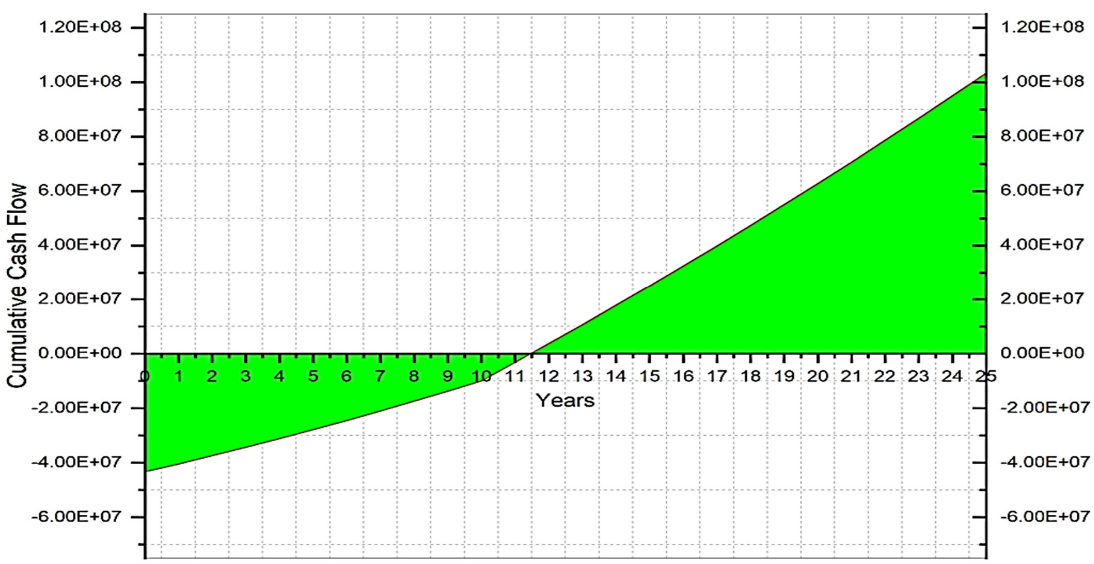


Fig. 7.10: Cumulative cash flow in a proposed solar power project

For wind power, a total investment of $106243200 will be made in the installation of a 100 MW capacity of the wind power project. In addition, USD 2419200 will be required per year for the operation and maintenance activities of this wind power project. The installed power project will export 232372 MWh of electricity per year to the grid for which it will earn total revenue of $11386216 per year. Thus, through assessing the capital cost, O&M cost, electricity generation, and total revenue earned calculated the energy production cost of $ 0.05 per kWh (5 US₵/kWh, and ₹ 3.65/kWh). In addition, the system has an equity payback period of 12.6 years, which means that the system moves from negative cash flow to positive cumulative cash flow during this time. The cumulative cash flow of the system is graphically represented in Fig. 7.11. From an environmental point of view, the wind power system will have the potential to save 6.8

million tons of greenhouse gases over its entire lifecycle. In addition, the wind power system will also have the potential to save 117 million liters of gasoline and 0.633 million barrels of crude oil.

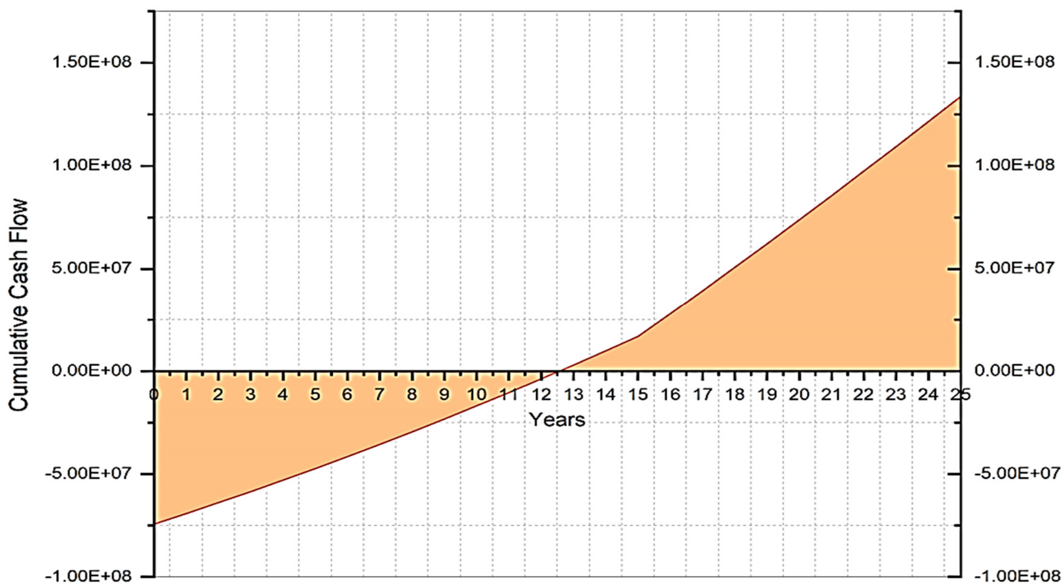


Fig. 7.11: Cumulative cash flow in a proposed wind power project

7.4.4 Sensitivity and Risk Analysis

To assess the robustness of the results of the proposed project, sensitivity analysis has been carried out for the initial cost, O & M cost, electricity export rate, debt interest rate, and payback period. Firstly, a sensitivity analysis is performed to assess the effect of initial cost on the payback period and LCOE. Sensitivity analysis has been performed for ±30% of the initial cost for which the minimum and maximum payback periods of 7.4 years and 14.5 years are obtained. Similarly, the LCOE for successive steps of initial cost -30%, -22.5%, -15%, -7.5%, 0%, +7.5%, +15%, +22.5%, and +30% are obtained as 0.031 $/kWh, 0.033 $/kWh, 0.035 $/kWh, 0.038 $/kWh, 0.040 $/kWh, 0.042 $/kWh, 0.044 $/kWh, 0.046 $/kWh and 0.048 $/kWh respectively. Similarly, sensitivity analysis has been carried out to assess input effects such as O & M cost, electricity exported to the grid, and debt interest rate on the system's output such as payback period and LCOE. Table 7.8 contains details of the relationship of system outputs with the variability of system inputs.

Table 7.8: Sensitivity analysis for different variable input parameters

Sensitive input parameters	Dependent output parameters	Sensitivity variability				
		-10	-5	0%	+5%	+10%
O & M cost	Payback period (years)	11.3	11.4	11.5	11.6	11.7
	LCOE ($/kWh)	0.0388	0.0393	0.0398	0.0403	0.0408
Electricity exported to grid	Payback period (years)	12.9	12.1	11.5	10.9	10.3
	LCOE ($/kWh)	0.044	0.0419	0.0398	0.0379	0.036
Debt interest rate	Payback period (years)	11	11.2	11.5	11.7	12
	LCOE ($/kWh)	0.0386	0.0392	0.0398	0.0404	0.041

Similar to sensitivity analysis, risk analysis is performed to assess the level of uncertainty that may occur in a project. The most salient feature of risk analysis is that the risk analysis allows all the parameters to assess the overall effect on each other in a range [387]. The risk assessment is carried out for the output parameters such as payback period and LCOE. For which it is assumed that the initial cost and debt term vary in the range of ± 30%, while other factors such as O & M cost, electricity exported to the grid, electricity export rate, debt ratio, and debt interest rate only vary in the range of ±10%. For the following conditions, the RETScreen software performs 5000 iterations of Monte Carlo simulations and draws an impact and distribution graph as the result.

According to the impact graph for solar energy, initial cost, electricity export rate, and electricity exported to the grid have a greater impact on the equity payback period. The equity payback period increases with an increase in the initial cost of the project while the equity payback decreases with an increase in the power export rate, and power exported to the grid. Similarly, LCOE will increase with an increase in initial cost and decrease with an increase in electricity exported to the grid. Whereas, in the case of wind energy, the equity payback period and LCOE are mainly affected by the initial cost, O & M cost, electricity export rate, and electricity exported to the grid. Here, initial cost and O & M cost have a positive relationship with output factors which means that the equity payback period and LCOE will increase with an increase in initial cost and O & M cost. Whereas the other two factors, the electricity export rate and the electricity exported to the grid have a negative relationship with the equity payback period and LCOE.

7.5 SUMMARY

The primary aim of the study is to assess the physical characteristics of the solar and wind site alternatives, as well as to conduct a case study on a conspicuous site to techno-economically validate the analytical outcome. The analysis began by identifying alternatives in highly suitable site areas. The study only considers them as a viable alternative if the land area for solar power is greater than 500 km^2 and the land area for wind power is greater than 50 km^2. In total, 45 solar site alternatives and 50 wind site alternatives are chosen for the study. Furthermore, the study used the fuzzy AHP integrated MAUT approach to prioritize them. The weights for the criterion are assigned using fuzzy AHP, and the alternatives are ranked using MAUT. The order of priority is contrasted with other fuzzy AHP integrated TOPSIS and WASPAS techniques. In addition, the outcome's robustness is also tested by altering the weights of the criterion.
The analysis identifies S2 (Bikaner, Rajasthan), S6 (Phalodi, Rajasthan), S40 (Bulandshahr, Uttar Pradesh), S43 (Kaithal, Haryana), S3 (Lunkaransar, Bikaner, Rajasthan), S38 (Biswan, Sitapur, Uttar Pradesh), S4 (Lunkaransar, Bikaner, Rajasthan), and S27 (Sivaganga, Tamil Nadu) sites as the conspicuous solar potential sites for solar power project installation. Similarly, the study marked W1 (Bikaner, Rajasthan), W2 (Phalodi, Jodhpur, Rajasthan), W12 (Kachchh, Gujarat), W35 (Ramanathapuram, Tamil Nadu), W46 (Manvi, Raichur, Karnataka), W34 (Radhapuram, Tirunelveli, Tamil Nadu), and W9 (Nakhtarana, Kachchh, Gujarat) sites as the conspicuous wind potential sites for implementation of wind power projects.

