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REVIEW ARTICLE

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Decentralised energy and its performance assessment models

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Abstract Energy development concerns not only the development of renewable energies but also the shift from centralised to clean, decentralised power generation. The development of decentralised energy (DE) is a core part of the energy and economic strategies being adopted around the world that drives the progress toward a highly sustainable future. This paper reviews the concepts, development status, trends, benefits and challenges of DE systems and analyses the existing models and methods for assessing the performance of these systems. A hierarchical decision model for evaluating the performance of DE systems is also constructed based on the framework of multiple criteria decision analysis, which considers the identification, definition and assessment grade of decision criteria. The evidential reasoning approach is applied to aggregate assessment information in a case study of the implementation of an intelligent decision system. Sensitivity and trade-off analyses are also conducted to show how the proposed model can be used to support decision making in DE systems.

Keywords decentralised energy, assessment model, MCDA, evidential reasoning, sensitivity analysis

1 Introduction

1.1 Energy trilemma and the benefits of decentralised energy (DE) systems

"Energy trilemma" is often used in the energy industry as an encompassing term that represents the integrated challenges in energy security, social impact (e.g., energy affordability) and environmental sensitivity (e.g., CO_2 emission) as illustrated in Fig. 1. Sustainable generation and consumption of energy plays essential roles in solving this trilemma while maintaining the welfare of the current and future generations and achieving the overarching goal of ensuring energy security, affordable energy supply and environmental protection. On the one hand, the efficiency and sustainability of the traditional model of centralised electricity generation, transmission and distribution have become increasingly difficult to be justified despite of economy scale, safety and reliability. For example, the most advanced centralised power station in the UK is estimated to achieve an energy efficiency of only 50%, and a further energy loss of 9% can be incurred from its transmission of power through distribution networks (Carson et al., 2008). On the other hand, a curtailment in solar and wind energy production has also been observed in Western China due to the insufficient capacity, and local congestion of transmission and excessive supply during periods of low demand.

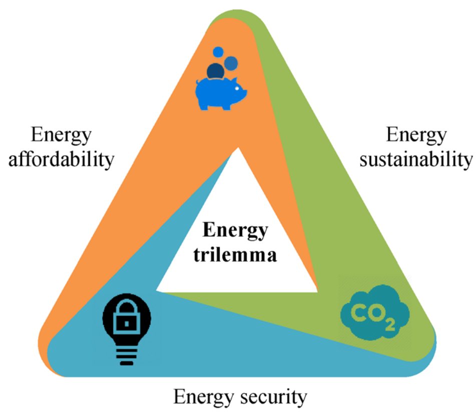

Fig. 1 Energy trilemma.

The requirements of future energy sustainability include long-term supply, stable prices, continuous technology improvement and simple installation and maintenance (Omer, 2008). Essentially, sustainable energy development

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should consider not only cost savings but also the efficiency of energy systems and the flexibility of replacing fossil fuels with renewable energy sources (Lund, 2007). DE and small-scale power grids are reliable and cost-effective alternatives to large grids, which tend to cause failures and inefficiencies. Promoting the use of DE among individuals and local communities can reduce the energy bills of households, businesses and even industries. Over the recent decades, the costs of solar panels and battery storage have been significantly reduced, hence motivating the adoption of alternative ways of producing and consuming energy in combination with smart meters and other fast-developing demand-side response measures. In this case, the trend of future energy development concerns not only the development of highly renewable energies but also the shift from a centralised power to a clean, decentralised power as illustrated in Fig. 2.

Europe has recently transitioned from centralised and largely fossil- or nuclear-based electricity delivery systems to highly DE systems (Directorate-General for Energy and Transport (European Commission), 2008; Heller, 2017) that mostly utilize renewable energy sources, such as small hydro, wind power, solar power, biomass, biogas and geothermal power. Meanwhile, the pollution levels in China are mainly driven by its continued reliance on fossil fuels for heating, manufacturing and transportation, and these pollution levels are anticipated to be reduced considerably via the widespread deployment of DE systems.

1.2 Challenges and difficulties faced by DE systems

In the development of renewable energy, making an informed choice regarding highly efficient, reliable, economical and environmentally friendly DE systems is critical. However, DE systems are still in their infancy and face many challenges that restrict their application. Relevant policies, legislations and mechanisms should be improved given that the implementation of DE systems involves many aspects, such as economic incentives, energy trading management, environment protection and demand-side management. Most studies on DE have focused on a single renewable energy sector or a centralised power network and have largely ignored the development of DE systems and their potential impacts. Evaluating the performance and impact of DE systems which combine different sources of renewable energy, involves multi-dimensional considerations (e.g., technical, economic, social and environmental criteria) and continues to pose a challenge in DE development and policy making. Recently, an increasing number of studies have examined the application of the multiple criteria decision analysis (MCDA) methodology in evaluating the performance of renewable energy systems. This paper therefore aims to (1) review the development of DE systems and summarize how MCDA has been applied in the literature to evaluate renewable energy systems, and (2) establish a hierarchical decision analysis framework for assessing the performance, cost-effectiveness and social and environmental impacts of alternative DE systems and for facilitating an informed decision making.

2 Review of the literature on the development of DE systems

2.1 DE systems with renewable energies

DE is usually produced near locations where this resource is consumed, whereas centralised energy is produced at large power plants and is transmitted through national grids (Alstone et al., 2015). DE involves a range of technologies that utilize various sources of renewable energy, such as small hydro, wind power, solar power (including solar photovoltaic and thermal power) and biomass. Several definitions of DE have been proposed (Alstone et al., 2015; UK Department of Trade and Industry, 2006), all of which broadly take into account (1) electricity-generating plants that are connected to a distribution network than to a large-scale transmission network; (2) small-scale plants that supply electricity in a local area and sell any surplus back to a distribution

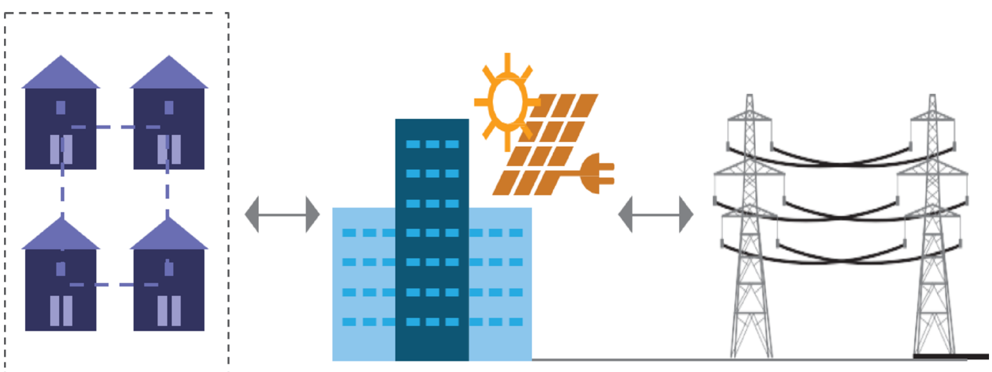


Fig. 2 Decentralised power in the future.

network; (3) small-scale installations of solar panels, wind turbines or other sources of renewable energy for local consumption and surplus selling; (4) combined heat and power (CHP) plants whose electricity output is primarily used for local consumption or fed into a transmission network and whose heat is often used locally in households, small-scale buildings or communities; and (5) non-gas heat sources, such as biomass, solar thermal panels or geothermal energy, that supply heat to only one household, building or local community. Different sources of renewable energy can be deployed at various scales ranging from households and buildings to local communities. Such deployment is usually accompanied by the implementation of demand-side measures for reducing or shifting energy consumption (Heller, 2017; Aiken, 2012).

