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Challenges and Opportunities of Distributed Renewable Power

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Preface

Currently, the world is moving through a global energy transition. Fossil fuels have supported improved living standards enormously since the industrial revolution. However, this has not only depleted the limited resources of fossil fuels rapidly but also caused a severe threat to future human survival on Earth, i.e., climate change. Emission from the use of fossil fuels is largely responsible for this possible impending disaster. Substituting fossil fuel-based power by renewable options and energy efficiency of power generation systems is a global need now. Distributed renewable power is considered to be one of the potential options to support this transition.

The International Society for Energy, Environment, and Sustainability (ISEES) was founded at the Indian Institute of Technology Kanpur (IIT Kanpur), India, in January 2014 to spread knowledge and awareness and to catalyse research activities in the fields of Energy, Environment, Sustainability, and Combustion. Society's goal is to contribute to the development of clean, affordable, and secure energy resources and a sustainable environment for society; spread knowledge in the areas mentioned above; and create awareness about the environmental challenges the world is facing today. The unique way adopted by ISEES was to break the conventional silos of specialisations (engineering, science, environment, agriculture, biotechnology, materials, and fuels, etc.) to tackle the problems related to energy, environment, and sustainability holistically. This is evident by the participation of experts from all fields to resolve these issues. The ISEES is involved in various activities, such as conducting workshops, seminars, and conferences, etc., in the domains of its interests. The society also recognises the outstanding works of young scientists, professionals, and engineers for their contributions by conferring awards in various categories.

The Seventh International Conference on "Sustainable Energy and Environmental Challenges" (VII-SEEC) was organised under the auspices of ISEES from December 16–18, 2022, at the Indian Institute of Technology, Banaras Hindu University, Varanasi (IIT-BHU), India. This conference provided a platform for discussions between eminent scientists and engineers from several countries, including India, the USA, Spain, Poland, Austria, the Czech Republic, and Korea. At this conference, eminent international speakers presented their views on energy, combustion, emissions, and alternative energy resources for sustainable development and a cleaner environment. The conference presented two high-voltage plenary talks by Dr. Ajay Kumar, Former Union Defense Secretary, GoI, and Dr. S. S. V. Ramakumar, Director (R&D), Indian Oil.

The conference included 29 technical sessions on energy and environmental sustainability topics, including two plenary talks, 15 keynote talks, 80 invited talks from prominent scientists, and 118 contributed talks by students and researchers. The conference included technical sessions on advanced engine technologies, air pollution monitoring, anaerobic digestion, combustion and flames, air pollution control, biodegradation of toxic chemicals, energy and exergy, desalination and wastewater treatment, environmental bioengineering, pollution and climate change: challenges and priorities, alternative transportation fuels and materials, emerging environmental contaminants, sustainable processing of biomass, human health and environmental sustainability, sprays and atomisation, solid waste: challenges and mitigation, solid waste management, sustainable food and agri biotechnology, modelling and simulations, renewable energy technologies, bioremediation, biofuels and biorefineries, engine emissions and control, cleaner technologies for pollution mitigation, microbial processes, energy and environment, coal and biomass gasification, and environmental challenges mitigation.

About 250+ participants and speakers attended the conference, where 14 ISEES books published by Springer, Singapore, under a dedicated series, "*Energy, Environment and Sustainability*", were released. This conference laid the roadmap for technology development, opportunities, and challenges in the Energy, Environment, and Sustainability domains. These topics are relevant for the country and the world in the present context. We acknowledge the support from various funding agencies and organisations for the successful conduct of the VII-SEEC, where the idea of these books germinated. We would therefore gratefully like to acknowledge IIT BHU (Special thanks to Prof. Akhilendra Pratap Singh); SERB, Government of India; Department of Scientific and Industrial Research (DSIR) (Special thanks to Dr. Vipin Shukla); and our publishing partner Springer (Special thanks to Swati Mehershi).

The editors would like to express their sincere gratitude to a large number of authors from all over the world for submitting their high-quality work on time and revising it appropriately at short notice. We want to express our special gratitude to our prolific reviewers: Dr. Sudip Simlandi, Dr. Prakash Ch. Roy, Dr. Santanu P. Dutta, Prof. V. S. Moholkar, Dr. Dudul Das, Dr. Hirakh Jyoti Das, Dr. Farrukh Khalid, Dr. Sandip Sarkar, Dr. Amitava Dutta, Dr. Avishek Ray, Dr. Susanta Roy, Dr. Debangshu Dey, Dr. Suddhasatwa Chakraborty, Dr. Nirmalendu Biswas, Dr. Biswajit Thakur, Dr. Arindam Dutta, Dr. Soupayan Mitra, Dr. Rajiv Ganguly, Dr. Partha Pratim Ray, Dr. Ratan Mondal, Dr. H. Lalhmingsanga, Dr. Pradip Mondal, Dr. Sudip Ghosh, Dr. Nilkanta Barman, Dr. Sudhir Murmu, and Dr. Kaustuv Pradhan who reviewed chapters of this monograph and provided their valuable suggestions to improve them.

This book explores some potential options for a possible successful energy transition using distributed renewable power. However, this transition is not expected to be very smooth specifically with respect to meeting the ever-increasing global energy demand without any compromise for affordability for all. To address this issue, a multi-disciplinary approach involving both technology and policies is required. In this book, several aspects of current technologies with possible retrofits, a few new technologies with good potentials as well as a few aspects of policies and their impacts involving distributed renewable power have been included.