Further, in order to assess the project's techno-economic feasibility, a case study is conducted at site alternatives S26 and W34 utilizing RETScreen software. The software analyses weather data from both ground measurements and NASA climate data. The software user interface necessitates data and information at seven different levels: (i) selection of facility and analysis type, (ii) location and weather conditions, (iii) energy modeling, (iv) cost analysis, (v) emission analysis, (vi) financial analysis, and (vii) sensitivity and risk analysis. The output of the project is assessed in terms of LCOE, payback period, and reduction in GHG emission over its operational life. In the case of solar energy, the project has an LCOE of $40/MWh, a payback period of 11.5 years, and a GHG reduction of 4.3 million tonnes throughout its operating lifetime. Similarly, the LCOE, payback period, and GHG emissions for wind energy are 50 $/MWh, 12.6 years, and 6.8 million tonnes of GHG emission reduction during its full life cycle, respectively.

The robustness of software outcome is tested by performing the sensitivity and risk analysis. Finally, it is concluded that the software outcome is completely similar and in line with the analytical results.

The study assesses the physical properties of highly suitable sites, such as solar radiation, land slope, distance from transmission lines, distance from the road network, and so on. As a result, this information would be useful to investors, shareholders, and stakeholders prior to the installation of electricity projects. In addition, the study illustrates the importance of this practical data, which will benefit data analysts, academics, and researchers. In addition, the study gave information on highly suitable sites in the form of site latitude, longitude, taluka, district, and state, which could be used to locate them more readily. The study also includes a case study, which is a significant feature. The main focus of the case study is on the three key components of economic, technical, and environmental modeling. The economic components of the case study are thoroughly examined, with capital cost, O & M costs, interest rates, and discount rates serving as input costs, and LCOE, net present value, and payback time serving as output values. The technical side, on the other hand, is concerned with a wide range of renewable energy generation equipment, as well as their technical data, CF, and efficiency, which aids in the correct computation of total electricity generation. Finally, the environmental element aids in determining the reduction in GHG emissions each year in comparison to million liters of crude oil and gasoline. All of this contributes to a better understanding of the techno-economic nature of sites, reduces the likelihood of economic losses, reduces the related economic and environmental hazards, and clarifies the project's future vision.

CHAPTER – 8

CONCLUSIONS

The world's prime concerns are the rapidly growing population, industrialization, and urbanization, which are also responsible for the widespread depletion of natural resources and fossil fuels. As a result, food and water availability, energy security, and a clean environment are going to remain key issues for the current and future generations. To address these concerns, a plan to tap the maximum amount of sustainable energy sources must be developed and proposed. Sustainable energy sources must be cost-effective, efficient, reliable, less hazardous to the environment and human health, must produce less waste, and finally, be available for long-term usage.

To meet these requirements, the current study planned certain objectives. In this regard, an extensive literature review was carried out, and Chapter 2 documents a total number of 301 articles. The articles were collected according to the objectives and progress of the study. The extensive literature review found that the majority of the articles do not consider the multi-aspect or multi-dimension nature of sustainability evaluation. In addition, it was also found that both renewable and conventional energy sources were not taken into account while evaluating sustainable energy sources and determining the optimal energy mix scenario. Furthermore, there was also a scarcity of studies on estimating the exploitable sustainable energy potential. Also, no study exists to first identify a suitable geographical area and then estimate the exploitable sustainable energy potential associated with it.

Prior to assessing the sustainable energy sources, it was essential to select the appropriate sustainability indicators, as these provide a clear and deeper understanding of the concept. Therefore, the primary aim of **Chapter-3** is to assess the sustainability indicators in the Indian geographical region in order to evaluate the sustainable energy sources. The following points are considered in this chapter:

- A total of 767 indicators were identified from the extensive literature survey. Further, a panel of experts reviewed the indicators and checked the relevancy of indicators by using the nominal grouping techniques.

- A total of 93 indicators pertaining to 15 categories were produced in the survey instrument which was further validated and pre-tested for simplicity and adequacy by a team of experts.
- A total of 442 responses were accepted for further processing, among them 278 were obtained through offline mode and 164 were received through online mode. After that, the SII of indicators was assessed cumulatively as well as category-wise.
- Furthermore, using a pre-defined and trusted scale, the responses were categorized into five suitability classes namely 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'.
- Finally, a total of 26 highly suitable indicators pertaining to economic, technical, social, environmental, political, and flexible categories were selected as the sustainability indicators in the Indian geographical region and also considered for further analysis.
- In addition, to validate the survey results, item and validity analysis was performed as part of the statistical analysis. At last, statistical analysis confirmed the survey's filtered criteria while extracting them as the final selected indicators.

Following the assessment of sustainability indicators, the primary aim of the study was to evaluate the most sustainable energy sources in India which are discussed in **Chapter 4**. The following are the chapter's significant outcomes:

- Firstly, the study considered seven major renewable and conventional energy sources, including thermal (coal), hydro, gas power, wind, nuclear, biomass, and solar energy as the energy alternatives after a detailed analysis of the Indian energy sector.
- The study developed a three-stage hierarchical framework model that encompassed the study's goal, criteria/sub-criteria to be applied, and the alternatives for research work.
- Energy alternatives were prioritized using two-hybrid MCDM approaches: (i) Shannon's integrated MCDM approach and (ii) hybrid fuzzy AHP MCDM approach. In addition, other MCDM approaches including TOPSIS, VIKOR, PROMETHEE-II, WSM, WPM, and WASPAS were used to compare the

prioritization order. Furthermore, the results were also corroborated by calculating Spearman's and Karl Pearson's correlation coefficients.

- Based on the study, solar energy was chosen as the most sustainable energy source in India, followed by wind, hydro, biomass, gas power, nuclear, and thermal energy.
- To determine the optimal energy mix scenario for India in the year 2030, the study developed a methodology that included (i) calculating electricity demand by 2030 based on India's futuristic case, (ii) analyzing multiple tools including IESS 2047 and TOPSIS, and (iii) developing 14 scenarios using the top five sustainable energy sources.
- It was found that the optimal energy mix scenario has a proportion of coal (49%), solar (14%), wind (13%), hydro (9%), gas (4%), nuclear (4%), small hydro (2%), biomass (2%), and imports (2%) in the overall electricity supplied to the customers.

After assessing the sustainable energy sources and optimal energy mix scenario, it becomes essential to select the potential sites and calculate the exploitable power potential of sustainable energy sources in India. Therefore, **Chapter 5** addresses the evaluation of potential sites for the installation of the most sustainable energy sources (solar and wind energy). This chapter includes the following salient points:

- Firstly, an exhaustive literature review was conducted in order to gather knowledge and increase comprehension of the assessment of suitable sites. The detailed literature review aids in the exploration of the study region, data gathering, decision criteria selection, hierarchal model creation, and GIS software analysis.
- The study chose five decision elements from the technical category: solar radiation, wind velocity, slope, aspect, and elevation; five decision factors from the socio-environmental category, namely, distance from coastline, water bodies, airports, wildlife designations, and land use; and finally, four decision factors from the economic category, namely, distance from urban areas, road network, transmission lines, and power plants.

- Further, the study employed a fuzzy AHP approach to assigning weights to these decision criteria. For solar energy, the highest preference (0.17) was given to solar radiation, followed by aspect (0.116), and distance from transmission lines (0.106). Similarly, for wind energy, the highest importance of 0.217 was given to wind speed, followed by elevation (0.135), and distance to transmission lines (0.106).

- Using both GIS and MCDM approaches, the study developed the site suitability map of India which had five classes, namely, 'highly suitable', 'suitable', 'moderately suitable', 'less suitable', and 'not suitable'. In terms of solar energy, the highly suitable category covers an area of 133874 km^2, the suitable category covers 2567836 km^2 area, the moderately suitable category covers 473309 km^2 area, and the less suitable category covers 64904 km^2. Similarly, the highly suitable, suitable, moderately suitable, and less suitable categories for wind energy had the respective areas of 29457 km^2, 2602763 km^2, 546636 $km^{2,}$ and 57044 km^2. In contrast, the current analysis for both solar and wind energy did not find a not-suitable category.

- Furthermore, in terms of states, Rajasthan is obtained as the leading state for both solar and wind energy with the potential areas of 20881 km^2 and 6323 km^2 respectively. In addition, for solar energy, Uttar Pradesh, Gujarat, Karnataka, Tamil Nadu, Maharashtra, Andhra Pradesh, Madhya Pradesh, Haryana, and West Bengal followed Rajasthan respectively. In the case of wind power, other states that follow Rajasthan are Andhra Pradesh, Karnataka, Gujarat, Tamil Nadu, and Madhya Pradesh.