DE is now regarded as a core part of the future energy and economic strategies being adopted around the world. The development of DE systems involves a range of considerations, such as increasing the utilization of green energy sources, reducing carbon emissions, improving energy efficiency, exploring new energy generation capacities and improving the security of power generation and supply (Heller, 2017). The deployment of these systems also produces a series of tangible benefits. First, a decentralised generation of green energy can reduce transmission losses and carbon emissions (Heller, 2017; Alstone et al., 2015), hence making this approach extremely helpful in combating climate change. Secondly, DE has a higher power generation and distribution efficiency compared with the traditional centralised electricity generation and increases the contributions from renewable energies. Thirdly, DE can improve the security of energy supply given that the widespread consumption of energy does not heavily rely on few, large and remote power stations. Fourthly, DE provides a cost-effective way of achieving carbon targets, and consumers can fully involve themselves in promoting locally generated, sustainable, competitive and smarter energy choices (Carson et al., 2008). For example, the increased use of DE in the UK is estimated to reduce approximately 30% of its greenhouse gas emissions associated with heat and power generation.

Despite these benefits, the wide implementation of DE systems is restricted by many factors. For example, grid connection and reverse metering pose technological problems in real implementation scenarios. Moreover, the new technologies that are suitable for specific implementation environments, such as fuel cells, are mostly at the early stage of their commercialisation. Large up-front capital costs and long payback periods can also hinder the adoption of DE systems without government subsidies. From the environmental perspective, the property leasing and management arrangements in the development of DE systems often focus more on short-term cost savings and the security of energy supply than on carbon emissions and energy efficiency. In addition, the acceptance of local communities should be considered in the development of small-scale DE systems, and forming new disciplines between suppliers and users to achieve a real-time matching of supply and demand is often difficult.

2.2 Development of micro-grids to overcome the challenges in DE adoption

DE can supply users with green power generated from locally available renewable energy resources. However, many interconnected DE systems in a large-scale power network may introduce security issues in operations. Micro-grid technology provides an interface to the interconnection of different DE systems (Hatziargyriou, 2014) and can maintain the efficient, safe, reliable and optimal operations of various DE systems through effective management. In other words, micro-grids can integrate generation, storage, demand-side response and system control as well as provide an infrastructure for addressing power security, affordability and sustainability issues. These micro-grids usually have a dispersed, locally controlled and independent energy system that can optimise the real-time matching of supply and demand, alleviate pressures on the national grid and be fully compatible with renewable energies. Figure 3 illustrates the structure of these micro-grids.

As small-scale distributed power generation and distribution systems, micro-grids can also integrate energy storage, energy conversion and related load monitoring and protection devices. They can be not only connected to external grids in parallel but also operated in an isolated environment. In the microscopic aspect, micro-grids are generally equipped with the fully configured functionality of power transmission and distribution, which helps achieve local power balance and energy optimisation. The key feature that differentiates micro-grids from a distributed power generation system with load is that the former has the capabilities of both grid-connected and independent operation. In the macroscopic aspect, micro-grids can be viewed as “virtual” power sources or load in a distribution network. Previous studies have shown that the use of micro-grids is among the most effective ways of facilitating DE supply and produces various social and economic benefits, such as significantly increasing the utilization of distributed power, ensuring a continuous supply of power to critical loads during grid disasters, avoiding the direct impact of intermittent power supply on the power quality of surrounding users, contributing to the optimal use of renewable energy and maximising energy savings from transmission losses in a centralised power grid. Given these benefits, micro-grid laboratories and demonstration projects have been launched across the US, Europe, Japan and other countries.

However, some issues related to the operation of micro-grids need to be addressed. Micro-grids have multiple energy inputs (e.g., photovoltaic, wind, hydrogen and

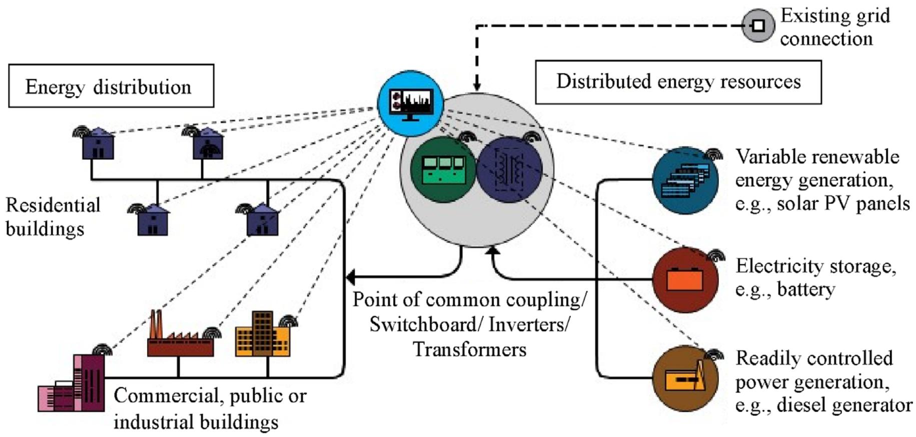


Fig. 3 Illustrative structure of micro-grids.

natural gas), energy outputs (e.g., electricity and heat) and energy conversion units (e.g., optical/electrical, thermal/electric, wind/electric and alternating current (AC)/direct current (DC)) as well as a variety of operating conditions (e.g., grid and independent), all of which make their dynamic characteristics more complex than those of a single distributed energy generation system. In addition to the dynamic characteristics of each distributed generation unit, the structure and type of network (e.g., DC or AC) can also affect the dynamic characteristics of micro-grids. Therefore, further research should be conducted to address those issues that hamper the application of DE and micro-grids in the renewable energy industry.

In sum, micro-grids are placed at the core of future DE development. Most micro-grids are hybrid systems that include different energy resources, such as solar, wind and biomass energy, and integrate supply- and demand-side properties. Therefore, how to evaluate the performance of such complex systems by using MCDA presents a key research topic in the assessment of DE systems.

2.3 Global development status of DE systems

In recent years, many countries have been actively seeking to develop renewable and distributed energy for environmental protection, sustainable development and other reasons. From 2015 to 2017, the annual installation capacity of new DE exceeded 130 GW as a result of the rapid development of the DE industry, and this capacity is expected to increase to more than 500 GW by 2026 (Alstone et al., 2015).

2.3.1 DE development status and planning in the US

DE stations began to emerge in the US in the late 1970s. Given that DE captures and uses excess heat for factories and businesses while simultaneously saving costs and protecting the environment, the US Environmental Protection Agency (EPA) has devoted much effort in promoting the development of DE for energy conservation and environmental protection. For instance, the EPA has established the CHP partnership to promote DE as an economically viable clean energy solution. Accordingly, promoting DE has become one of the top priorities of the US.

From 2001 to 2015, the distributed energy collaboration group of the EPA assisted in the completion of 1047 distributed energy projects with a total installed capacity of 7600 MW and cumulative CO_2 emission reductions amounting to 170 million tons. As of 2016, the installed capacity of DE in the US reached approximately 82.5 GW according to the International Energy Agency.