Contributions to this book are on sustainability assessment tools, overview of some emerging technologies, potential new technologies, simulation and modelling of new energy systems, application case studies as well as socio-economic impacts of distributed renewable power. Chapters include recent results and are focussed on current trends in the distributed renewable energy sector. In this book, readers will get an idea about promising as well as future useful technologies of distributed renewable power, their performance assessment, modelling and simulation, application, and socio-economic assessment. A few chapters of this book are based on the overview of state-of-the-art technologies, with a special focus on the theory, development, and applications of these technologies. We hope the book greatly interests the professionals and post-graduate students involved in renewable energy in general and distributed renewable power in particular.

Jadavpur, India — Sudipta De
Kanpur, India — Avinash Kumar Agarwal
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About the Editors

Dr. Sudipta De is currently Professor, Mechanical Engineering Department, Jadavpur University, India. His area of interest is sustainable energy. He received his research funding from UGC, DST (India); EU; Swedish Research Council; DFG-Germany; SIU and DIKU-Norway etc. He is an editorial board member of the Springer Nature journal 'Clean Technologies and Environmental Policy'. He received the Indian National Science Academy (INSA) Teacher Award, a lifetime award for distinguished contribution. He was the leader of the Indian Delegation in the 13th Plenary Meeting of ISO/TC 238: Solid Biofuels. He is Fellow of West Bengal Academy of Science and Technology and International Society for Energy, Environment and Sustainability.

Prof. Avinash Kumar Agarwal joined IIT Kanpur in 2001. He worked as Post-Doctoral Fellow at the Engine Research Center, UW@Madison, USA (1999–2001). His interests are IC engines, combustion, alternate and conventional fuels, lubricating oil tribology, optical diagnostics, laser ignition, HCCI, emissions and particulate control, 1D and 3D simulations of engine processes, and large-bore engines. He has published 525+ peer-reviewed international journal and conference papers, 63 edited books, 129 chapters, 16200+ Scopus, and 24300+ Google Scholar citations. He is Editor of FUEL, Associated Editor of the SAE Journal of Engines, and the ASME Open Journal of Engineering. He is India's number one Energy researcher in the recently declared Stanford University listing of the top 2% of researchers globally.

Dr. Pankaj Kalita received his bachelor's degree in mechanical engineering from the Jorhat Engineering College, (Under Dibrugarh University, Assam) and subsequently M.Tech. in Fluids and Thermal Engineering and Ph.D. degrees in clean coal technologies from the Indian Institute of Technology Guwahati. Currently, he is Associate Professor in the School of Energy Science and Engineering, Indian Institute of Technology Guwahati. He worked as Assistant Professor in the Department of Energy at Tezpur University, Assam, before joining at IIT Guwahati in 2015. He has more than 10 years of teaching experience and 16 years of research experience in the field of clean energy technologies. He has published more than 100 research articles in various reputed journals and conferences. So far, he has published 3 edited books and contributed 16 book chapters. He has completed several research and consultancy projects in the areas of clean energy technologies.

Chapter 1
Challenges and Opportunities of Distributed Renewable Power

Sudipta De, Avinash Kumar Agarwal, and Pankaj Kalita

Abstract The global energy sector is now going through a transition. Energy is a basic need of modern civilization and often per capita energy consumption is considered as an index of the living standard of people of a country. Starting from the industrial revolution till date, the majority of the energy supply has been from fossil fuel resources. As a result, sixty per cent of the global fossil fuel reserves have been consumed in the last two hundred years. Moreover, the emissions, mostly carbon dioxide, have caused a severe threat to the future human survival, called climate change. There is a desperate need to replace the fossil fuel-based power sector with suitable renewable power. However, renewable power options are widely varying with several limitations like intermittency, low density, not cost-effective, etc. In addition to large-scale renewable options, smaller distributed power generation with or without grid may be a future suitable option for a smoother energy transition. For this, opportunities are to be explored and simultaneously addressing the challenges involved for distributed renewable power. In this book, this issue is addressed from several viewpoints including sustainability. New technology assessment, overview of potential technologies, reporting of promising future technologies, modelling and simulations as well as applications and socio-economic impacts are reported in different chapters of this book. The book is a state of the art but brief compilation of the field for both researchers/senior students as well as industry professionals.

Keywords Distributed renewable power · Potential technologies · Addressing challenges · Applications · Socio-economic impacts

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Energy sector is currently going through a global transition. Both the fast depletion of fossil fuels and threat from climate change have forced us to explore a new regime of renewable power with a paradigm shift. However, there are several obstacles to overcome during this transition. Developing suitable technologies may be the major challenge. However, retrofitting new technologies with existing infrastructure may add benefits to this process. With the global goal of sustainable development, this transition path should also comply with sustainability. In addition to large-scale renewable power, distributed renewable generation will add more flexibility to follow the path of sustainable development. This book addresses this aspect of distributed renewable power in a brief but effective compilation. Overall content of this book is distributed in six sections.

The first section includes a chapter on the demonstration of a tool integrating SWOT analysis to assess the overall sustainability of any distributed renewable power generation. As the several criteria of sustainability may not be the best for any single solution, a multi-criteria decision-making (MCDM) has to be done with the decided priority of these criteria. This method of SWOT integrated MCDM tool may be very effective for assessing the overall sustainability of any new future renewable power generation option or the existing ones. Such tools may be very useful for policymakers as well as researchers to decide the acceptable optimum solutions for renewable power.