- The study also assessed the robustness of the analysis by performing sensitivity analysis for the four cases and discovered that the output results are sensitive to the weights of the criteria and each considered criterion.

As part of the study, a site suitability map of India was created, and a highly suitable land area for the installation of solar and wind generating plants was identified. Consequently, the purpose of **Chapter 6** is to determine the exploitable power potential with the economic viability and environmental sustainability. The study addresses many geographical constraints, theoretical limitations, technical losses, economic barriers, and environmental problems in order to realize the actual power potential.

- At the beginning, the study conducted a thorough literature review in order to obtain knowledge about various potentials and comprehend their interrelationships. As a result, the study adopted the top-down approach for assessing the geographical, theoretical, technical, economic, and environmental potential.
- Firstly, the geographical potential is estimated in terms of highly suitable land areas of 133874 km^2 and 29457 km^2 for solar and wind power, respectively. Further, the study estimated the maximum theoretical power potential of 3653 GW and 213 GW for solar and wind power respectively at these sites.
- The theoretical potential was narrowed down to technical potential by taking into consideration the specific technical constraints, efficiency, and losses. The study calculated a maximum technical solar and wind power potential of 507 GW and 44 GW, respectively.
- Solar and wind technical power potential may be obtained at the least economic potentials of (LCOEs) 40 $/MWh and 51 $/MWh respectively. From an environmental standpoint, solar and wind power have the technical capability to reduce the maximum life cycle GHG emissions of 3429 and 314 million tonnes per year respectively.
- The study also considered the country's and individual states' demand potential scenarios. It is determined that solar energy has three times the potential of the country's current energy needs. In terms of availability, 16 states are power-rich implying that their potential is greater than their current demand.

As in previous chapters, the investigation identified potential sites and calculated the various potentials on them. As a result, the purpose of present **Chapter 7** is to evaluate the physical characteristics of the potential sites and validate the techno-economic feasibility of the project.

- The study assessed the physical characteristics of the potential site in the form of qualitative and quantitative data using a GIS software tool. Further, these characteristics are analyzed using the fuzzy AHP integrated MAUT approach. In addition, the outcome was validated through the fuzzy AHP integrated TOPSIS and WASPAS approach.

- Few conspicuous potential sites for solar energy are identified as S2 (Bikaner, Rajasthan), S6 (Phalodi, Rajasthan), S40 (Bulandshahr, Uttar Pradesh), S43 (Kaithal, Haryana), S3 (Lunkaransar, Bikaner, Rajasthan), S38 (Biswan, Sitapur, Uttar Pradesh), S4 (Lunkaransar, Bikaner, Rajasthan), and S27 (Sivaganga, Tamil Nadu).
- Similarly, for wind energy, a few conspicuous potential sites are W1 (Bikaner, Rajasthan), W2 (Phalodi, Jodhpur, Rajasthan), W12 (Kachchh, Gujarat), W35 (Ramanathapuram, Tamil Nadu), W46 (Manvi, Raichur, Karnataka), W34 (Radhapuram, Tirunelveli, Tamil Nadu), and W9 (Nakhtarana, Kachchh, Gujarat).
- Further, to validate the techno-economic feasibility of the project and potential outcomes, a case study was conducted at the conspicuous sites (S21 and W34) using the RETScreen software.
- Finally, the outcome of the project was assessed in terms of LCOE, payback period, and reduction in GHG emission over its operational life. In the case of solar energy, the project had an LCOE of $40/MWh, a payback period of 11.5 years, and a GHG reduction of 4.3 million tonnes throughout its operating lifetime. Similarly, the LCOE, payback period, and GHG emissions for wind energy were 50 $/MWh, 12.6 years, and 6.8 million tonnes of GHG emission reduction during its full life cycle, respectively.

8.1 MAJOR CONTRIBUTIONS OF THE THESIS

The major outcomes of the current thesis are as follows:

- A thorough and comprehensive analysis of the literature on the evaluation of sustainable energy sources is conducted.
- Sustainability indicators are being analysed and identified for the Indian energy sector's long-term development.
- The evaluation of sustainable energy sources for India will aid in financial management, meeting international obligations, regulating GHG emissions, developing a self-sustaining energy industry, generating energy at a cheaper cost, creating more jobs, and providing social benefits.

- The study examined the optimal energy mix scenario in India for the time frame of the year 2030 which recommends a growth rate in the installation of solar and wind energy facilities to reach a share of 14% and 13% respectively in the country's overall energy supply.
- The study also created a site suitability map of India taking into account economic, technological, social, and environmental factors. The most suitable region of the site suitability map has 4.13% land area for solar energy development and 0.91% land space for wind energy development.
- Further, the study takes into account all-natural and realistic restrictions and considerations to determine geographic, theoretical, and technical power potential, as well as economic viability and environmental sustainability.
- The study also evaluated the physical characteristics of highly suitable sites and conducted a case study on a conspicuous site to verify the prospective outcome from a technological and economic standpoint.

8.2 LIMITATIONS AND FUTURE SCOPE

The analysis has been carried out with publicly available data from different reliable sources. The results can be further improved with the available ground measured data and commercially available data. Moreover, the uncertainties in the estimation of renewable power can be minimized in further research by involving more academia, industrialists, policy-makers, investors, stakeholders, and other experts who are actively involved in renewable power deployments. However, the study facilitates the reproduction of improved results using the developed methodology, MCDM concepts, open-source GIS data, assumptions, and potential estimation. It is hoped that the incorporation of such extensive information related to its spatial and temporal variability in renewable energy capacity and system planning studies may provide policymakers and appropriate rules for increasing the renewable energy contribution to the overall energy supply that can go a long way.

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Appendix-I

GROWTH OF THE INDIAN POWER SECTOR WITH THEIR ACHIEVEMENTS, AND HIGHLIGHTS

As on financial year ending	**Installed capacity (MW)**	**Per Capita Electricity Consumption (kWh)**	**Highlights, solutions, and accomplishments**
31.12.1950	1713	18	Pre-independence installed hydro and thermal power plant and achieved an installed generation capacity of 1713 MW.
1st five-year plan (1951-52 to 1955-56)	2886	31	Allocated about Rs. 260 crores for the power sector. Major work is done on river valleys such as Damodar valley, Bhakra Nangal, Tunga Bhadra, and Hirakud. Targeted capacity could not be achieved due to dependency on foreign imports.
2nd five-year plan (1956-57 to 1960-61)	4653	46	Allocated about total Rs. 427 crores to initiate the new schemes and carry out the old schemes. The hydroelectric plant achieved install capacity double than the thermal plants. The installed capacity reached a level of 6900 MW by 1960-61.
3rd five-year plan (1961-62 to 1965-66)	9027	74	In this plan, the main focus area was rural electrification. To proper utilization of power capacity, the country was divided into five regions of Northern, Western, Southern, Eastern, and North-Eastern. In the third five-year plan, the capacity of 10,170 MW was achieved.
Three annual plans (1966-1969)	12957	98	A special focus is given to the completion of under-construction projects. Nearly 4120 MW power capacity was added during three annual plans.
4th five-year plan (1969-70 to 1973-74)	16664	126	This plan showed the worst performance with a 50.2% shortfall in achieving the target of the fourth five-year plan. In this plan, the power sector suffered from a power shortage due to high transmission and distribution losses.
5th five-year plan (1974-75 to 1979-80)	26680	172	A total of Rs. 7399.50 crores were spent out of which Rs. 3324 crores on power generation and the remaining Rs. 1634 crores on power distribution and transmission schemes.
One annual plan (1980)	28448	172	Establishment of two important organizations namely – (i) National Thermal Power Corporation (NTPC) (ii) National Hydro-Electric Power Corporation (NHPC)

As on financial year ending	Installed capacity (MW)	Per Capita Electricity Consumption (kWh)	Highlights, solutions, and accomplishments
6th five-year plan (1980-81 to 1985-86)	42585	229	A total of Rs. 19,265 crores provided out of which Rs. 14293 crores were the state governments share. During the sixth five-year plan, 14226 MW power capacity was added.
7th five-year plan (1986 to 1990)	63636	329	The plan proposed the addition of 22245 MW power capacity which comprising of 15,999 MW thermal, 5541 MW hydel, and 705 MW of nuclear power capacity. The proposed target was achieved with no slippage occurring.
Two annual plans (1990-91 and 1991-92)	69065	348	A total capacity of 5803 MW comprising 4702 MW thermal, 881 MW hydel, and 220 MW nuclear power capacities were added.
8th five-year plan (1992-93 to 1997-98)	85795	465	This plan focused on issues of reduction of technical and distribution losses, improvement in existing thermal power units, minimize running costs of power plants. A total fund of Rs. 79588.70 crores were allotted. Total 16422.6 MW power capacity was added.
9th five-year plan (1997-98 to 2001-02)	105046	559	The plan focused on maximizing the profit by proper utilization of already existing power plants. The actual capacity addition was only 19015 MW against a proposed target of 40245 MW.
10th five-year plan (2002-03 to 2006-07)	132329	672	The installed power capacity reached 132329 MW. Started commission of renewable energy plants in India with high subsidies.
11th five-year plan (2007-08 to 2011-12)	199877	884	Electricity consumption in the agriculture sector shows a tremendous growth of 99023 GWh to 140960 GWh. A total 556633 number of villages were electrified in India.
12th five-year plan (2012-13 to 2016-17)	326833	1122	A capacity addition target of 88537 MW (excluding RES) but achieved capacity addition of 99209.5 MW. First time in history, the capacity addition target has been overachieved.