To further promote its development as a long-term development plan, the CHP should contribute 50% of the energy for new office or commercial buildings in 2020, and 15% of the energy supply for existing buildings needs to be converted into CHP. By 2035, the commercial distributed generation capacity is expected to reach 9.8 million kilowatts.

DE in the US is mainly installed in its western, eastern and southern coasts. DE is mainly based on natural gas and CHP, which accounts for 71% of the total energy supply of the US and is distributed in more than 3700 industrial and commercial projects. Among the applications of DE projects in the US, only 15% are being used for cooling and heating in hospitals, schools, hotels and office complexes, and the rest are distributed across various sectors (29% in the chemical industry, 18% in the petroleum refining industry and the rest are distributed in industrial and manufacturing sectors).

2.3.2 DE development status and planning in Europe

Denmark is a European country with very high energy efficiency (Directorate-General for Environment (European Commission), 2009). The case of Denmark shows that an increase in GDP does not automatically translate to an increased energy consumption and may even correspond to a considerable decline in pollutant emissions. One of the main measures adopted by Denmark to achieve such high energy efficiency is to develop its DE vigorously. Around half of its electricity is generated by DE systems, more than 80% of its district heating energy is produced by CHP and its distributed power generation exceeds 50% of the total generated power. For example, the total installed capacity of wind power distributed to the low-voltage distribution network of Denmark exceeds 3 million kilowatts. Denmark aims to promote the large-scale utilization of CHP plants with heat storage capacity and to encourage regional district heating plants to use natural gas, waste energy and biomass instead of coal. The Danish government also actively supports district heating and CHP projects, especially those launched by companies and located in remote areas. An increasing number of CHP projects in densely populated areas use natural gas as their fuel, and their thermal efficiency indicators are slightly higher than those of coal-fired technologies.

Meanwhile, Germany has achieved great success promoting distributed photovoltaic power generation. At the end of 2017, Germany has reported an installed photovoltaic power generation capacity of 41.7 GW, and rooftop photovoltaic power systems have been mainly used (Bauwens et al., 2016).

2.3.3 DE development status and planning in Japan

Given its scarce natural resources, Japan has started very early in promoting energy-saving and emission reduction technologies to maximise its energy efficiency. Since 1980, with the operation of the first thermal power unit of the Tokyo National Arena, Japan has vigorously developed natural gas DE with an average annual installed capacity of 300 MW, which increased to 400 MW in the 1990s and to 500 MW in 2007. Despite the declining domestic investment in DE and the effects of rising fuel prices and the 2008 Financial Crisis, the DE installed capacity of Japan managed to reach 9.4 million kilowatts in 2011. Since then, the DE development of Japan has decelerated, with an installed capacity exceeding 10 million kilowatts in 2016, of which civilian use accounts for 21% (Narula et al., 2012).

The strategic energy plan of Japan systematically elaborates the country's goal of developing and popularising DE, including CHP, solar power, wind power, biomass and waste energy. The distributed generation of Japan mainly relies on CHP and solar photovoltaic power generation, and distributed power generation projects are widely conducted in both commercial environments (e.g., hospitals, restaurants and public recreation facilities) and industrial sectors (e.g., chemical, manufacturing, steel and other industries). According to the Ministry of Economy, Trade and Industry of Japan, the CHP capacity of the country is expected to reach 16.3 million kilowatts by 2030 with the launch of thousands of commercial and industrial distributed power generation projects. Japan also aims to generate 20% of its total electricity supply by using DE systems by 2030. Photovoltaic power generation is widely used for both residential rooftop photovoltaic and public facilities in Japan, including parks, schools, hospitals and exhibition halls (Guidehouse Insights, 2020).

Japan is also the market leader in the development of micro-grids. The development of new energy and industrial technologies in the country has facilitated the research and development (R&D) and demonstration of many micro-grid projects around the world.

2.3.4 DE development status and planning in China

A summary of DE development in 2017 shows considerable variations in the growth rates of gas-fired power, wind power, small hydro and photovoltaic power generation in China. For instance, in 2017, the cumulative installed capacity of gas-fired power generation reached 87.93 million kilowatts with an annual increase of 13.99%, whereas that of wind power reached 188 million kilowatts with an annual increase of 11.7%. Photovoltaic power generation was identified as the fastest growing renewable energy in China. According to the 13th Five-Year Plan for Power Development, the total installed capacity of gas-fired power generation in China is expected to reach 110 million kilowatts in 2020, of which the CHP supply will account for 15 million kilowatts. The 13th Five-Year Plan for Photovoltaic Development proposes that the total installed capacity of photovoltaic power will reach 150 million kilowatts by the end of 2020 (Wu et al., 2018). China has built a series of micro-grid demonstration zones where both solar and wind energies dominate the power generation. The country has also pushed for the construction of 100 new energy demonstration cities. By the end of 2016, the installed capacity of distributed power supplies in China reached 10.32 million kilowatts, and more than 90 pilot projects for micro-network trials are still under planning and construction (Lo, 2014).

As the country continues to strengthen its environmental protection policy along with its optimisation and upgrading of its energy consumption structures, the prospect of DE is relatively broad in China (Zou, 2020). Recycling energy grids for residential and public buildings, energy centers with high load density and energy centers for industrial parks can all adopt the DE scheme to achieve the economies of scale of DE and the social benefits of energy conservation and emission reduction.

In sum, given its low cost, better energy policy and focus on renewable energy, global distributed generation is expected to show a rapid growth over the next few years. Distributed power generation has already contributed to a high proportion of total energy generation in the US, Europe, and many other developed countries. While the growth of DE development is expected to decelerate in these developed countries, a boom in DE investments is expected in emerging markets, such as Asia Pacific and South America.

3 Review of the literature on DE systems performance assessment

3.1 Application of MCDA in renewable energy evaluation and assessment

To support an informed and insightful decision making, the performance and impact of various renewable energy systems, which involve multi-dimensional aspects and performance factors, should be evaluated systemically (Menegaki, 2008). Many researchers have developed different criteria, methods and models for assessing the impact of DE systems (Dong et al., 2014). The following literature review focuses on four different application areas (Wu et al., 2017).

(1) Renewable energy planning and policy making

Doukas et al. (2007) used MCDA to analyze the relative importance of the different attributes and features of desired energy efficiency for supporting energy policy making. Lee et al. (2009) exploited fuzzy theory and the analytical hierarchy process (AHP) to determine a set of criteria for analyzing the competitiveness of national energy policy making in South Korea. Mahdy and Bahaj (2018) explored the combined application of AHP and Geographical Information System (GIS) for assessing the development potential of offshore wind energy in Egypt. Köne and Büke (2007) applied the analytical network process (ANP) to formulate multiple independent attributes for determining the best power supply technology in Turkey. Önüt et al. (2008) used ANP to evaluate alternative renewable energies for the manufacturing industry in Turkey. San Cristóbal (2011) used the VlseKriterijumska Optimizcija I Kaompromisno Resenje (VIKOR) method, which is based on compromise ranking, to evaluate several renewable power generation resources for supporting green energy planning in Spain.