The second section of the book includes five chapters, each one to discuss an overview of a potential emerging technology of distributed renewable power generation and utilization. Grid integration of distributed renewable power generation has several challenges. Intermittency as well as wide variability over a short period, no control on the resource input according to the demand pattern, etc. are to be addressed properly before distributed renewable generation can be integrated with the main grid. In the first chapter of this section, a good overview is presented on this issue with possible solutions to overcome the challenges. A similar comprehensive overview on the thermochemical conversion of biomass is presented in the second chapter of this section. Though the technology of thermochemical conversion of biomass is old, it has regained its importance again after a long time not only as a renewable power option but also as a way of waste recycling and circular economy towards better sustainability. Different technology options of thermochemical conversion as well as integration of those processes for efficient power generation and assessment of those processes are presented in this chapter. Biochemical process of conversion of biomass is another alternative path for biomass conversion for renewable power. It happens without any heat requirement and by an anaerobic digestion process. In addition, several algae have drawn special attention for good reasons. These can absorb carbon dioxide at a much faster rate and deliver useful value-added chemicals including biofuels. Thus, the integration of biochemical conversion processes with the cultivation of suitable algae may be a good option for distributed power generation. An extensive overview on this integrated process has been presented in a chapter of this section. Energy storage is a critical component of reliable renewable power. With variable demand and more uncertain resource availability in nature, energy storage plays a critical role in reliable renewable power supply. Heat is one of the possible options of energy that can be stored effectively. Phase change materials along with micro/nano encapsulation have been discussed as an effective way of energy storage for renewable power generation. Integration of these energy storage processes with suitable efficient renewable power generation options has been discussed in this chapter. Solar photovoltaic and solar thermal are generally considered as two different technology options for solar power. Also though the higher temperature improves the performance of the solar thermal system, solar photovoltaic operates at a lower temperature. In a new technology of Photovoltaic-thermal collectors, both effects can be combined for a micro-cogeneration system. Such technology not only improves the overall utilization of solar radiation, but also saves the required area for solar installation. A comprehensive overview of such systems including both opportunities and challenges is reported in another chapter of this section.

New technology developments and exploring new options of energy resources are two imperative needs of the global energy transition. In the next section, either such resources or such technologies are explored in four chapters. Geothermal energy is a significant renewable resource, though available in limited areas. The largest share of the cost for power from geothermal energy is due to drilling to reach the source of hot water/steam. However, similar drilling is done during the extraction of oil from oil mines. A significant amount of hot water is produced from many new oil mines at the stage of high water cut. On the other hand, hot water is also available in depleted oil fields which do not require any additional cost of drilling. Utilizing geothermal heat both from the new oil fields as well as from the depleted oil fields can be a good option for future energy sustainability. A chapter in this section includes a discussion on both potential and associated challenges for the utilization of such geothermal energy resources. Buildings consume a significant amount of energy. With the emerging concept of sustainable buildings, buildings are not only made more ‘smart’ with energy-efficient options but also can be used for distributed renewable power generation. Thus, the future energy-efficient buildings are not only energy consumers but also producers of renewable power in a distributed generation process. Real-time monitoring of such ‘smart buildings’ needs automation supported by data analytics integrated with IoT with proper decision logic. Such an efficient building energy management system with distributed renewable power generation is discussed in one chapter. The gap between demand and supply happens in any power generation and consumption. This gap becomes more prominent when uncertainty in the generation is more, specifically for renewable power generation with solar or wind energy. Conventional electrochemical storage devices cannot compensate for this gap with larger values. Pumped hydro storage is an efficient option for such periodic large gaps between generation and consumption. Several aspects of pumped hydro storage systems are discussed as an efficient solution for integrating more distributed renewable power into the main grid. Ocean is a vast resource of renewable energy. Extracting power from the waves is a possible option for distributed renewable power. Though oscillating water column (OWC) in a duct with water waves on one side and open atmosphere on the other side is a common option for wave power, it has poorer efficiency with such periodic change of flow velocity including its direction. A fluidic diode (FD), similar to an electrical diode, is proposed to convert this bidirectional flow into a unidirectional flow with a variable resistance. A detailed discussion on the prospects and challenges of this technology along with numerical study results are reported in another chapter of this section.

For any new technology implementation, modelling and simulation is a standard process as it helps in estimating the expected performance of the developed system at a much lower cost without fabricating it. Subsequently, on the basis of simulation results, the optimum system may be developed as a prototype. Thus, modelling and simulation is an integrated part of engineering system development, specifically new and emerging systems. A few modelling and simulation results are demonstrated in the next section of this book. Biofuels from ligno-cellulosic biomass (LCB) rich in lignin is a prospective option to replace fossil fuels. However, to make this process as a future more sustainable option, detailed process modelling is required. Modelling of different reactors used for syngas fermentation for bioethanol formation has been reported in a chapter of this section. Different challenges along with possible remedies are also recommended in this chapter. Power supply using renewable resources at remote isolated locations faces difficulties associated with fluctuations both on the demand and the supply side. Maintaining constant voltage and frequency with these fluctuations is a critical challenge for such systems. Self-excited Induction Generator (SEIG) is an effective solution for such systems to sustain consistent voltage and frequency at the bus bar. Real-time simulation results are reported for such a system for a better understanding of the operation and performance of such systems in a chapter of this section. Micro hydro-based power generation is more environment friendly as it does not affect local inhabitants through the creation of any water storage upstream of the dam. However, continuous fluctuations both at the generation and demand side may be a difficult challenge to address for such systems. A self-excited induction generator (SEIG) with the power grid for micro hydro small-scale distributed renewable power systems is thoroughly simulated in the MATLAB/ Simulink environment with reported results in another chapter. Results are useful for grid integration of such micro hydro systems. In a further extension of this work, simulation results of a new capacitor excitation topology integrated with an induction generator (CET-IG) for single-phase power from a three-phase SEIG driven by the micro hydro system are reported. The results are satisfactory for single-phase power supply with acceptable voltage regulations. In a further extension of studies on the efficient operation of micro hydro power plants, another chapter is included. Harmonics, poor power factor, unbalanced load as well as voltage regulations for standalone power systems are difficulties to address. In this chapter, a shunt active power filter with a modified P-Q controller is reported through simulation in the MATLAB environment.

