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Reliability and economic evaluation of power system with renewables: A review

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ABSTRACT

The share of renewable energy generation has been increasing as a result of the world-wide concern on environmental deterioration and climate change associated with burning fossil fuel. Due to the stochastic and intermittent characteristics of renewable energy resources, assessing the reliability of power systems with renewables has become challengeable and been widely studied for the past several decades. This paper provides a review of the studies on the reliability and economic evaluation of power system with renewables. It starts from a summary of the key indicators and models for assessing the reliability and economics of power systems. Different studies are then compared in terms of type of renewables, evaluation method, application area, level of study and country involved, through which the main features of past studies are identified. We also discuss the relationship between economics and reliability that shows the necessity of evaluating reliability and economics of power system with renewables simultaneously. A case study is finally proposed to illustrate the differences between alternative system settings in reliability and economic evaluation. It is found that the types and scales of renewable energy generation have significant impacts on system reliability and economics, which needs to be taken into account in the development of renewable energy power systems.

Contents

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1. Introduction

Renewables, also known as renewable energy, is energy that is derived from natural processes (e.g. solar and wind) that are replenished at a higher rate than they are consumed [1]. Promoting renewable energy consumption has widely been regarded as one viable way of reducing carbon dioxide emissions, improving energy supply security and developing green economy. Past decades have seen a rapid growth of the installed capacity of renewable energy power generation in the world. For example, in 1996 the installed capacity of wind turbine generator (WTG) was only 6.1 GW, but it reached 318.2 GW in 2013 with an annual growth rate lying between 20 and 40 percent [2]. For solar PV power generation, the global installed capacity increased from 0.96 GW in 1998 to 141.5 GW in 2013 [3]. It is no doubt that the renewable energy power generation will play more and more important role in the future energy mix [4].

There are two inevitable and fundamental characteristics for renewable energy power generation, i.e. reliability and economics. Reliability is composed of adequacy and security. Adequacy refers to the ability of a system to meet the aggregate power and energy requirement of all consumers at all times, and security is the ability of a power system to deal with sudden interruption [5]. Economics represents an ultimate cost-benefit evaluation of a power system on an acceptable level of reliability. Reliability is connected with economics that has impacts on investment decisions. When electricity generated from renewables parallels in the grid, several issues may arise in power grid operation and management. First, renewable energy is highly random and intermittent due to the uncertainty in wind speed and solar irradiance. Second, the volatility of distributed power is high but the electricity output is small. Third, the co-existence of in-grid and off-grid modes increases the complexity of power system. These issues will certainly affect the reliability of power system. In addition, the initial investment cost of renewable power generation, including both installment cost and equipment replacement cost, is substantially higher than the conventional fossil fuel -fired power generation. One main goal of modern power grid is to transmit electricity uninterruptedly at a relatively lower cost, and reliability and economics become two crucial characteristics of electric power system [6].

Many earlier studies inclusive of several review ones have contributed to examine the reliability and economics of renewable power system. For example, Lin et al. [7] reviewed the models and algorithms for evaluating the reliability of wind power system in the planning and operational phases. Jiang et al. [8] reviewed the reliability evaluation methods and models for wind power generation. Borges [9] summarized three types of reliability evaluation methods for electricity distribution with renewables. Chaiamarit and Nuchprayoon [4] reviewed the reliability models for power generation by renewable energy resources. Fathima and Palanisamy [10] provided a review of models for reliability assessment of renewable power generation with an applications to micro-grid optimization. It can be found that these earlier review studies summarize the models and algorithms in a relatively comprehensive way but provide insufficient discussions on the application features of past studies. In addition, they mainly deal with wind power. On the other hand, economics as an indispensable characteristic in renewable power system assessment was not discussed in the earlier review studies. In view of the connection between reliability and economics, it is worthwhile conducting a review of the studies on both reliability and economic evaluation of power system with renewables, which is the purpose of the study. It is expected that such a review study not only provides a useful guide to the beginners but also helps identify the potential future research directions in this area from both theoretical and application perspectives.

The remainder of this paper is organized as follows. In Section 2, several commonly used reliability indicators of power generation and distribution are introduced. The conventional reliability evaluation methods as well as their extensions to renewable power generation are categorized into the analytical, simulation and hybrid methods. Section 3 reviews the methods for economic evaluation of power system with renewables. In Section 4, we summarize the main features of past studies in terms of type of renewables, evaluation method, application area, level of study and country involved. Possible future research directions in this field have also been identified. Section 5 provides a case study to show the necessity of considering economics in reliability evaluation of power system. Section 6 concludes this study.

2. Reliability evaluation

Assessing the reliability of electric power system with renewables as an important research area in energy systems modeling has continuously been developed and advanced. The study by Billinton and Hossain [11] provided a foundation for quantifying the impacts of component uncertainty such as unexpected generator outages on power system reliability. Since then, many methods for evaluating the reliability of electric power system have been proposed. In the followings, we summarize the key indicators and models employed in the earlier studies.