(2) Renewable energy evaluation and assessment

Zhao et al. (2009) developed an AHP model to evaluate the environmental and security aspects of different power supply solutions and applied this model to determine the optimal location for a power plant in Guangdong Province, China. Aragonés-Beltrán et al. (2010) combined ANP with a network-based model to manage all information that can aid in the selection of the best photovoltaic project planning. Aras et al. (2004) used AHP to determine the most convenient location for building a wind observation station by evaluating alternative wind power plants. Cavallaro and Ciraolo (2005) applied MCDA for a preliminary evaluation of alternative solar thermal solutions and further explored the application of the technique for order of preference by similarity to ideal solution (TOPSIS) in comparing different heat transfer fluid options. Kaya and Kahraman (2010) combined the fuzzy VIKOR and AHP methods to determine the best production site and energy policy in Istanbul. Stein (2013) proposed an AHP model with empirical data to rank different renewable and non-renewable power generation technologies. Wątróbski et al. (2015) proposed an evaluation framework with multiple criteria for selecting the best site of different renewable energies.

(3) Energy project selection and allocation

Latinopoulos and Kechagia (2015) performed a multi-criteria decision analysis based on spatial GIS to choose optimal wind-farm development projects. Myllyviita et al. (2012) used MCDA to calculate weights in life cycle assessment for evaluating the environmental impact of two alternative raw materials in biomass production chains. Linkov et al. (2011) proposed an MCDA model for assessing the impact of nanomaterials on the environment and human health. Wanderer and Herle (2015) constructed a web-based spatial decision support system based on MCDA for determining preferable locations of solar power plants. Burton and Hubacek (2007) explored a renewable energy provision in Yorkshire, UK and utilized MCDA to compare the small-scale schemes that are implemented in Kirklees with large-scale alternatives. Chatzimouratidis and Pilavachi (2009) used hierarchically structured criteria in evaluating the technical, economic and sustainability performance of 10 power plants. Haralambopoulos and Polatidis (2003) applied the preference ranking organization method to build a group decision-making framework for analyzing renewable energy projects and then used this model to exploit a geothermal resource in Greece. Kahraman and Kaya (2010) proposed the axiomatic design methodology under fuzziness for selecting renewable energy alternatives in Turkey based on objective and subjective criteria and in consideration of the functional requirements of experts.

(4) Environmental impact assessment

Oberschmidt et al. (2010) investigated a multi-criteria methodology that considers the motivations behind technological change to evaluate the performance of power generation technologies. Nigim et al. (2004) used MCDA to analyze four wind turbine configurations by comparing them against a series of criteria and to rank the available solutions. Cavallaro and Ciraolo (2005) evaluated the feasibility of building wind turbines on the island of Salina in Italy. Pilavachi et al. (2006) used 7 criteria and the AHP method to evaluate 9 electrical energy generation options across 19 scenarios. Baumann et al. (2019) comprehensively reviewed MCDA studies on energy storage systems. Ezbakhe and Pérez-Foguet (2020) applied the modified elimination and choice translating reality (ELECTRE) III model to evaluate the renewable energy resources in Turkey, including small hydro, wind, geothermal, solar and biomass, based on five main criteria, namely, technological, technical, economic, environmental and socio-political criteria, and concluded that wind energy is the best alternative energy resource for Turkey.

In general, assessing the performance of different renewable energy systems is considered a complex multi-dimensional problem that mainly involves four criteria, namely, technical, environmental, economic and social criteria (Zhou et al., 2006). MCDA frameworks can be used along with traditional cost–benefit analysis to incorporate objectives, apart from costs, in making decisions related to renewable energy selection and planning. However, different MCDA methods may generate various solutions even when applied to the same problem and data, and determining which method is the most appropriate is usually difficult. By contrast, most of the reviewed literature have applied MCDA to single renewable energy systems instead of multi-vector hybrid systems. Therefore, how to choose an appropriate MCDA methodology for assessing multi-vector hybrid systems becomes imperative. The optimality of different renewable energy systems in a specific region also warrants further study.

3.2 Typical MCDA methods used for DE assessment

The typical MCDA methods used for DE assessment can be categorised as follows:

(1) Methods based on a functional model

Multi-attribute utility theory (MAUT) can be used together with different approaches for generating weights, such as simple weighted average (SWA) and AHP. SWA is one of the simplest and most popular methods for solving problems associated with MCDA. Proposed by T. L. Saaty in 1970s, AHP is another popular approach that requires a pairwise comparison analysis of the hierarchy of factors and their internal relationships.

(2) Methods based on a relational model

These methods, which include the ELECTRE and PROMETHEE, are based on the concept of outranking. ELECTRE is a relational model proposed by Roy (1990), whereas PROMETHEE is a method proposed by Brans et al. (1986) that uses the preference function to discriminate the superiority or inferiority of alternatives based on some criteria.

(3) Methods based on fuzzy set or rough set theory

These methods analyze the decisions that are made under uncertainties by extracting decision rules from past decision examples.

Given that evaluating the performance of renewable energy systems should take into account many interrelated factors from the technical, economic, environmental and social perspectives, this evaluation can be formulated as a complex multi-criteria decision problem and then apply MCDA methods to get comprehensive and reliable analysis for decision making in alternative renewable or DE systems as discussed in the above literature review. However, even by using the same data sources, different MCDA methods may produce different decision outcomes. The above literature review provides some insights about the development trend of using MCDA methods in the context of renewable energy. Although the existing MCDA methods, such as MAUT, AHP and TOPSIS, have been used to support the analysis of various DE systems, the interrelationships among several criteria lack rigorous research, and whether the conditions or assumptions behind specific MCDA methods justify their application is yet to be tested.

Based on MAUT, Bayesian inference and Dempster–Shafer theory, the evidential reasoning (ER) approach has been developed following the principles of probabilistic inference and evidence-based decision making to deal with MCDA problems under various types of uncertainties, including ambiguity and randomness (Yang, 2001; Yang and Xu, 2002). The ER approach uses a belief structure to represent both quantitative and qualitative criteria consistently, a belief decision matrix to formulate an MCDA problem under various types of uncertainties and the evidential reasoning algorithm to enable a probabilistic inference for aggregating multiple criteria and generating distributed assessments. Further advancing the evidential reasoning rule provides a unique method of combining multiple pieces of independent evidence conjunctively with weights and reliabilities (Yang and Xu, 2013). The ER approach requires that the assessment of a renewable energy system based on any criterion should be independent of assessments based on other criteria. In other words, the assessment standard of any criterion for a renewable energy system should be independently determined irrespective of whether its assessments on other criteria are known or not. This condition is more realistic and easier to satisfy and check than those for many other MCDA methods, such as the additive preferential independence condition for MAUT and AHP.

The unique features and realistic application conditions of the ER approach provide opportunities for modeling and assessing the performance of renewable or distributed energy systems within a specific region and under certain situations where the key performance indicators (KPIs) are too strongly correlated to the extent that applying simple additive approaches, such as MAUT and AHP, to aggregate multiple KPIs (criteria) becomes unsuitable. Meanwhile, most MCDA applications in DE systems often analyze each decision alternative as a single renewable energy source. However, DE systems may include a mixed configuration of renewable energies, such as solar and wind energy. The following sections construct a specific MCDA evaluation model by taking into account the characteristics of mixed or multi-vector DE systems.