Successful application of new technologies and commercialization depends on several other factors. It involves socio-economic issues in addition to efficient technology development. A downdraft gasifier-based distributed power generation system in the Indian context is reported in a chapter in the next section.

Technologies are for social development. Proper policy support is also required for promoting technologies suitable for any society. Also review of social impacts after introducing/increasing any technology is a required study to decide the future path of it. Thus, the socio-economic impact studies of major introduction of technologies are required. India has a mission of enhancing solar power at the national level. Several policies are implemented both at national and sub-national levels in India. In the last chapter of the last section of this book, a comprehensive assessment of the impact of Indian solar energy missions/implementations till date is reported. Issues like green job creation and rural development are also reported in this study.

The book consists of seventeen chapters arranged according to the needs of its readers. Starting from the sustainability assessment, the book addresses an overview of the status of a few important technologies, a few promising future technologies, modelling and simulation results, possible applications as well as policy and implementation impacts of different distributed renewable power options. The book may be useful for students at the postgraduate levels of sustainable/renewable energy, researchers as well as practising professionals in this field of distributed renewable power. However, to help any reader to explore articles of specific interests, the whole content is divided into seven different sections: Part I Tool for Sustainability Assessment; Part II Technology Overviews; Part III Potential Technologies; Part IV Modelling and Simulations; Part V Applications; and Part VI Socio-economic Impact Studies. The editors believe that this book will be useful for the current researchers and professionals working in this field.

Part I
Tool for Sustainability Assessment

Chapter 2
Application of MCDM Tool Integrated with SWOT Analysis for Prioritization of Strategies to Optimize Distributed Hybrid Energy Systems for Better Sustainability

Sayan Das, Souvanik De, and Sudipta De

Abstract Energy transition is a current global challenge. Deciding a right path to meet the ever-increasing global energy demand at an affordable cost with low-carbon options is a critical challenge. Deciding appropriate energy strategies and determining their priorities are necessary for proper energy transition. Energy strategy determination is decided on the basis of the country's strengths, weaknesses, opportunities, and threats (SWOT) related to the energy sector. Evaluating proper energy strategies is a perpetual process to prioritize issues in energy planning. Different authorities are responsible for deciding the proper priorities of energy strategies on the basis of new and improved alternative solutions to achieve sustainable development. As energy strategy prioritization correlates several conflicting and interlinked issues and the SWOT method is unable to decide the priority, integrating a multi-criteria decision-making (MCDM) approach is critical. Integrating SWOT with an MCDM method is generic yet novel and one of the best possible options to formulate and prioritize energy strategies for a better energy transition towards sustainability. The study comprehensively reviewed the SWOT-MCDM methods along with the future direction of the research applied in different fields specially focused on energy transition.

Keywords Energy strategy prioritization · SWOT · MCDM

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2.1 Introduction

For the overall sustainable development of a country, energy is an indispensable requirement. The economic and societal development of any country is closely linked to appropriate energy planning [1]. Ever-increasing population, rapid industrialization, and urbanization increase the global energy transition. Till date 2.7 billion people throughout the world are using conventional resources to meet their daily energy needs. Approximately 95% of this is from remote villages [2]. The high dependency on conventional resources not only causes environmental degradation but also has an adverse effect on human health [3]. Considering environmental degradation, countries under the UN signed an agreement in Paris in 2016 [4]. According to the agreement, restricting the global temperature by 1.5 °C from pre-industrial levels is a global target. To achieve carbon–neutral economic development, shifting towards renewable energy resources is a critical need [5]. Additionally 17% of the total world population, especially from remote villages, are living without reliable electricity. For sustainable development of society, providing energy security is the key to success. The United Nations (UNs) decided 2014–2024 as the "Decade of Sustainable Energy for all" by supplying sustainable and affordable energy through non-conventional resources. It is the key factor for achieving the Sustainable Development Goal 7 (i.e., SDG-7) [6]. To address the issues that come in the path of sustainable development, non-conventional resources can play a critical role. Utilizing non-conventional resources without affecting the environment is a crucial goal. Energy management with proper strategy determination and prioritization are essential for this [7].

Due to ever-increasing energy demand and environmental issues, energy policy-making is a widely discussed issue [8]. During this energy transition phase, proper energy conservation and sustainable development have recently become an important aspect of energy planning. Deciding on a proper energy strategy at all levels is a critical need for a better energy transition towards sustainability [9].

Determining appropriate energy strategy and deciding the priority of implementation increases the reliability of the power supply by simultaneously minimizing the cost. It also improves resource utilization [10]. Ideal strategy determination targets several short as well as long-term goals to improve resource distribution, depending on the capabilities of the potential of various regions under different constraints such as technical restrictions, geo-political constraints, and budgetary limitations [11].

The Strengths, Weaknesses, Opportunities, and Threats (SWOT) method is used to develop the appropriate energy strategy [9]. This method is widely used and accepted by all in energy planning and strategic management studies [12]. It is a strategies analysis tool that combines the study of the strengths and weaknesses of the strategies, organizations, or sectors with the study of opportunities and threats in its territory [13]. Besides developing policies and strategies, it must be prioritized for successful implementation [14]. However, the SWOT method has few limitations. It is unable to decide the priority of implementation for determined strategies [9].