BRIEF DEFINITION OF DIFFERENT POTENTIALS

Potential	**Explanation**
Theoretical	The highest level of (resource) potential is the theoretical potential.
Geographical	The geographical potential is the geographical locations that are suitable for installation of specific technology.
Technical	This is the geographical potential which can be attained using technically feasible technologies while accounting for conversion efficiencies.
Techno-economic	This is the potential which can be availed by applying technically feasible and economic viable technologies which are being universally used in competitive markets.
Practical	The amount of energy that can realistically be utilized after marked barriers and barriers such as; social acceptance; environmental factors; and area conflicts are considered.
Realizable	The energy which can be realized within a given timeframe. This energy potential depends on economic conditions as well as global market production capacity.
Economic	The economic potential is the technical potential at cost levels considered competitive.
Market	The market potential is the total amount of renewable energy that can be implemented in the market taking into account the demand for energy, competing technologies, the costs and subsidies of renewable energy sources, and barriers.
Net Potential	The amount of potential that is supplied to the grid, is available only at the aggregate plant level.
Environmental	It has the potential to quantify the savings of life-cycle greenhouse gas emissions.

Appendix-III

LIST OF IDENTIFIED INDICATORS

S.No.	Authors	Sub-Criteria
1.	Kagazyo et al. (1997)	Resource availability, supply stability, social acceptability, international aspects, development time, technical characteristics, environmental burden cost
2.	Akash et al. (1999)	Cost of fuel, Hardware cost, maintenance cost, auxiliary system, environmental constraints, system's efficiency, system's reliability, availability of fuel, national economy, social benefits, system's safety,
3.	Azadeh et al. (2014)	Population and human labour, Distance from power distribution network, Land cost,
4.	Chatzimouratidis and Pilavachi (2009)	Accident fatalities, Land requirement, Radioactivity, Non-radioactive emission, Job creation, Social acceptance, and Compensation rates
5.	Buyukozkan and Guleryuz (2016)	Efficiency, Reliability, Resource availability, Capacity of investment, Technology maturity, Technological maturity, Investment cost, O & M cost, R & D cost, Return on investment, Production cost, Foreign dependency, Compatibility with political legislative situation, Compatibility with national energy policy objective, Public policy and financial support, Social benefits, Social acceptability, Job creation, Greenhouse emission, Land use/requirement, Impact on ecosystem
6.	Alizadeh et al. (2020)	<u>Benefits</u> Utilization of native resources, Protection of the environment, Development of the allied industries, Pursuing the international commitments such as UNFCCC and Kyoto protocol <u>Opportunities</u> Developing environment friendly resources, Job creation, Reduction in energy prices

S.No.	Authors	Sub-Criteria
		Costs Investment costs, Operation costs, Maintenance costs, Land use, Ecological damage Risks Dependency on foreign technology, Lack of financial mechanism to endeavor RE development, Insufficient technological infrastructures, Instability of energy resources, Lack of public awareness about RE, Business failure
7.	Wu et al. (2017)	public recognition (V1), energy reserves (V2), policy of SHP (V3), management level (V4), Risk of damage (V5). employment creation (C1), human health (C2), Improvement of quality of life (C3), impact on landscape (C4).
8.	Shen et al. (2011)	Energy price stability, stability for energy generation, security for energy supply, low energy prices, carbon emission reduction, SOx and NOx emissions reduction, environment sustainability, low land requirement, increasing employment, market size, local economic development, technical maturity, reasonableness for investment cost, potential for commercialization
9.	Hocine et al. (2018)	Investment cost, Operation and maintenance cost, Primary energy saving, Realization time, Sustainability of climate change, Job creation
10.	Kouaissah and Hocine (2020)	Investment costs, Operating and maintenance costs, Primary energy saving, Sustainability of climate change, Job creation
11.	Mourmouris and Potolias (2013)	Economic benefits for the region, Creation of development, Environmental quality, Visual impact, Impacts on flora/fauna, CO2, SO2, NOx emissions, Social acceptability, Land use, Employment in the energy sector, Efficiency, Safety, Availability,
12.	Sagbansua and Balo (2017)	output, rotor diameter, capacity factor, nominal wind speed, hub height, cut out, state support, total cost, electromagnetic, noise, spare parts, service, and reliability
13.	Malkawi et al. (2017)	Levelized capital cost, Levelized cost of electricity, Energy payback ratio, Life cycle emissions, Water consumption, Land usage, Social acceptance, Permanent jobs created, Accident fatality, Accident impact assessment, Average efficiency, Dispatchable or not, Capacity factor

S.No.	Authors	Sub-Criteria
14.	Lee et al. (2012)	System conversion rate, Wind turbine operation, Utilization rate, Construction reliability, Net present value (NPV), Capital costs, Operation and maintenance costs, Land use, Aesthetics, Noise and waste pollution, Ecological impact, Satisfaction level of supplier, Integration capability of system, R&D capability of supplier
15.	Shirgholami et al. (2016)	Rotor efficiency, Capacity factor, Availability, Capital cost, Operation & maintenance cost, Political stability, Impact on wildlife, Delivery, Noise, Visual impact, Satisfaction level,
16.	Arce et al. (2015)	Efficiency, Exergy efficiency, Primary energy ratio, Maturity, Investment costs, Operational and maintenance costs, Fuel costs, Gas emissions, Human/technological impact
17.	Bojesen et al. (2015)	Production potential, Potential stock of alternative biomass, Distance to heat plant and CHPs, Distance to natural gas grid, Visibility, Sensitivity to noise and smell, Population density, Job creation potential
18.	Neofytou et al. (2020)	Public awareness and acceptance, Carbon-lock in, Human capital, Ease of doing business, Infrastructure and innovation, Political will & compliance with EU energy policy, Financial market sector soundness Regulatory indicator for sustainable energy rise
19.	Mirjat et al. (2017)	Feasibility, Risk, Reliability, Preparation Phase, Implementation Phase, Continuity and Predictability of Performance Local Technical Knowhow, Pollutant Emission, Land Requirements, Need of Waste Disposal, Compatibility with the Energy Policy Objectives, Political Acceptance, Social Acceptance Labor Impact, Implementation Cost, Availability of Funds, Economic Value
20.	Tasri and Susilawati (2016)	wind speed, topography, access to grid, access to road, construction cost, cost of land, operating cost, and environmental concerns
21.	Chaouachi et al. (2017),	Capacity factor, Congestion, Balancing, Volatility, Correlation, Investment
22.	Shen et al. (2010)	Energy price stability, Reasonableness for investment cost, Carbon emissions reduction, Local economic development, Security for energy supply, SOx and NOx emissions reductions, Increasing employment Stability for energy generation, Environmental sustainability, Technical maturity, Low land requirement Potential for commercialization, Market size, Low energy prices
23.	Heo et al. (2010)	Superiority of technology, Completeness of technology, Reliability of technology and operation, Possibility of acquiring original technology, Domestic market size and competitiveness, Global market size and

S.No.	Authors	Sub-Criteria
		competitiveness, Competitive power of domestic technology, Economic C1. Supply capability Economic feasibility, Supply durability, Reduction of greenhouse gas and pollutants, Requirement of resources, Acceptability of local residents, Contribution to achieve dissemination goal, Spillover effect Linkage with R&D program, Influence of existing social system
24.	Guleria and Bajaj (2020)	Public acceptance, Protection law, Legal and Regulation compliance, Availability of Water, Environment Aspect Water Storage, Environment Affect, Distance from Major Road, Distance from Power Network, Potential Demand, Construction Cost, Operation and Management Cost, New Feeder Cost, Land Use, Ecology
25.	Kannan et al. (2020)	Initial investment, Construction cost, Maintenance cost, Solar radiation intensity, Wind intensity, Distance to sub-station, Land availability, Distance to catchment basins, Protected areas, Ecosystem destruction, Social acceptance, Job creation, Distance to farmlands, Economic risk, Investment risk, Time delay risk,
26.	Ali et al. (2020)	Net present cost, investment cost, operating cost, cost of energy, efficiency, reliability, Technology maturity, Force majeure risk, Noise, Effect on ecosystem, Social acceptance, Social benefits, Political and legal risks,
27.	Sitorus and Brito-Parada (2020)	Capacity factor, Water consumption, GHG emissions, Area requirement, Levelized energy cost, Prospective jobs
28.	Waewsak et al. (2020)	GHI, Wind speed, Slope, Elevation, 33 kv transmission lines, Roads, Floodplains, Airports, Waterbodies, Forests, Important places,
29.	Ramezanzade et al.(2020)	Initial cost, Total net present cost, Penalty cost, Cost of energy, Renewable capacity, Renewable fraction, Excess electricity, CO2 emission, Number of renewable and storage technology,
30.	Özkan et al. (2015)	Capital cost, Operation & Maintenance cost, Energy cost, Storage cost, Lifetime, Maturity, Storage capacity, Discharge ratio, Efficiency, Density, Political acceptance, Social acceptance, Ecological impacts, Human health impacts, Green land impacts, Toxic impacts,
31.	Alao et al. (2020)	Carbon di oxide emission, Electricity generation potential, Investment cost, Technology maturity, Operation & Maintenance cost, Cost of energy,