4 MCDA model based on the ER approach

4.1 Hierarchical assessment framework

In the performance modeling and assessment of renewable energy systems, multiple criteria can be identified and weighted to systematically produce informative assessment results. This approach can also provide an in-depth understanding of the key advantages and inherent impacts and facilitate an informed decision making. Papadopoulos and Karagiannidis (2008) adopted an interdisciplinary approach to analyze the technical, economic, environmental and social factors for the implementation of renewable energy systems. Wang et al. (2009) summarized the different criteria for assessing energy supply systems. Akella et al. (2009) systematically analyzed the social, economic and environmental impacts of renewable energy systems. Ezbakhe and Pérez-Foguet (2020) formulated a model for evaluating renewable energy resources based on technological, technical, economic, environmental and socio-political criteria. Following previous research, a hierarchical assessment framework for a multi-criteria performance modeling of a DE system that can be broken down into technical, economic, social and environmental dimensions is constructed as illustrated in Fig. 4.

4.2 Selection of main criteria

(1) Technical criteria

Technical feasibility and effectiveness are fundamental criteria for assessing renewable energy systems. We can use thermodynamics to assess how effectively and efficiently a renewable DE system works. Technical criteria, such as technical maturity, safety, reliability and self-sufficiency, should be primarily considered in the evaluation (Mamlook et al., 2001; Yu et al., 2006; Madlener et al., 2007; Chatzimouratidis and Pilavachi, 2008; Wang et al., 2009; Twidell and Weir, 2015).

(2) Economic criteria

To maintain economic sustainability and opportunities, the affordability and accessibility of renewable energy systems should be evaluated. The key economic attributes to be considered in the evaluation include initial investment, construction time, operation and maintenance costs, payback time and service life cycle (Doukas et al., 2007; Wang et al., 2009; Karakosta et al., 2013; Ahmad and Tahar, 2014).

(3) Social criteria

Given that most distributed energy systems are located near local communities, the development of renewable energy systems during construction and local consumption

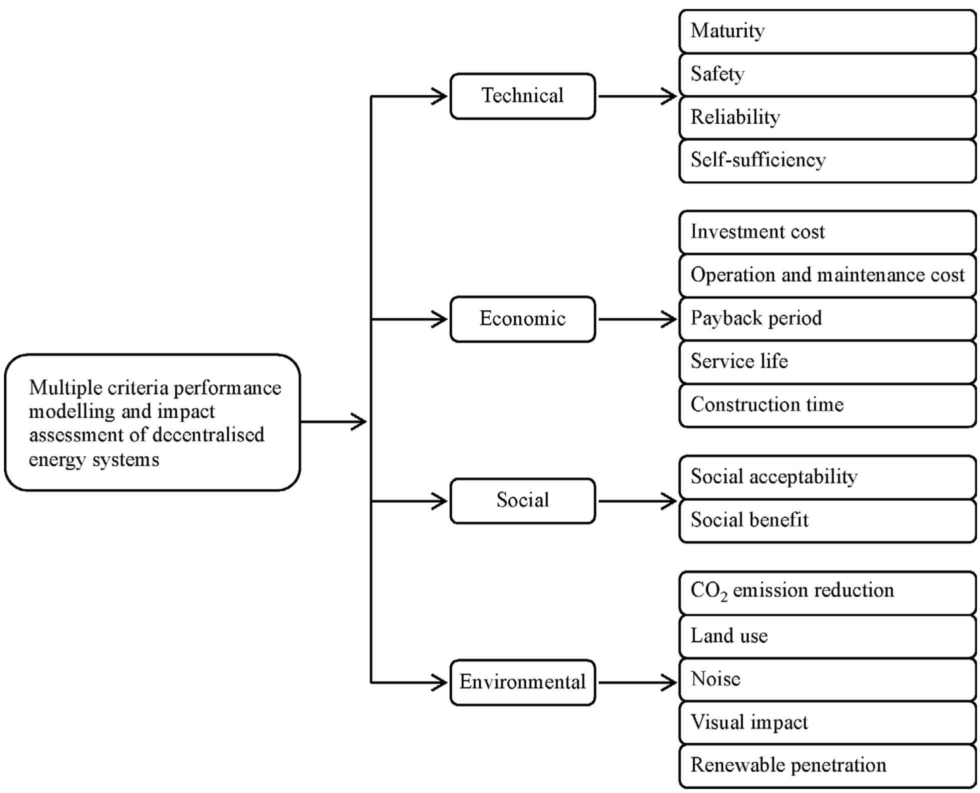


Fig. 4 Hierarchical assessment framework for DE systems.

period plays an important role in shaping the society and involves every aspect of human participation and activity. For example, the development of these systems provides technical and managerial job opportunities. The introduction of some new technologies also regards social acceptance and benefit as criteria (Chatzimouratidis and Pilavachi, 2008; Wang et al., 2009; Mourmouris and Potolias, 2013; Zhao and Guo, 2015).

(4) Environmental criteria

Sustainable development aims to overcome a series of economic, energy and environmental problems, especially global environmental pollution and the unbalanced relationship among the economy, energy and environment. With the increasingly intense environmental protection situation, the requirements for evaluating the environmental efficiency of different energy types have increased, thereby providing new directions for relevant decision-making problems (Lawrence, 2007; Directorate-General for Environment (European Commission), 2009). The stakeholder mapping approach (Mitchell et al., 1997) as illustrated in Fig. 5 can be used for the environmental impact assessment.

Typical environmental impact factors, including CO_2 emissions, SO_2 emissions, land use, noise, exposure to electromagnetic fields and visual impact, should be considered in evaluating various renewable energy systems (Haralambopoulos and Polatidis, 2003; Lawrence, 2007; Wang et al., 2009).

All of the above criteria or factors that are used to assess the performance of renewable energy systems should be identified in a consistent and systematic manner. Furthermore, the relative importance of each category and its impact factors should be taken into account.

4.3 Description of main lower-level criteria

4.3.1 Technical criteria

(1) Maturity

Definition: Maturity is often used to evaluate technologies, and the degree of maturity can be approximated based on whether a certain technology has been widely adopted at the regional, national and international levels. This measure also indicates whether a technology has reached its theoretical efficiency limit or can be further improved. In practice, the maturity of technologies is measured based on whether these technologies have been tested in laboratory settings, used in some private companies, show potential improvements or have reached their maturity and theoretical efficiency limits (Beccali et al., 2003). The assessment grades can be defined as follows:

i) Technologies that are only tested in laboratories (immature);

ii) Technologies that are only used in demonstration projects with the goal of experimenting the operating and technical conditions (poorly mature);

iii) Technologies that are increasingly applied with the scope of further improvement (mature);

iv) Technologies that are consolidated and are close to their theoretical limit of efficiency (sufficiently mature).