Multi-criteria decision-making (MCDM) is a method to decide the most acceptable solution among the alternatives by evaluating them under various criteria [15].

This technique is classified as classical and fuzzy-MCDM, which are used to decide the rank of the alternatives [16]. This MCDM technique is essential to decide the proper ranking of implementing the decided policies. During energy planning, several criteria such as technical, economic, environmental, and social must need to be considered. In energy decision-making problems, alternatives must be evaluated in terms of these criteria. Due to this, it becomes a multi-dimensional composite decision-making process [1]. MCDM method is also effectively used to determine the order of the criteria during decision-making. Various conditions add different aspects to energy planning and make them more complex and uncertain to decide the priority of implementation [9].

Siksnelyte et al. [17] reviewed different MCDM methods for dealing with sustainable energy development issues. Ayan et al. [18] comprehensively reviewed different MCDM methods that were used for determining the weights of the criteria. Espino et al. [19] studied detailed MCDM methods used in the construction industry. Sousa et al. [20] studied different MCDM methods used to achieve SDGs. Abanda et al. [21] studied different MCDM methods used to evaluate National Determination Contribution projects. Benzaghta et al. [22] studied the application of the SWOT method in different sectors. Kabir et al. [23] reviewed the applications of SWOT-Analytic hierarchy method (AHP)-MCDM method in smart power management problems.

2.2 Research Topic

Most of the reported literature focused on analyzing the use of MCDM methods in different sectors. Recent studies reviewed the MCDM and SWOT methods application in energy strategy determination for achieving sustainable development goals. These studies mostly studied these methods separately. No previous analysis comprehensively reviewed the applications of hybrid SWOT-MCDM methods in energy strategy determination and prioritization. Due to the lack of substantial review of this hybrid method, it becomes difficult to select the appropriate MCDM method suitable with SWOT techniques for the specific problems.

Considering the identified research gaps, this study aims to comprehensively review the hybrid MCDM-SWOT method used in energy strategy determination and prioritization for achieving sustainable development. The SWOT method is used to determine the strengths, weaknesses, opportunities, and threats of the energy policies for better energy management. Subsequently, this research also aimed to report the application of different MCDM methods to decide a priority of implementing the decided strategies developed through SWOT analysis.

2.3 Strengths, Weaknesses, Opportunities, and Threats (SWOT) Method

American businessman and management consultant Albert Humphrey developed the SWOT analysis method in the 1960s to 1970s [24]. Evaluating complex strategies, developing a strategy plan, and organizing them as external and internal factors are the major tasks of this method [25]. The objective of the SWOT method is to evaluate the internal and external factors to detect the internal strengths to benefit from external opportunities by highlighting the internal weaknesses and external threats [26]. The methodological steps are described in Fig. 2.1.

SWOT factors are defined as relevant information or data. The structure of this method depends on this information or data which is gathered as input. Internal factors are the factors that can be controllable whereas the external factors are uncontrollable. Strengths and opportunities are the helpful factors that aid success, while the threats and the weaknesses are the harmful factors that prevent the success [26,

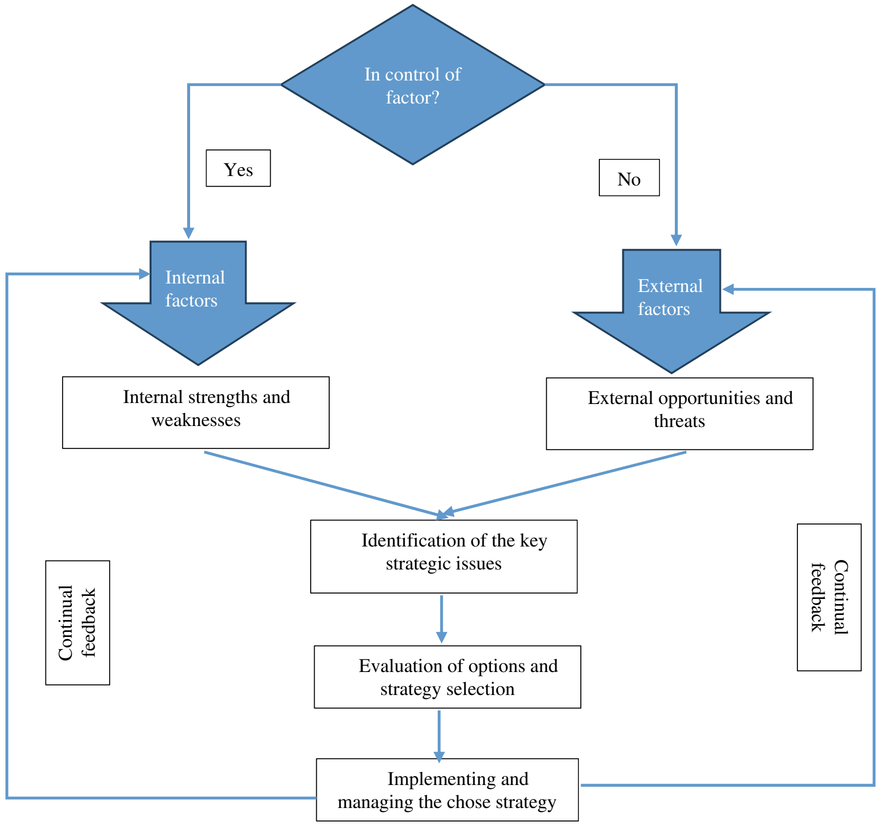

Fig. 2.1 Schematic arrangement of SWOT method

27]. Strength factor is considered as the internal enhancer of the ability, rewarding resource. Internal hindrances to the skills, resources, or qualities required for success are the weaknesses. Opportunities improve performance and can be utilized to one's advantage. The threats are an external factor that reduces the prospective achievement. In a 2 × 2 matrix, strengths are labeled as internal performance enhancers and weaknesses are labeled as internal permeance inhibitors. Opportunities are external inhibitors, while threats impose performance restrictions [28]. This SWOT matrix involves the following:

- Strength-opportunity (SO): It focuses on how to use the system's strength to seize chances on the basis of opportunity.
- Strength-Threats (ST): It ensures to stay safe so that the advantages can be used.
- Weakness-Opportunities (WO): It seeks to reduce gaps to generate new opportunities.
- Weakness-Threats (WT): These are mostly defensive and work to reduce vulnerabilities to neutralize threats.