2.1. Reliability indicators

An electric power system can be classified into power generation, transmission and distribution systems. Modeling the reliability of an electric power system may be conducted from three hierarchical levels [12]. The first level considers only the adequacy of electricity generated. The second level, covering both generation and transmission, evaluates the transmission continuity from supply point to load point. The third level encompasses the first and second levels but mainly evaluates the reliability of distribution system due to the complexity of the whole power system. In literature, most studies evaluate the reliability of power system from the perspective of the third level. Evaluating the reliability of power system often consists of three steps, i.e. state selection, state estimation and the calculation of indicator value. As such, the reliability evaluation of power system is heavily dependent on the definition of reliability indicators and their calculation process. A sketch of past studies shows that different indicators have been used to evaluate the system reliability for power generation and distribution systems. Furthermore, we classify the reliability indicators for power distribution system into two groups, i.e. load point reliability indicators and system reliability indicators. Table 1 provides several popular indicators used in the past studies.

For power generation system, three reliability indicators are often used, namely frequency (F), average duration (D) and unavailability (U). F denotes the frequency of a component from

Table 1
Reliability indicators of power system.

Power system		Reliability indicators
Generation		Frequency (*F*) [4,12]
		Average duration (*D*) [12]
		Unavailability (*U*) [4,12]
Distribution	Load point	Failure rate (λ) [9,13]
		Annual outage time (*UOT*) [9,13]
		Outage time (*r*) [9,13]
	System	System average interruption frequency index (*SAIFI*) [9,13,14]
		System average interruption duration index (*SAIDI*) [9,13,14]
		Average service availability index (*ASAI*) [9,13,14]

service state to outage state. *D* refers to the average duration of a component under outage condition. *U* is the probability of a component at outage state. Eqs. (1) to (3) show the mathematical expressions of the three indicators.

$$F = \frac{s \cdot \lambda}{s + r} \tag{1}$$

$$D = \frac{r}{s \cdot \lambda} \tag{2}$$

$$U = \frac{r}{s + r} \tag{3}$$

where *s* is a component's mean duration in service, *r* is its mean duration under outage condition, and λ is its failure rate [12].

For the load point of distribution system, the main indicators used are failure rate (λ), annual outage time (*UOT*) and outage time (*r*). λ is defined as the failure frequency of load point. *UOT* denotes the annual outage time of the load point in system. *r* refers to the mean time required to repair once the system is at outage state. Their mathematical expressions are given by

$$\lambda = \frac{\sum \lambda_{ij}}{NS}(\text{times/year}) \tag{4}$$

$$U = \frac{\sum \lambda_{ij}}{NS}(\text{hour/year}) \tag{5}$$

$$r = \frac{U}{\lambda}(\text{hour/times}) \tag{6}$$

where *i* is the number of interruption states in each simulation for load point, *j* is the number of simulations, λ_{ij} is the failure rate, r_{ij} is the outage repair time [13].

The reliability indicators of distribution system include system average interruption frequency index (*SAIFI*), system average interruption frequency index (*SAIFI*) and average service availability index (*ASAI*). Eqs. (7) to (9) show their mathematical expressions.

$$SAIFI = \frac{\sum_i \lambda_i N_i}{\sum_i N_i}(\text{times/customer} \cdot \text{year}) \tag{7}$$

$$SAIDI = \frac{\sum_i U_i N_i}{\sum_i N_i}(\text{hour/customer} \cdot \text{year}) \tag{8}$$

$$ASAI = \sum_i N_i \times 8760 - \frac{\sum_i U_i N_i}{\sum_i N_i \times 8760}(\%) \tag{9}$$

where λ_i is the failure rate of load point *i*, N_i is the quantity of customers, U_i is the yearly interruption hours of load point *i*, *SAIFI* is defined as the yearly average interruption times for all customers in the system, *SAIDI* refers to the yearly average interruption duration of all the customers in the system, and *ASAI* denotes the ratio of electricity supply hours to electricity demand hours [14].

It can be observed that the load point reliability indicators of distribution system provide a basis for calculating other indicators. In contrast, the system reliability indicators are more encompassing, which usually measure the frequency or duration of interruption events during the time period. These indicators play a fundamental role in assessing the reliability of power systems.

2.2. Reliability evaluation models

Once reliability indicators are defined, the next stage is to select an appropriate method to compute the reliability indicators efficiently. In literature, there are a number of classical methods for evaluating power system reliability. Some methods are later refined to adapt the case when renewable energy generation parallels in power system. Following [15], we classify the methods into three groups, namely analytical method, simulation method and hybrid method. In the followings, we shall give an introduction to the methods as well as their extensions.