(2) Safety

Definition: Safety concerns the well-being of people working in power plants and the protection of infrastructures from any types of damage. Two generic safety indicators are often used in the literature. One is the specific power generation accident, which accounts for the proportion of total power accidents (PA), whereas the other

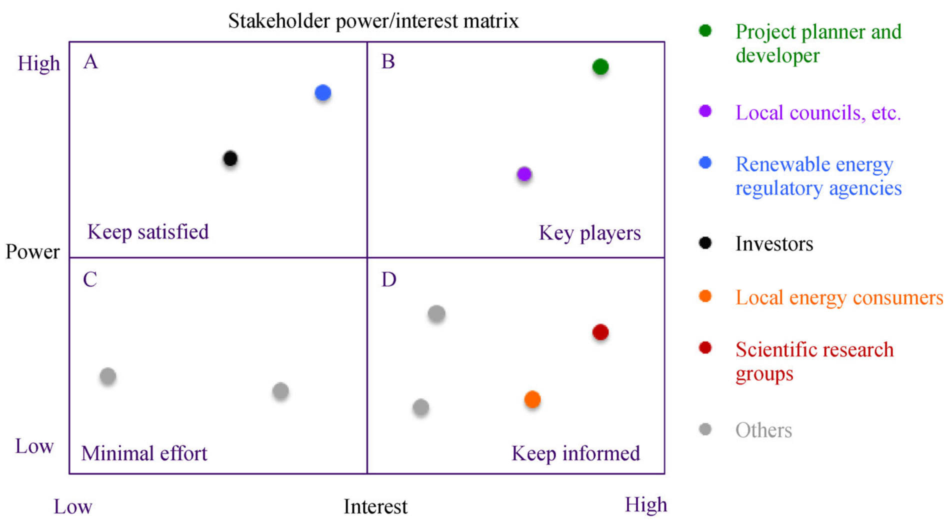


Fig. 5 Stakeholder analysis for environmental impact assessment.

is the proportion of casualties due to accidents to the total number of power casualties (PC) in the previous year. In a hybrid power system (i.e., including multiple types of energy resources), an additive function can be used to calculate PA and PC (Morris and Langari, 2012). The assessment grades can be defined as follows:

i) PA > 0.4 or PC > 0.4 (low safety);

ii) 0.2 < PA < 0.4 and 0.2 < PC < 0.4 (medium safety);

iii) PA < 0.2 and PC < 0.2 (high safety).

(3) Reliability

Definition: Reliability has a wide range of definitions. A reliable power system should be able to provide an uninterrupted power supply to meet the demand with acceptable quality standards. Power system reliability can be broken down into the two basic aspects of system adequacy (or static reliability) and system security (or dynamic reliability). System adequacy relates to the existence of an adequate number of facilities within the system to generate sufficient energy that can satisfy the consumer load demands and meet the operation constraints of power transmission and distribution (Amjady, 2004). Adequacy mainly concerns static conditions, whereas security relates to the ability of a system to respond to dynamic or transient disturbances or faults, which are associated with the conditions where both local and widespread disturbances and the abrupt loss of major generation or transmission facilities can potentially lead to the dynamic, transient or voltage instability of the system (Amjady, 2004).

In practice, static reliability can be measured by the unavailability duration of the system (UDTS), which represents the reliability of equipment based on the mean time to failure (MTTF) of each main component (Fowler and Silver, 2015). For example, if UDTS is less than 8 days per year, then the system will be considered statically reliable. However, if UDTS is longer than 8 days per year, then the system will be considered statically unreliable.

Under the assumption that the load level requires a normal reliability of power supply, two other reliability indicators can be used, namely, loss of load frequency (LOLF) and loss of load expectation (LOLE). In general, the LOLE of reliable energy system ranges from 0.1 to 5 days per year. Practical and theoretical research findings can be used as guides for assessing system reliability:

i) Wind and photovoltaic hybrid power generation have excellent complementary benefits;

ii) If only powered by wind or photovoltaic energy, then the system reliability will deteriorate when the capacity exceeds 500 MW;

iii) A hybrid system with low installed capacity has no obvious advantage. Reliability can be improved when the installed capacity reaches a certain level;

iv) For hybrid systems that store wind power and photovoltaic energy, when the proportion of photovoltaic energy is large, any change in energy storage capacity can greatly affect system reliability;

v) When the installation capacity of a system is less than 400 MW, the access to renewable energy can alleviate the insufficient power supply of the system, reduce the probability of extreme conditions and improve the reliability of the system. When the capacity exceeds 400 MW, the impact on system reliability is related to the access point by which the DE system is connected to the national grids.

(4) Self-sufficiency

Definition: The degree of self-sufficiency can be measured by the ratio between the total generation capacity of a system and the maximum load of consumption. Taking into account the characteristics of DE systems and micro-grids, the optimal situation is that the total power generation can meet the demands and is consumed by the local load (Ruppert-Winkel and Hauber, 2014). Therefore, the degree of self-sufficiency should ideally range between 0.8 and 1.0.

4.3.2 Economic criteria

(1) Investment cost

The investment cost for DE systems covers all costs relating to the purchase and installation of mechanical equipment, engineering services, construction of roads and connections to the national grid (Wang et al., 2009). Further operation and maintenance costs are usually excluded from this cost. Investment cost is the most commonly used economic criterion for evaluating DE systems.

(2) Operation and maintenance cost

Operation cost includes the wages of employees and the funds spent on energy, products and services associated with the operation of an energy system. Maintenance cost is used to extend the lifespan of the energy system and prevent failures. Maintenance cost is much lower than the financial losses incurred from energy system failure, and maintenance also increases the credibility and confidence index of an energy system.

(3) Payback period

Payback period refers to the period during which the lump sum of investment should be paid back to investors. This criterion is often used to assess the profitability of a system. From a financial perspective, investors always favor those projects with short payback periods over those with longer ones.

(4) Service life

Service life refers to the expected lifetime of a system (i.e., how many years a system can be on service). Service life usually follows a U-curve. At the beginning of its service life, a system has high chances of failing before reaching a stable condition. Meanwhile, at its later stages, a system becomes prone to failure again. Those projects with a long service life and a short payback period are undoubtedly highly competitive in attracting investment.

(5) Construction time

Construction time refers to the entire period of constructing an energy system. The length of construction can somehow reflect the degree of difficulty of implementing an energy system.

4.3.3 Social criteria

(1) Social acceptability

Social acceptability measures the overall opinion of the local population directly affected by an energy project (Kaya and Kahraman, 2010). Such opinion may heavily influence the amount of time needed to complete such project. Therefore, the social acceptability of a project can be evaluated via surveys or focus group meetings. For example, a rating ranging from –2 and +2 can be used to reflect the expected attitudes of the population toward the installation of power plant technologies in their local regions (Brand and Missaoui, 2014). Meanwhile, a 0 score can be given to those technologies on which the local population have no explicit preference or in cases where the local reserved opinions are outweighed by the generally positive reputation of the technology in a wider community. A +2 score is given to those technologies that are proven to positively affect the ecosystem and environment, do not incur extra costs and have no negative effects on property value.

(2) Social benefit

Social benefit covers many aspects, such as job creation, tax redemption and income generation, that are to be brought to a local region, especially less developed ones, upon the introduction of an energy project. This criterion can be recapitulative in the assessment.

4.3.4 Environmental criteria

(1) CO_2 emission reduction

CO_2 emission reduction is a key consideration in the development of DE systems. This quantitative criterion can be calculated approximately.

(2) Land use (km^2/1000 MW)

Each energy power plant needs to occupy land, which will lead to environmental and landscape changes. Therefore, land use is broadly regarded as a social impact criterion.

(3) Noise

The noise pollution generated by aerodynamic and mechanical sources, including energy power plants, can be disruptive to both animals and humans. Noise pollution not only affects the environment but also harms human physiologic heath given that humans can suffer from hearing loss if they are exposed to a very noisy environment for extended periods. Noise may also indirectly lead to operational accidents. Sound pressure level can be used to measure noise levels in residential areas (Walker and Jenkins, 1997). This criterion can be measured quantitatively in dB. In general, the noise levels within the proximity of residential areas must be lower than 45 dB.