Based on various considered criteria, i.e., technical, economic, environmental, social, policy, and socio-political issues, the sub-factors of each SWOT factor are formed [29]. To make the questionnaire or to calculate the collected data, this approach does not require any software or tool [30]. The important aspect of this method is open interviews and open groups to determine the strengths, weaknesses, opportunities, and threats [24].

2.3.1 Energy Planning and SWOT Method

To determine the energy strategies, SWOT methods are used. It helps to determine the strengths, weaknesses, opportunities, and threats of the decided energy strategies and policies.

By assessing the internal state of renewable energy of each country, resources, and capabilities of the energy strategies, the sub-factors of the internal factors (Strengths and weaknesses) are developed. Whereas the external factors, i.e., opportunities and threats are decided by examining the environment of the strategies.

Resource potential, financial strength, and technical advancement are the strengths of the developing renewable energy sector. The weaknesses rely on infrastructure, business cost, financial liquidity of the company, tariff, cost and availability of debt, etc. Factors like government policies, green financing, and international threats are the major concerns of the opportunities, and threats are related to the political environment, energy supply, international scenario, availability of fossil fuels, and economic stability.

Initially, a literature review is conducted to design the current energy situation of the country. Then, core decision groups are formed. Subsequently, SWOT factors and sub-factors are decided. Finally, Alternative strategies are identified.

Qaiser [31] compared various energy strategies developed for the renewable and sustainable energy sector of different Asian countries. According to the study of the poor financial situation of the distribution companies, lack of credit opportunities is the major weakness for the growth of the renewable energy sector of this region. There is a conflict of interest between manufacturers of renewable energy equipment and the developers of renewable energy projects in terms of government policies which become the major concern for imposing the import duties. Kamran et al. [32] analyzed the current status and future roadmap for nurturing the renewable energy sector of Pakistan by using the SWOT method. The study reported that the validated resource maps, abundant renewable energy resources, environment-friendly conditions, and growing private sectors are the major strengths, while inefficient technologies, immature institutional framework, hazardous technology-related environment, and huge capital investment are the substantial internal weaknesses. The study also identified significant opportunities as well as threats for the potential renewable energy sector of Pakistan. Elavarasan et al. [33] developed a framework to comprehensively evaluate the drivers and barriers for renewable energy development in significant countries by using the SWOT method. This study majorly focused on India, China, US, Sweden, and Iceland. Agyekum [34] analyzed the strengths, weaknesses, opportunities, and threats of the renewable energy sector of Ghana by using the SWOT method. The study reported that political stability, abundant renewable energy resources, and geographical location are the major strengths, whereas bureaucratic procedure and high capital cost are the key internal weaknesses. The study also identified the opportunities and threats for developing the future roadmap of the renewable energy sector of Ghana. Shi [35] assessed the energy mix situation of ASEAN countries by using the SWOT method. This study reported that the region must provide an effort for establishing cleaner energy by removal of subsidies of fossil fuels and needs to promote renewable and energy efficiency. Fertel et al. [12] analyzed a Canadian energy and climate policy in terms of the coherence between federal and provincial strategies by using the SWOT method. The study showed that the lack of consistency is the major weakness of the Canadian climate and policy. The study also reported different strengths and opportunities of the sector for developing renewable energy in Canada. Terrados et al. [36] developed renewable energy planning through the SWOT analysis method. The study also analyzed the Impact of this method on renewable energy development. Jing and Tao [37] reported a SWOT framework for developing clean energy strategies in China on the basis of environment, social constraints, economic, etc. Zhou et al. [38] designed a model on the basis of 12 SWOT sub-factors for sustainable energy strategies in rural areas.

Most of these studies mainly focused on finding the strengths, weaknesses, opportunities, and threats for the renewable energy sector in different countries. These studies also developed the future pathways for increasing renewable energy share in the power mix for better energy transition towards sustainability. However, due to the above-mentioned limitation, it becomes difficult for this SWOT method to find the proper priority of implementation of these determined strategies. Therefore, implementing strategies becomes critical. It demands to integrate a different MCDM approach with the SWOT method to decide the proper ranking of implementing these determined strategies.

2.4 Multi-criteria Decision-Making (MCDM)

Decision analysis is an important tool to solve a problem with multiple factors, criteria, and objectives. MCDM problems come with five steps: goal, decision-maker's preference, criteria, alternatives, and results [39]. Figure 2.2 classifies the MCDM methods [40]. Depending on the number of alternatives, MCDM methods are classified into two parts: multi-objective decision-making (MODM) and multi-attribute decision-making (MADM); otherwise, the characteristics of both these MCDM are similar [41]. To evaluate continuous alternatives for which we predefined constraints in the form of vectors of decision variables, an objective function set is optimized depending on the constraints when the performance of one or more objectives is degrading [42].