S.No.	Authors	Sub-Criteria
32.	Ali et al. (2020)	Social benefits, generation cost, GHG emission, installed capacity, land use, life expectancy, water consumption, efficiency,
33.	Babatunde et al. (2019)	Number of jobs created, Balanced development across regions, Technology maturity, Production capacity, Land requirement, Emission reduction, Investment cost, Affordability of cost of energy
34.	Veysel Çoban (2020)	solar irradiance, plant location, operation management, maintenance and repair, system technology, technical infrastructure, contingency plan, energy policy, energy price change, permission, power demand, project finance, value change of money
35.	Garni et al. (2016)	Resource availability, Efficiency, Ease of decentralization, Technology maturity, Energy system safety, Capital cost, O&M cost, Energy Cost, National economic development, Land requirement, Impact on emission level, Job creation, Maintain energy leading position, Socio-political acceptance
36.	Ghenai et al. (2020)	Area intensity, capacity factor, capital intensity (construction), lifetime, energy intensity(fuel), delivered cost of energy, energy intensity (construction), CO2 intensity (construction), capital intensity (fuel), growth rate, material intensity, system efficiency, CO2 intensity (fuel), current installed capacity,
37.	Adar et al. (2017)	Total annual cost, Investment cost, Payback period, Source state, Efficiency, Continuity, Air pollution, Noise pollution, Safety, Foot print,
38.	Kahraman et al. (2010)	Feasibility, Local technical know-how, Reliability, Continuity and predictability of performance, Risk, The duration of implementation phase, The duration of preparation phase, Need of waste disposal, Pollutant emission, Land requirement, Availability of funds, Economic value, Implementation cost, Political acceptance, Social acceptance, Compatibility with the national energy policy objectives, Labour impact,
39.	Jha and Puppala (2017),	CO2 emission, SO2 emission, NOx emission, Land requirement, Turnkey investment, Current energy cost, Future potential energy cost, Energy input-output ratio, Design period, Capacity factor, Water requirement,
40.	Streimikiene et al. (2016)	Economic efficiency, Production cost (energy price), Technology's competitiveness, Value of the technological complex, Technology's rated capacity, Technology's innovativeness, Technology's reliability (risk of accidents), Durability of technology, Contribution of renewable energy resources to the total energy

S.No.	Authors	Sub-Criteria
		balance, Effect on climate change and pollution cuts, Compliance with local natural conditions, Treatment of waste, Public acceptance/opinion, Influence on sustainable development of society (education, science, culture), Influence on social welfare (jobs, economic security), Compliance with international obligations, Legal regulation of activities, Support of government institutions, political organizations, Technology's autonomy, Influence on sustainable development of energy,
41.	Vasileiou et al. (2017)	Wind velocity, Wave energy potential, Shipping density, Distance from shore, Distance from ports, Water depth, Population served, Connection to local electrical grid
42.	Wu et al. (2019)	Investment cost, Operation and maintenance cost, LCOE, Payback period, Ecological impacts, Carbon dioxide emission reduction, Land occupation, PM 2.5 emission reduction, Power quality improvement, Poverty alleviation promotion, Residential satisfaction, Technology innovative promotions, 4
43.	Haddad et al. (2017)	Technology maturity, Energy systems safety, Reliability, Energy production capacity, Investment cost, Operation and maintenance, Life service, Payback period, Impact on ecosystem, Potential for reduction of greenhouse gases, Social benefits, Social acceptability, Political acceptance,
44.	Yuan et al. (2020)	Investment cost, Operation and maintenance cost, Reduction in carbon emissions, Loss of energy supply, Environmental benefits, Purchased external energy cost, Comprehensive energy utilization
45.	Zhang et al. (2019)	Technology efficiency, Technology maturity, Land requirement, GHG emission reduction, Impact on environment, Job creation, Investment cost, Operation and maintenance cost,
46.	Zhou et al. (2020)	Construction cost, Payback period, Possibility of capacity expansion in near future, Impact on the power grid, Public recognition, Government support, Direct normal irradiance, Annual average temperature
47.	Büyüközkan and Güleryüz (2016)	Efficiency, Reliability, Resource availability, Capacity of investment, Technology maturity, Technological innovation, Investment cost, Operation and maintenance cost, R&D Cost, Return on investment, Production cost, Foreign dependency, Compatibility with political legislative situation, Compatibility with national energy policy objectives, Public policy and financial support, Social benefits, Social acceptability, Job creation, Greenhouse emission, Land use/requirement, Impact on ecosystem

S.No.	Authors	Sub-Criteria
48.	Atmaca and Basar (2012)	Efficiency coefficient, Availability, Capacity, Reserve to production ratio, Capital costs, Operation costs, External costs, Operation and maintenance costs, Accident, Land requirement, Radioactivity, Employment opportunities, Social acceptance
49.	Chen and Pang (2010)	cost, quality, relational alignment, strategic alignment, technological alignment, facility, and design advantages
50.	Giner-Santonja et al. (2012)	Implementation cost, Energy cost, Resource consumption, Workers health, Waste water management, Waste management, Air emission management.
51.	Kabak and Dağdeviren (2014)	Evaluation of native resources, Social resistance, Preservation of the environment, Instability of energy resource, Development of related industry, Unsuitability of potential site, Orientation to international regulations, Technological immaturity, Decreasing dependency of importation of fuel, Challenges regarding investments, Developing new energy resources, Dependency on foreign technology, Job creation, Ecological damage, Decrease in energy prices, Land use, Investment cost, Operation cost, Maintenance cost
52.	Kang et al. (2011)	Wind resources, Wind speed distribution, Renewable energy policies, Continuous operation, Compatibility with environmental policy, Wind turbine, Wind generator, Connection and foundation, Repair and maintenance cost, Operating cost, Windstorm, Technical support issues, Various environmental issues, Business operating risks,
53.	Pasaoglu et al. (2018),	Supply Reliability, Investment Costs, Contribution to National Economy, Environmental Impacts under Normal Conditions, Raw Material Costs, Raw Material Supply Continuity, Reliability of Meeting the Peak Demand, National/Foreign Finance Availability and Financial Costs, Completeness and Applicability of the Existing Legal Propositions, Raw Material Dependency to Abroad, Raw Material Price Stability, Compliance Level with Long-and Short-term Government Policies, Operating Costs, Knowhow Dependency to Abroad, Environmental Impacts in Emergency Conditions, Maintenance Costs, Contribution to Local Economy, Construction Time, Transmissions Availability, Waste Disposal Costs, Compliance with International Environmental Law, Decommissioning Costs

S.No.	Authors	Sub-Criteria
54.	Yeh and Huang (2014),	Secure set-up distance, Establishment of complete supply chain, Power transmission safety, Energy subsidy policy, Spare parts stock, Planning of land near the road, Regular wind farm testing, Regulation for energy safety, Optimal wind power benefits, Ecological restoration control, Reasonable power pricing program, Energy conversion and carbon reduction effect, Visual coordination, Environmental ecology monitoring, Local benefits,
55.	Büyüközkan and Güleryüz (2017),	Investment cost, Operation and maintenance cost, Technology/know how cost, Return on investment, Revenue/financial structure, Efficiency, Reliability, Resource availability, Installed capacity, Technology maturity innovation, Social benefits, Acceptability, Job creation, Greenhouse emissions, Land use/requirement, Impact on ecosystem, Foreign dependency, Compatibility with legal compliance, Compatibility with national energy policy objectives, Legal incentives,
56.	Şengül et al. (2015)	Investment cost, Operation and maintenance cost, Fuel cost, Electric cost, Net present value, Payback period, Service life, Equivalent annual cost, Efficiency, Exergy efficiency, Primary energy ratio, Safety Reliability, Maturity, NOx emission, CO2 emission, CO emission, SO2 emission, Particles emission Non-methane volatile organic compounds, Land use, Social acceptability, Job creation, Social benefits
57.	Boran et al. (2013)	Total generation cost, Efficiency, CO2 emission, Acceptability
58.	Kurtuluş Boran (2017)	Installation cost, Efficiency, Emission of CO2, Electricity cost, Social acceptance
59.	Brand and Missaoui (2014)	Specific generation cost, Net present value of total cost, Local manufacturing share, Average jobs created, Social acceptance, Total natural gas consumption, Aptitude to respond to peak load events, Contribution to energy independency, CO2 emission, NOx emission, SO2 emission, Fine dust emission, Nuclear emission
60.	Papapostolou et al. (2017)	Static efficiency, Political acceptability, Flexibility, Applicability
61.	Kaya and Kahraman (2011)	Exergy efficiency, Efficiency, CO_2 emission, NO_x emission, Land use, Investment cost, Operation & maintenance cost, Job creation, and Social acceptability
62.	Gumus et al. (2016)	Employment, Total GHG, Income, Water withdrawal, Government tax, Energy use, Import, Business profit, Land footprint