(4) Visual impact

Visual impact reflects the visual nuisance that may be caused by the development of an energy project in an area (Wang et al., 2009). This criterion is often used to evaluate alternative solar and wind energy plants. Evaluating the visual impact of alternative DE systems needs to consider the landscape of different sites, the distance from nearest observers, the type and size of plants to be installed and the possibility to integrate these plants into their surroundings.

(5) Renewable penetration

Renewable penetration refers to the percentage of electricity generated by a renewable resource (Wu et al., 2019). This criterion can be quantified by the percentage relative to the total amount of electricity either generated or consumed.

5 Case study of a micro-grid project in an industrial park

This case study examines a large micro-grid project that is constructed in an industrial park in China. This project is a multi-vector DE system that integrates solar panels, wind turbines, storage and diesel backup. Solar panels and wind turbines are installed on the roofs of all buildings, and a battery storage system is included in the combined system as a characteristic of intermittent power supply of solar and wind energy. The whole system is integrated into an intelligent management platform of power utilization in order to coordinate and integrate multi-vector energies efficiently. Given that the system is off grid and has its own distribution network, the generated power can be consumed locally to reduce the load during peak hours and to improve the efficiency of final energy consumption. This project was initially launched for demonstration purposes without prior performance modeling and decision analysis.

The hybrid distributed energy system includes 400 kW of roof photovoltaic energy, 100 kW of carport photovoltaic energy, 10 kW of wind energy, 450 kW lithium-ion batteries and 1500 kW diesel generators for backup. To analyze the performance of different hybrid energy systems and make the optimal choice, four alternatives have been proposed, namely, A1, A2, A3 and A4, of which A1 has only 500 kW of photovoltaic energy, A2 has a combination of 500 kW of photovoltaic energy and 10 kW of wind energy, A3 includes an additional energy storage into A2 and A4 adds another diesel generator into A3 for backup.

According to the survey data of this project and the assessment framework, the detailed information of each criterion in each alternative is shown in Table 1.

Table 1 Information for all criteria in four alternatives

Top criteria	Lower criteria	Unit	A1-PV	A2-PV+Wind	A3-PV+Wind +Storage	A4-PV+Wind +Storage+Diesel
Technical	Maturity	scale	[0, 0, 0, 1]	[0, 0, 0.3, 0.7]	[0.5, 0.3, 0.2, 0]	[0.6, 0.3, 0.1, 0]
	Safety	scale	[0, 0.1, 0.9]	[0, 0.2, 0.8]	[0, 0.3, 0.7]	[0, 0.3, 0.7]
	Reliability	score	–2	0	1.5	2
	Self-sufficiency		1	1	1	1
Social	Social acceptability	scale	[0, 0.2, 0.8]	[0, 0.3, 0.7]	[0, 0.4, 0.6]	[0, 0.35, 0.65]
	Social benefit	scale	[0, 0.2, 0.8]	[0, 0.15, 0.85]	[0, 0.1, 0.9]	[0, 0.1, 0.9]
Economic	Investment cost	million £	0.48	0.52	0.93	1.29
	Service life	year	25	25	18	18
	Construction time	month	5	6	8	8
	Payback period	year	6	8	15	18
Environmental	Renewable penetration		1	1	1	0.95
	CO_2 emission reduction	ton/year	449	580	580	430
	Noise	dB	0	36.5	41.2	44.5
	Land use	km^2/1000 MW	0	0	0	0
	Visual impact	scale	[0.2, 0.6, 0.2]	[0.5, 0.5, 0]	[0.6, 0.4, 0]	[0.6, 0.4, 0]

Four top-level criteria, namely, technical, economic, social and environmental criteria, are used. Weights are directly assigned to these criteria by taking into account the project itself. This demonstration project intends to promote the development of technologies in hybrid multi-vector energy system if operated and managed successfully. Therefore, the highest weight is assigned to the technical criterion. Given that this system includes renewable energy, which has minimal impacts on the environment compared with conventional energy sources, the environmental criterion is regarded as the second important criterion. The other two criteria are given the same importance. The weights for the technical, social, economic, and environmental criteria are set to w_1 = 0.45, w_2 = 0.15, w_3 = 0.15 and w_4 = 0.25, respectively.

The 4 top-level criteria are divided into 15 sub-criteria. To generate the weights for these sub-criteria, the direct assignment method is applied following the opinions of stakeholders. The weights for each sub-criterion are summarized in Table 2.

The decision problem is then analyzed based on the MCDA model described in Section 4. The analysis results generated by using the intelligent decision system (IDS) (Xu and Yang, 2003) are shown in Figs. 6 and 7. Figure 6 shows that A4, which includes PV, wind energy, battery storage and diesel generator, ranks first, followed by A3, which includes PV, wind energy and storage. Meanwhile, Fig. 7 shows that the single PV system A1 outperforms all the others in terms of the economic criterion given that A1 has the shortest construction time and payback period. However, A1 ranks the lowest in terms of the technical criterion given its low reliability and intermittent power generation.

Table 2 Weights of different levels of criteria

Top criteria	Lower level criteria
Technical w_1 = 0.45	Maturity w_{11} = 0.1
	Safety w_{12} = 0.1
	Reliability w_{13} = 0.5
	Self-sufficiency w_{14} = 0.3
Social w_2 = 0.15	Social acceptability w_{21} = 0.5
	Social benefit w_{22} = 0.5
Economic w_3 = 0.15	Investment cost w_{31} = 0.2
	Service life w_{32} = 0.3
	Construction time w_{33} = 0.2
	Payback period w_{34} = 0.3
Environmental w_4 = 0.25	Renewable penetration w_{41} = 0.3
	CO_2 emission reduction w_{42} = 0.3
	Noise w_{43} = 0.2
	Land use w_{44} = 0.1
	Visual impact w_{45} = 0.1

The alternative A4 is a hybrid system that outperforms the other three systems not only in terms of overall performance but also in terms of the technical criterion. Assuming that the weight of the technical criterion is relatively high, a change in the weight of this criterion can change the overall performance rankings of the evaluated systems. However, a balance point is found in the process. Specifically, alternatives A1 and A2 outperform A3 and A4 in terms of the top-level economic criterion, but their overall performance is lower than that of the other two

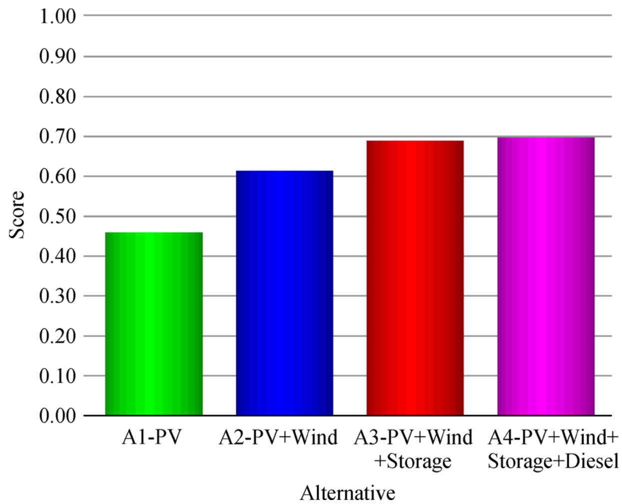


Fig. 6 Ranking of the four alternatives in terms of overall performance.

alternatives given that the economic criterion has a relatively low weight. Similarly, a change in the weight of the economic criterion also leads to a change in the overall ranking and performance of these systems as shown in Fig. 8. Therefore, eliciting the weight of each criterion is very important in solving the MCDA problem, and the generation method needs to consider each alternative and the preferences and opinions of different stakeholders. Different weights directly affect the decision outcomes of alternative energy systems. Results of the sensitivity and trade-off analyses are presented in Figs. 8 and 9, respectively.