In MADM, the inherent characteristics that are covered lead to considering a lesser number of alternatives and it makes the evaluation more complex because prioritizing the alternatives becomes difficult [43]. The final outcome is decided by pairwise comparing the alternatives with respect to the considered attributes. MCDM is a broader classification and different MCDMs are used in energy strategy prioritization [44]. As per the designer perspective, these models are developed. It may be a direct or an indirect approach. Figure 2.3 shows the classification of such models [45]. Different factors such as technical, institutional, social, economic, environmental, stakeholders, and standards are included in this process which makes MCDM more complex. It involves both managerial and engineering analysis. Based on the priority of the objectives, this process can lead to different outcomes at different times.

Moreover, a particular problem can be solved by different methods on the basis of the decided objective functions. Each method has its own advantages and limitations. Figure 2.4 illustrates the general procedure of the working principle of MCDM.

In energy strategy prioritization problems, different MCDM approaches are used. A few important MCDM models are as follows [46–51].

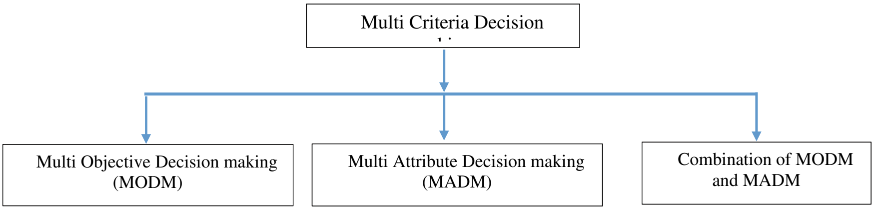

Fig. 2.2 MCDM methods classification [40]

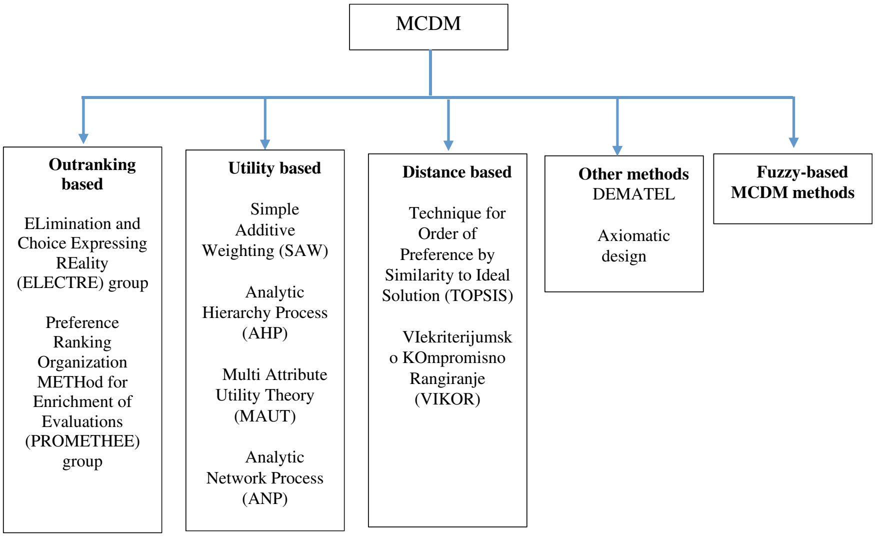

Fig. 2.3 MCDM models [45]

(i) AHP
(ii) ANP
(iii) Weighted Sum Model [47]
(iv) Weighted Product Model
(v) ELECTRE [51]
(vi) PROMETHEE [60]
(vii) TOPSIS
(viii) VIKOR [49]
(ix) Fuzzy-based MCDM.

2.5 Energy Planning and MCDM

In energy planning, different MCDM models are successfully utilized. These methods are considered as most suitable options for solving energy planning-related issues. Different MCDM models that are utilized in energy planning are reviewed in this section. Broadly three types of MCDM models, i.e., outranking methods, utility-based methods, and distance-based methods are considered in this analysis. These models have been used in combination also.