Appendix-IV

BRIEF DEFINITION OF SELECTED INDICATORS

Category/Indicator	**Explanation**
Economic (EC)	
Capital Cost/ Investment Cost	The total amount of money required to install a power plant.
Operation & Maintenance Cost	It consists of employees' wages, costs of products and equipment, operation costs, energy expenses, the maintenance cost of equipment.
Research & Development Cost	The cost allocated in the process of development of new goods and services that fulfills the needs of the company and consumer in a better way than the existing resources.
Payback period	The time period required for the return of the overall investment of the project.
Levelized Cost of Electricity (electricity cost per unit)	This criterion refers to per unit energy generation cost. It represents Rs./kWh or $/kWh.
Useful/operational Life	The expected lifetime of a power plant, the time period in between installation and decommissioning.
Fuel Cost	The number of funds spent on the processes of mining, extraction, fuel processing, and transportation cost of the fuel. It is expressed in Rs./liter or $/liter.
Market Maturity	Market maturity means a state of equilibrium when there is an absence of significant growth or a lack of innovation. In the situation of market maturity, supply matches the demand and the price is decided by those market forces.
Site Advantage	A suitable or appropriate site is always advantageous in terms of the cost of land and taxes, transmission facilities, transport facilities, pollution, and noise, etc.
Availability of Funds/Incentives	The economic support of the government and funds are given by national and international agencies.
Future Potential Energy Cost	It is the future cost of technology considering the development, potential, exploitation, and policy support to the particular energy resource.
Technology Cost	The technology cost means the cost incurred in the adoption or implementation of the particular technology.

Category/Indicator	**Explanation**
Technical (TE)	
Technology Maturity	It shows the easy availability of technology at the local, national, and international markets.
Efficiency	It is the ratio of final obtained energy and the overall available energy.
Capacity Factor	It is the ratio of actual energy output in a given time period to the theoretical energy output.
Reliability	A system continuously performing well which means it has higher reliability. In general words, reliability means the probability of failure.
Deployment Time	The time required to install a power plant until it starts power production.
Expert Human Resource	Expert human resource means the availability of expert human resource persons for easy and smooth handling of the technology.
Distribution grid availability	Easy availability of grid or transmission facilities near energy resources would be helpful in maximizing the exploitation of energy potential and in minimization of transmission & distribution losses.
Safety of energy system	The variable indicates the safety and security of the system.
Ease of decentralization	The sub-factors indicate the level of difficulty of the decentralization of the system.
Safety in covering peak demand	The system should be safe and secure during the supply of peak power load demand.
Energy input-output ratio	It is termed the energy ratio or energy input-output ratio. The power taken from the grid is considered as the energy input, while the power supplied to the grid is considered as the output power. In the case of solar energy, the input power is required by the solar photovoltaic modules for sun tracking and automatic cleaning by the robots.
Exergy efficiency	It is defined as the ratio of the thermal efficiency of an actual system compared to an idealized or reversible version of the system for a heat engine.
Technical Feasibility	It is the process of validating the technology assumptions, architecture, and design of a product or project.
Local technical knowledge	A group of local experts should have a substantial ability to complete complex tasks.

Category/Indicator	Explanation
Social (SO)	
Social benefits	Social benefits represent the development of the social community and region by introducing an energy project. Social benefits in the form of job creations, local income, and social welfare aspects.
Job creation	It includes direct or indirect jobs created during the life cycle (install, operations, and decommissioning) of an energy source.
Social acceptance	It is related to the opinions of acceptance and rejection of local social groups, authorities, and stakeholders about the energy system.
Impact on human health	It is a qualitative assessment based on the emission of harmful products. It is analyzed based on the problems of cancer, skin diseases, and respiratory.
Local manufacturing share	To promote the local manufacturers the established or matured organization should use the products or parts made from the local manufacturer. An increase in local manufacturing share will be beneficial in terms of easy and quick availability of products by eliminating the transportation and holding wages.
Feasibility	A feasibility study represents the success ratio of the project.
Worker Safety	It includes the safety and security of the working staff. Therefore, they will delicately work for the development of the organization.
Environmental (EN)	
Land requirement	It considers the requirement of land (km^2) to install an energy source (GW).
Pollutant Emission	It considers the emission of all the harmful products in the atmosphere such as greenhouse gases, solid and liquid waste.
Impact on ecosystem	It mainly covers ground contamination, land use, water consumption, liquid and solid waste, visual and noise pollution.
Disturbance of ecological balance	Ecological disturbance is an event or force, of non-biological or biological origin, that brings about mortality to organisms and changes in their spatial patterning in the ecosystems they inhabit.
Need for waste disposal	Waste disposal is the method that is employed to destroy or recycle unused, old, or unwanted domestic, agricultural, medical or industrial waste. Generally, landfills, incineration, waste compaction, composting, and vermicomposting are waste disposal methods.
Noise	Noise is the high-frequency propagation of sound which

Category/Indicator	Explanation
	impacts the activity of human or animal life, most of them harmful to a degree.
Visual amenity	Visual amenity relates to the way in which people visually experience the surrounding landscape.
Climate change	It is a phenomenon that will happen due to the harmful emission in the environment by the power plants.
Severe accidents (Fatalities)	The variable defines the frequency of severe accidents that occurred in the past or fatalities involved in the previous years.
Legislations	Legislation is a set of laws and regulations which aim at protecting the environment from harmful actions.
Political (PO)	
Political acceptance	Political acceptance is the government support given in policies or technologies developed by its compatibility in administration, legislation, and political situations.
Foreign dependency	It mainly analyzes the dependency of fuel imports from foreign countries.
National energy security	National energy security is the association between national security and the availability of natural resources for energy consumption.
National economic benefits	National economic benefits such as an expansion of employment opportunities, a reduction in the trade deficit, promoting technological improvements, and the falling price of renewable energy sources are given by the renewable energy sources.
Compatibility with national energy policy	Higher compatibility with national energy policy will get higher support from government and organizational institutes.
Maintain leading position as a supplier	The variable indicates that the country should hold the leading position in the particular technology development, supply, adoption, and improvements.
Fuel reserve years	Fuel reserve year is defined as the duration of the time period until fossil fuels are completely depleted on the earth.
Net import as a percentage of consumption	The term is the ratio of the quantity of imported fuel to the total fuel consumed. The country's concerns should be on the minimization of this ratio.

Category/Indicator	Explanation
Quality (QU)	
Sustainability	Sustainable energy is the energy produced and used in such a way that it "meets the needs of the present without compromising the ability of future generations to meet their own needs."
Durability	The factor defines the exhaustible or inexhaustible nature of energy sources.
Distance to user	The factor defines the distance between the power source and load center or user. From the economic perspective, the factor should have a minimum value.
Natural (NA)	
Geological and topological conditions	The geological and topological condition examines the natural potential of ground-based sites such as rock quality, tectonic situation, groundwater situation, and surface morphology.
Weather conditions	Weather conditions are an important factor because it affects the consumers, electricity companies, and the government by disrupting the electricity supply chain, transmission, and distribution system.
Hydrological conditions	Hydrological condition is the provisional criteria for the design of various water control structures such as dams and storage reservoirs, storm sewers, bridges, and irrigation systems.
Risk (RI)	
Political risk	Political risk indicates the commencement of risk arises due to a change in the government body of a country and therefore poses a risk to the investors who have invested in the energy sector.
Environmental risk	Environmental risk concerns the damage of the environment through the emission of greenhouse gas emission, deforestation, mining operations, disposal of untreated industrial sewage into water bodies, etc.
Economic risk	Economic risk can be due to rising prices of raw materials, exchange rate fluctuations, a shift in government policies or regulations, political instability etc.
Social risk	The social risk includes the actions that affect the lower communities around them such as labor issues, human rights violations within the workforce, and corruption by company officials.
Time delay risk	The variable includes the losses that occur due to time overrun either beyond the completion date specified in a contract.
Food safety risk	The food safety risk is a qualitative indicator used for the

Category/Indicator	Explanation
	qualitative assessment of the risk that using biomass fuels will put stress on food supply safety and food prices.
Usability (US)	
For secondary power generation (Reuse)	Selected waste and by-products with recoverable calorific value can be used as the fuel for secondary power generation such as second-generation biofuels convert cellulose to liquid fuel.
For other applications (Recycle)	The variable indicates the useful application of waste or byproducts of power plants such as the waste product of coal power plant is used in bricks making. Similarly, in nuclear power plants, valuable enriched uranium is obtained as a byproduct.
Direct disposable (Disposability)	The factor qualitatively defines the level of hazardousness of waste or by-products of power plants.
Decommission (DE)	
Salvage value	Salvage value is an estimated value of an asset at the end of its useful or operational life.
Usability of plant land area	An application or value of land area after decommissioning the system.
Energy required	The amount of energy required to decommission the system.
Manpower required	The quantity of manpower required to decommission the power project.
Flexibility (FL)	
In integration with another source	It shows the capability of energy sources to generate power with the integration of another source. It mainly considers increasing the availability of energy sources and the maximum utilization of available resources.
In running with alternative fuels	The capability of the system to run with the alternative fuel and to produce capacity power.
In increasing the installed capacity of the plant	The possibility of a system to increase the installed capacity of an already operating power plant.
In fulfilling the peak load demand	It considers the flexibility of power plants to respond to peak-load events or changes in demand variation.
To fulfil the demand variation	The system should have the ability to cover the fluctuations in the power demand. Fluctuating power supply can often cause power surges, spikes, and voltage fluctuations.