A trade-off analysis is conducted between any two top- or lower-level criteria. In Fig. 9(a), reliability is chosen as the lower-level criterion, whereas the economic is used as the top-level criterion in the trade-off analysis. Results in Fig. 9(a) clearly show that A1 has a high economic performance yet low reliability, whereas A4 has a very high reliability. Results in Fig. 9(b) show that A4 has a high technical performance yet long payback period, while A1 has a short payback period. Any other two top- or lower-level criteria can be subjected to a trade-off analysis. This analysis is closely related to the preferences of stakeholders.

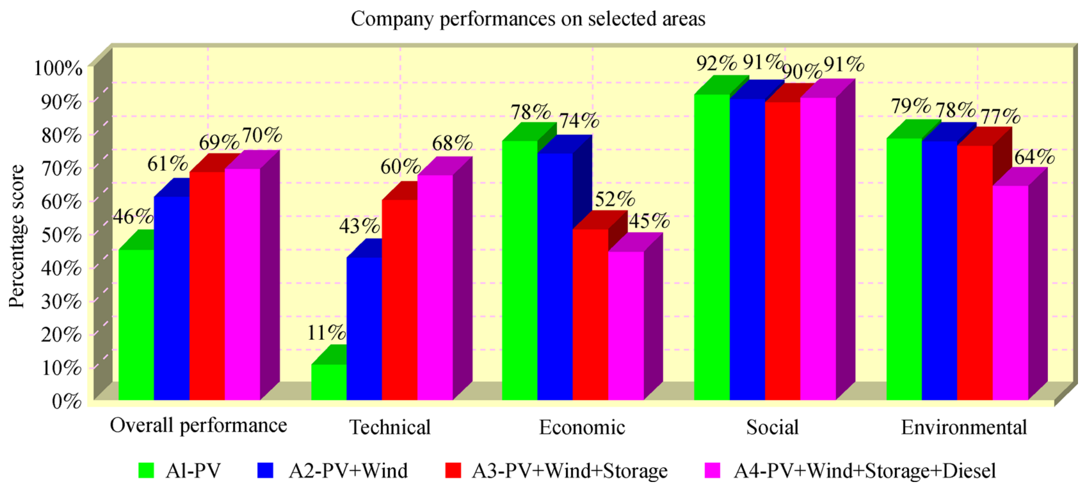
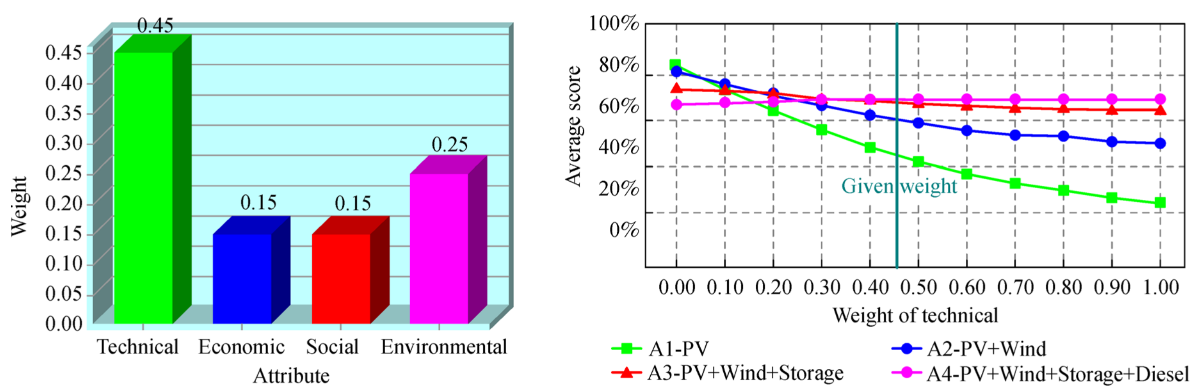


Fig. 7 Ranking of the four alternatives for the overall performance as well as each top-level criterion.



(a) Change weights for overall performance

(b) Average scores of alternatives on overall performance

Fig. 8 Sensitivity analysis after changing the weight of the technical criterion.

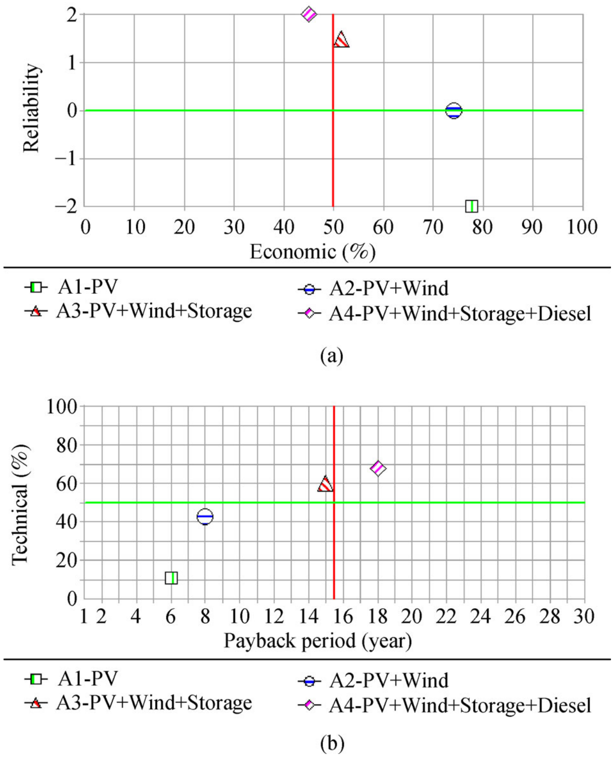


Fig. 9 Trade-off analysis among economic criterion, reliability, technical criterion and payback period.

6 Conclusions

DE is one of the most effective solutions to the energy trilemma. Therefore, systemically modeling and assessing the performance of alternative DE systems are crucial. The assessment of DE systems is considered a complex MCDA problem that needs to take into account technical, environmental, economic and social aspects. The literature review in this paper provides a holistic overview of the trend of future energy development amidst the energy trilemma, highlights the importance of DE systems (especially multi-vector decentralised renewable energy systems) and describes the challenges in the performance evaluation of these systems. According to the nature and characteristics of DE systems, this paper presents performance modeling and multiple criteria decision analysis models for multi-vector decentralised renewable energy systems. The proposed model is applied in a case study of alternative micro-grid energy systems in an industrial park in China. The results of the sensitivity and trade-off analyses reveal how the proposed MCDA model can be used to support an informed decision making regarding alternative multi-vector DE systems. Future research should identify highly granular performance indicators in real-world applications and quantify the relationships and dependence among several criteria in value or utility functions. Additional case studies should also be performed for different decentralised renewable energy systems across various regions or countries.

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