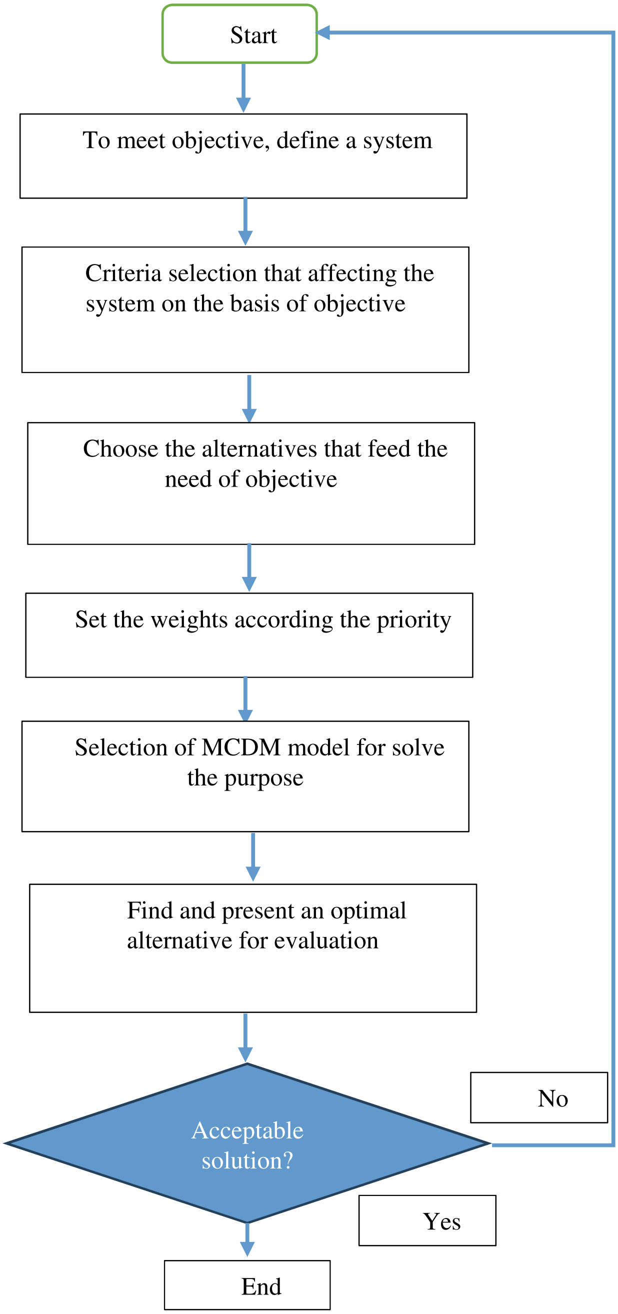

Fig. 2.4 Common methodology of MCDM

2.5.1 Outranking Methods

In this group, ELECTRE and PROMETHEE methods are the most important models. Out of these models, ELECTRE methods are the most common ones that are considered for energy planning. This method has the broader perception to give a practical view for the problem by inculcating all the queries and suspicions. This ELECTRE method is mostly preferred in energy allocation at the demand side.

2.5.1.1 ELECTRE Method

This MCDM method established strong preferences on the basis of given information. Different mathematical functions are used to indicate the dominance degree of one alternative over another. It is the operation research method and uses pseudo-criteria and binary outranking relations [52]. This technique uses a pseudo-criteria for comparison to evaluate a number of strategy options.

Lin et al. [53] reported that ELECTRE method were used to prioritize the alternatives for sustainable hydrogen production pathways determination. Beccali et al. [54] proposed to use ELECTRE method for selecting renewable energy technologies for different locations. Hwang and Frank [55] compared five different MCDM methods and presented the use of this outranking method in a distributed energy system. In ref. [56], authors studied the energy planning situations of Greek Island. The study identified the energy strategy factors, selected the criteria, and formulated the alternative strategies. In this study, the researchers use the ELECTREE III method and highlight those aspects which are crucial in regional energy planning problems. In ref. [57], ELECTRE III methods were used in the power distribution method followed by a simple ranking method. The study showed that ELECTRE III was a healthy and reliable method to support power distribution support planning for Cynthia. Flourentzou et al. [58] considered the ELECTRE method for renovating and rating the present building scenario considering different criteria such as energy required for heating, cooling, and impact of other appliances on foreign and indoor environment quality and cost. In ref. [59], researchers used the ELECTRE method to determine the strategies for improving the economic investment in solar photovoltaic (PV) systems.

2.5.1.2 PROMETHEE Method

The Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) is an outranking MCDM method that decides the rank of the finite set of alternatives on the basis of the conflicting criteria [60]. Brans developed this method in 1982 which was used for partial ranking of alternatives. Vincke and Brans further expanded this method in 1985 to PROMETHEE II for complete ranking determination of the alternatives [60]. Recently PROMETHEE III and IV were also used. It is the preference function-based MCDM and it is the most accepted one for determining ranking. It is applicable in many fields for ranking purposes [61].

Bortoluzzi et al. [62] proposed to use PROMETHEE MCDM methods for selecting energy technologies to develop an economic distributed energy system. Demirel et al. [63] reported the PROMETHEE method for deciding energy-efficient steam boilers for industrial applications. Chisale et al. [64] reported that PROMETHEE method was suitable to decide a techno-economically optimal solution for Malawi. Georgopoulou et al. [65] used the PROMETHEE II method in a group decision support system to advise the decision experts in promoting renewable energy resources usage. Tsoutsos et al. [66] exploited the decision-making methodology to plan the sustainable energy for the island of Crete in Greece. For this study, authors used the PROMETHEE I and PROMETHEE II methods for finding the alternative energy strategy to develop techno-economic, environmentally friendly, and socially acceptable renewable energy systems.

2.5.2 Utility-Based Method

Different utility-based MCDM methods, i.e., Analytic Hierarchy Process (AHP), Weighted Sum Model (WSM), MAUT, SAW, and ANP are extensively used in energy strategy planning. To rank the decided strategies, these methods are commonly used.

2.5.2.1 AHP, ANP, Delphi, and MAUT Methods

Saaty in 1980 developed the AHP decision-making method. This method decomposes a complex MCDM method into a hierarchical order. Hierarchical structuring of the model, pairwise comparison of alternatives, and the criteria and priorities synthesis are the three steps of the AHP MCDM method [67].

ANP considers the dependencies between elements in internal and external sets. Inner dependency shows the interaction between criteria in the same cluster and external dependency represents the interaction of criteria in a different set. The dependencies are shown in arrows. This method is a control hierarchy used to evaluate the different dimensions of criteria. Defining clusters and deciding the dimension of the criteria, designing the model, creating interdependencies, and pairwise comparison are the four steps performed under this method, respectively [68].

Delphi method systematically collects the data from the anonymous experts and connects it in written, discussion and provides feedback on a specific topic. This method enables a chance for a completely diverse expert's opinion [67].

Multiple Attribute Utility Theory (MAUT) method is based on Vonn Neumann and Morgenstern's utility theory foundation. It was developed by Keeney and Raiffa. It simplifies the multi-attribute evaluation process. It gives a logical and reasonable process to decide between conflicting criteria. In this method, quantitative and qualitative both the criteria are used [69].