Category/Indicator	Explanation
Resource required (RR)	
Land	Land is considered an important resource because it carries the major economic share in the overall investment.
Water	Water is an essential resource therefore all kinds of power plants are installed near the water reservoirs.
Fuel/coal	Fuel is an essential element to operate power plants. It reacts with other substances so that it releases energy as heat energy or to be used for work.
Skilled manpower	An optimum number of skilled manpower is essentially required to complete a project, task, or goal within the given time.
Market (MA)	
Existence of stakeholder support	Stakeholder support is necessary for the successful implementation of a project. Stakeholder provides useful resources such as skills and knowledge required for the project's implementation.
Stability of sufficient market base	A sufficient stable market base of any technology has played an important role. It is the most important multiplier and effective engine in the development of technology.
Influence of stakeholder groups	Stakeholder influences the opinion of the public regarding the projects. To secure the support of stakeholders, it is important to inform the stakeholders about the projects in the interactive forums.
Consumer interest about technology	Consumer interest in technology can lead to easy adaptability, serviceability, development, and fine-tuning of technology with marketing programs.
Supply Security (SS)	
Aptitude to respond to peak load events	To operate the system safely and securely the system should have the ability to fulfill the uncertain peak power fluctuations.
Total fuel consumption	The variable indicates the amount of total fuel consumption in a power plant to generate the rated power capacity.
Contribution to energy independency	The objective of the indicator is to minimize the dependency on imported fuel in the overall mixed energy scenario of the country. For the variable, subjective weights are collected using the linguistic scale.
Security of plants/grid	Electric grid security refers to the activities that utilities, regulators, and other stakeholders play in securing the national electricity grid.

Category/Indicator	Explanation
Emission (EM)	
CO_2 emission	Carbon dioxide (CO_2) emissions are the primary driver of global climate change. It is mainly released into the earth's atmosphere by the burning of carbon-containing fuels and the decay of wood and other plant matter.
SO_2 emission	Sulfur dioxide (SO_2) is a major air pollutant and has a significant impact on human health. Primarily SO_2 emissions are due to the burning of high-sulfur content coals and heating oils in power plants, followed by the industrial boilers.
NOx emission	Nitrogen oxides (NOx) emission has a harmful direct effect on human health and indirect effects on agriculture crops and ecosystems. Gasoline and diesel engines are the main sources of NOx emissions.
Fine dust particle emission	Particles less than 2.5 micrometers in diameter, also known as fine particles or PM 2.5, pose the greatest risk to health. Power plants, industry, and households are the major human responsible fine particle production sources.
Particulate matters	Particulate matter emission is a complex mixture of small liquid droplets and solid particulates suspended in the air. Particulate matter can originate from natural (volcanoes, fires, dust storms) or manmade sources (industrial. Combustion, vehicle emissions).
Radioactive waste	Radioactive waste is a type of hazardous waste that contains radioactive material. Radioactive waste is a result of many activities, including nuclear power generation, nuclear weapons, nuclear medicines, nuclear research, and rare-earth mining.

Appendix-V

SURVEY INSTRUMENT ON SUSTAINABLE ENERGY INDICATORS

(A Construct for Sustainable Energy Sources)

Thank you for giving your consent to participate in this survey. Your participation will be critical in this scientific study, conducted by researchers at BITS Pilani, which intends to the identification of sustainability indicators and for evaluation of most sustainable energy sources. Your individual information and organizational information will be highly confidential and will not be shared with anyone. Only aggregate or average data will be used for research and publication purposes.

Primary Contributor Information:

Name:
…………………………………………………………………………..…………………….……

First Name Middle Name Last Name

Gender:………

Position: …………………………………………………………..……………………….…….……

Profession: ………………………………………………………………………………………

Personal Demographics:

Firm/Company Name: …………………………………………………………………

What entity do you work for? Click all that apply if there are multiple respondents

Utility (public) [ ]
Regulatory body [ ]
Government body [ ]
Utility (private) [ ]
Private Sector [ ]

Your education level (completed) …………….…………………………………………

How many years of business/job experience do you have? ……………………….......

In which country your company/organization based? ……………………………

In which other countries your company are mainly activated? ……………………………

Is your company/organization also activated or invested in Energy sector? Yes[ ], No[ ]

If Yes, In which source your company is invested ………………………………………

INTRODUCTION

Energy is a crucial factor in the socio-economic development of societies. Energy consumption in India rises very fast in the last few decades due to industrialization and urbanization, growing population, or an increase in living standards. It will further increase in the future; according to predictions in the year 2030, it will reach double than energy consumption in the year 2010. At the present, significant power is produced from conventional power plants but due to their depletion and environmental effects, we have to search for the most sustainable energy sources. Sustainable energy is the "Energy that meets the need of the present generation without compromising the ability of future generations to meet their own energy needs." For most sustainable energy sources, we selected nine different energy sources which are the leading source in the present energy generation scenario i.e. thermal energy (coal), large hydro, gas, wind, nuclear, biomass, solar, fuel cell, and geothermal energy sources. To obtain the most sustainable energy source, selected 93 indicators subjected to 15 categories from the literature review and expert discussion.

Questionnaires

Q.1	**Mark the suitability of Economic indicators in Indian condition, for evaluation of most sustainable energy source.**	**Highly Suitable**	**Suitable**	**Moderate Suitable**	**Less Suitable**	**Not Suitable**
i	Capital Cost/ Investment Cost	5	4	3	2	1
ii	Operation & Maintenance Cost	5	4	3	2	1
iii	Research & Development Cost	5	4	3	2	1
iv	Payback period	5	4	3	2	1
v	Levelized Cost of Electricity (electricity cost per unit)	5	4	3	2	1
vi	Useful/operational Life	5	4	3	2	1
vii	Fuel Cost	5	4	3	2	1
viii	Market Maturity	5	4	3	2	1
ix	Site Advantage	5	4	3	2	1
x	Availability of Funds/Incentives	5	4	3	2	1
xi	Future Potential Energy Cost	5	4	3	2	1
xii	Technology Cost	5	4	3	2	1

Q.2	**Mark the suitability of Technical indicators in Indian condition, for evaluation of most sustainable energy source.**	**Highly Suitable**	**Suitable**	**Moderate Suitable**	**Less Suitable**	**Not Suitable**
i	Technology Maturity	5	4	3	2	1
ii	Efficiency	5	4	3	2	1
iii	Reliability	5	4	3	2	1
iv	Deployment Time	5	4	3	2	1
v	Expert Human Resource	5	4	3	2	1
vi	Distribution grid availability	5	4	3	2	1
vii	Safety of energy system	5	4	3	2	1
viii	Ease of decentralization	5	4	3	2	1
ix	Safety in covering peak demand	5	4	3	2	1
x	Energy input-output ratio	5	4	3	2	1
xi	Exergy efficiency	5	4	3	2	1
xii	Risk	5	4	3	2	1
xiii	Technical Feasibility	5	4	3	2	1
xiv	Local technical knowledge	5	4	3	2	1

Appendix-VI

ADVANTAGES AND LIMITATIONS OF DIFFERENT MCDM APPROACHES

Approach	Advantages	Limitations
AHP (Analytic Hierarchy Process)	• Provides a simple and very flexible model for a given problem • AHP provides an easy applicable decision-making methodology that assist the decision maker to precisely decide the judgments. • AHP relies on the judgments if experts from different backgrounds; so the main focus or the problem can be evaluated easily from different aspects. • Decision maker can analyze the elasticity of the final decision by applying the sensitivity analyzes. • It is possible to measure the consistency of decision maker 's judgments. • Computer software help decision makers to apply AHP fast and precisely	• Not always a solution to the linear equations • The computational requirement is tremendous even for a small problem. • AHP allows only triangular fuzzy • numbers to be used. • AHP is based on both probability and possibility measures. • AHP has a subjective nature of the modeling process is a constraint of AHP. That means that methodology cannot guarantee the decisions as definitely true. • When the number of the levels in the hierarchy increase, the number of pair comparisons also increase, so that to build the AHP model takes much more time and effort.
TOPSIS (Technique for Order Preferences by Similarity to Ideal Solutions)	• Has a simple process • Easy to use and program • The number of steps remains the same regardless of the number of attributes	• Its use of Euclidean Distance does not consider the correlation of attributes • Difficult to weight and keep consistency of judgment
VIKOR (Multicriteria Optimization and Compromise Solution)	• Usable for situation with many alternatives and attributes • Appropriate to utilize when quantitative or objective data are offered • Ability to immediately recognize the proper alternative	• Lack provision to weight calculation and check consistency
PROMETHEE (Preference Ranking for Organization Method for Enrichment Evaluation)	• Easy to use • Does not require assumption that criteria are proportionate	• Does not provide a clear method by which to assign weights
WSM (Weighted Sum Method)	• Easy to understand and use	• Attribute weights are assigned arbitrarily • Difficult to adopt in case of numerous criteria • Common numerical scaling is used to calculate the final score
WPM (Weighted Product Method)	• Can eliminate any element to be measured and utilize proportional values instead of real ones	• Do not provide any solution with equal decision matrix weight

CALCULATION PROCEDURE OF BEST-WORST METHOD (BWM)

Step – I, Determine the set of decision criteria

Step – II, Determine the best i.e. most desirable or most important criteria and the worst i.e. least desirable or least important criteria

Step – III, Determine the preference of the best criterion over all the other criteria using a number between 1 and 9.

Step – IV, Determine the preference of all the criteria over the worst criterion using a number between 1 and 9.

Step – V, Find the optimal weights

$Min\ \xi_L$ Subject to

$$\left|W_b - a_{Bj}W_j\right| \leq \xi_L \quad for\ all\ value\ of\ j \qquad \text{(Eq. A.1)}$$

$$\left|W_j - a_{jW}W_W\right| \leq \xi_L \quad for\ all\ value\ of\ j \qquad \text{(Eq. A.2)}$$

$$\sum W_j = 1 \qquad \text{(Eq. A.3)}$$

$$W_j \geq 0, \quad for\ all\ value\ of\ j$$

where, W_b is the weight of best criteria, a_{Bj} is the preference score of best criteria with respect to each other criteria, W_W is the weight of worst criterion.

CALCULATION PROCEDURE OF FUZZY WASPAS

It is a unique combination of two well-known MCDM approaches, WSM and WPM.

$$A_i^{WSM} = \sum_{j=1}^{n} W_j . x_{ij} \quad \text{(Eq. B.1)}$$

$$A_i^{WPM} = \prod_{j=1}^{n} x_{ij}^{Wi} \quad \text{(Eq. B.2)}$$

$$Q_i = \lambda Q_i^1 + (1-\lambda) Q_i^2 \quad \text{(Eq. B.3)}$$

$$Q_i^1 = WSM, Q_i^2 = WPM, 0 \leq \lambda \leq 1, and\ Q_i = \text{Joint generalized criterion of WASPAS}$$

Based on the joint generalized criterion of WASPAS, rank will be given. A higher value will be given higher rank.

List of Publications

Journal Publications

1. S.K. Saraswat, A.K. Digalwar, Empirical investigation and validation of sustainability indicators for the assessment of energy sources in India, Renewable and Sustainable Energy Reviews 145 (2021) 111156. https://doi.org/10.1016/j.rser.2021.111156. (SCI Impact factor: 14.982, H index: 295)
2. S.K. Saraswat, A.K. Digalwar, Evaluation of energy alternatives for sustainable development of energy sector in India: An integrated Shannon' s entropy fuzzy multi-criteria decision approach, Renewable Energy. 171 (2021) 58–74. https://doi.org/10.1016/j.renene.2021.02.068. (SCI Impact factor: 8.001, H index: 191)
3. S.K. Saraswat, A.K. Digalwar, S.S. Yadav, G. Kumar, MCDM and GIS based modelling technique for assessment of solar and wind farm locations in India, Renewable Energy. 169 (2021) 865–884. https://doi.org/10.1016/j.renene.2021.01.056. (SCI Impact factor: 8.001, H index: 191)
4. S.K. Saraswat, A.K. Digalwar and S. S. Yadav, Sustainability Assessment of Renewable and Conventional Energy Sources in India Using Fuzzy Integrated AHP-WASPAS Approach, Journal of Multiple-Valued Logic and Soft Computing. 37 (2021) 335-362. (SCI Impact factor: 0.861, H index: 24)
5. S.K. Saraswat, A.K. Digalwar, Evaluation of energy sources based on sustainability factors using integrated fuzzy MCDM approach, International Journal of Energy Sector Management. 15 (2020) 246–266. https://doi.org/10.1108/IJESM-07-2020-0001. (Scopus indexed, H index: 22)

Conference Publications

1. Santosh Saraswat, and Abhijeet Digalwar, Identification of Sustainable Energy Source for Indian Climatic Conditions: A MCDM approach, in proceedings of 2nd ISEES International Conference on Sustainable Energy and Environmental Challenges (SEEC-2018), Indian Institute of Science, Bangalore, India, 31st December 2017 – 3rd January 2018.
2. S. K. Saraswat, Abhijeet Digalwar, and S. S. Yadav, Evaluation of Sustainable Energy Sources in India: A Fuzzy AHP Approach, presented in 12th Annual ISDSI Conference held at SPJIMR, Mumbai from 27th to 30th December 2018.
3. S. K. Saraswat, Abhijeet Digalwar, and S. S. Yadav, Applications of Fuzzy AHP Approach for Evaluation of Sustainable Energy Sources in India, in the proceedings of International Conference and 22nd Annual convention of Vijnana Parishad of India on Advances in Operation Research, Statistics and Mathematics (AOSM 2019) organized by Department of Mathematics, BITS-Pilani, Pilani Campus during December 28-30, 2019.

4. S. K. Saraswat, Abhijeet Digalwar, and S. S. Yadav, Application of Hybrid MCDM Approach for Selection of Sustainable Energy Sources in India, in proceedings of 1st International Conference on Mathematical Modeling, Computational Intelligence Techniques and Renewable Energy (MMCITRE-2020) organized during February 21-23, 2020 conducted by Department of Mathematics, Pandit Deendayal Petroleum University (PDPU), Gandhinagar, Gujarat, India.
5. S. K. Saraswat, Abhijeet Digalwar, and S. S. Yadav, Development of Assessment Model for Selection of Sustainable Energy Sources in India: Hybrid Fuzzy MCDM approach, presented at International Conference on Intelligent and Fuzzy Systems organized by Industrial Engineering Department of Istanbul Technical University in July 21-23, 2020.

Book Chapters

1. S.K. Saraswat, A.K. Digalwar, S.S. Yadav, Application of fuzzy AHP approach for evaluation of Sustainable energy sources in India, in: R. Kulshrestha, C. Shekhar, M. Jain, S.R. Chakravarthy (Eds.), Math. Model. Comput. Real-Time Probl. Interdiscip. Approach, First, CRC Press, 2021: pp. 145–158. https://doi.org/https://doi.org/10.1201/9781003055037.
2. S.K. Saraswat, A. Digalwar, S.S. Yadav, Development of Assessment Model for Selection of Sustainable Energy Source in India: Hybrid Fuzzy MCDM Approach, Springer International Publishing, 2021. https://doi.org/10.1007/978-3-030-51156-2_75.

Working Papers

1. S. K. Saraswat, Abhijeet Digalwar, and S. S. Yadav, Assessment of solar and wind energy potential in India: A framework for integrating geographical, theoretical, technical, economic, and environmental criteria for sustainability analysis (under-review).
2. S. K. Saraswat, and Abhijeet Digalwar, Analysis of multi-renewable energy potential sites in India using spatial and temporal characteristics: A GIS and AHP based approach (under preparation).

Brief Biography of Candidate, Supervisor, and Co-Supervisor

About the author (Santosh Kumar Saraswat)

Santosh Kumar Saraswat is a Ph.D. candidate in the Department of Mechanical Engineering at Birla Institute of Technology and Science, Pilani, Rajasthan, INDIA. He is pursuing his Ph.D. in the area of Application of Decision Making in the Renewable and Sustainable Energy Sector from BITS Pilani, India. He has published more than 15 research papers in National and International journals and conferences. His teaching and research interests are primarily in the field of decision making, renewable and sustainable energy.

About the Supervisor (Prof. Abhijeet Digalwar)

Dr. Abhijeet Digalwar, at present working as a Associate Professor in the Mechanical Engineering Department of BITS Pilani, he has received Ph.D. in 2006 from BITS Pilani. Prior to that, he has completed his B.E. in Mechanical Engineering from Amravati University in 1995 and M.E. from BITS Pilani in 1998. He has over 24 years of teaching and research experience at graduate and post-graduate levels. He mainly teaches and conducts research in the area of sustainable development, decision sciences, manufacturing systems engineering, and management. He has published more than 100 research papers in national, and international journals and proceedings. He has edited two books, and two lab manuals and written various book chapters. Till date he has supervised 6 Ph.D. students (2 completed; 4 In Progress), more than 50 Postgraduate students, and 100+ undergraduate students for their project/ thesis and dissertation work. He has completed two funded projects and presently working on DST-YASH funded project.

About the Co-supervisor (Dr. Shyam Sunder Yadav)

Dr. Shyam Sunder Yadav is an Assistant Professor in the Department of Mechanical Engineering at BITS Pilani, Rajasthan, he received Ph.D. in 2015 from the Indian Institute of Science Bangalore (IISc Banglore). Prior to that, he completed his B. Tech. in Mechanical Engineering from the National Institute of Technology Kurukshetra in 2004 and M.E. from the Indian Institute of Science Bangalore in 2010. He has over 07 years of teaching and research experience at graduate and post-graduate levels, in addition, he has 04 of industry experience. He works in the areas of computational fluid dynamics of multiphase flows, two-phase electrohydrodynamic flows, high-performance scientific computing, etc., mostly with open-source codes for scientific computing. He has published more than 20 research papers in national, international journals and proceedings. He is also having two research projects for DST India and National Supercomputing Mission.