2.2.1. Analytical method

In the analytical method, the first step is to establish a reliability probability model for the system according to system structure and function as well as the relationships between system and components. The model is then solved by operating the recursive or iterative process and calculating the reliability indicators. Several commonly used analytical methods are fault tree analysis, failure mode and effect analysis, minimal path method, minimal cut method, and fault traversal algorithm. For example, Awosope and Akinbulire [16] proposed a fast evaluation method based on minimal path, which evaluates the influence of load point reliability indicator by considering the minimum and non-minimum path elements simultaneously. Chanda and Bhattacharjee [17] presented a fuzzy fault-tree that is based on reliability analysis of an optimally planned transmission system. Kobayashi and Yamamoto [18] combined minimal path method with the network equivalent method for complex distribution system. Hong and Lee [12] presented a method that integrates deterministic approach with fault tree analysis for reliability evaluation of generation and transmission in power system.

Despite the usefulness of the conventional analytical methods described above, they cannot be directly applied to evaluate the reliability of renewable power generation. For example, the uncertainty in wind speed results in the intermittent characteristic of wind power output, which cannot be handled by the conventional analytical methods. Researchers have thus improved the algorithms in the analytical methods to evaluate the power system reliability with renewables (see Table 2). In this line, Stember et al. [19] improved the traditional fault tree model and Markov chains to evaluate the reliability of solar PV system. Later, many other models were developed to reduce the complexity of system state and optimize the process of reliability evaluation, e.g. [20–22].

The analytical methods have been widely used in reliability evaluation of power system owing to its simplicity. However, the algorithms used in the analytical methods are often very complicated. As such, the scale of the power system being studied might be limited.

2.2.2. Simulation method

Compared to the analytical method, the simulation method has certain strengths, e.g. higher computation efficiency, larger-scale system applications and the capability in dealing with the variation of load points. Their difference mainly lies in state selection. In

Table 2
Studies on the analytical method with renewable power generation.

Study	Renewable energy	Algorithm	Reliability indicators	Result/findings
Stember et al. [19]	Solar	Fault tree model, Markov chains	MTBF, TE	Demonstrate the functional models can be expended to more detailed and applied to PV system
Iniyanet al. [20]	Solar & Biogas	Optimal renewable energy mathematical	ER	Optimize the values in the utilization of renewables options and reach maximization of efficiency
Kaviani et al. [21]	Solar & Wind	Particle swarm optimization	LOLE, LOEE, LPSP, ELF	Reduce the complexity system state from 6000 to only 2 and the computation time
Dobakhshari and Fotuhi-Firuzabad [22]	Wind	Markov chains, Probabilistic model	FOR, LOLE, LOLF, LOLD, EENS	Seasonal patterns significantly affect the reliability indexes
Bouhouras et al. [6]	General	Multi-objective dynamic combinatorial	SAIDI, CAIDI, ASIDI	Improve the level of system reliability with renewables

MTBF-mean time between failure, TE-total energy output, ER-efficiency ratio, LPSP-loss of power supply probability, LOLE-loss of load expectation, LOEE-loss of energy expectation, ELF-equivalent loss factor, LOLD-loss of load duration, LOLF-loss of load frequency.

Table 3
Studies on the simulation method with renewable power generation.

Study	Renewable energy	Algorithm	Reliability indicators	Result/findings
Stember et al. [19]	Solar	Event-structured simulation	failure, repair and time event	The model simulates the system over its entire lifetime ranging from 20 to 30 years
Billinton et al. [27]	Wind	Sequential simulation	LOLE, LOEE	LOLE decreases exponentially as WTG units added or wind penetration level increased
Karki and Billinton [28]	Wind	Monto Carlo simulation	EWES, ESWE	Capacity expansion should be determined by both the reliability and economics advantages
Billinton and Cao [29]	Wind	Monte Carlo state-sampling simulation	LOLE, LOEE	The power output of a WTG is dependent on the wind regime

EWES-expected wind energy supplied, ESWE-expected surplus wind energy, WECS-wind energy conversion systems.

the reliability evaluation of power system, the simulation method include Monte Carlo Simulation (MCS), artificial neural network (ANN) and non-exponential distribution methods. For example, Chen [23] used ANN method to predict the distribution system reliability with historical data. Goel [13] calculated the load point reliability indicators and system reliability indicators by using the MCS method. Pievatolo [24] developed an analytical model to deal with non-exponential life and repair time distributions.

Of the alternative simulation methods, MCS is widely used in power system reliability evaluation for stochastically sampling the states of components in the system. The MCS method can be classified into two different representations, i.e. state space and chronological representations. In the chronological representation, the sequential simulation generates a system state sequence of components according to their failure and repair rates. The continuous time information in service state of system is obtained by sequential MCS. In the representation of states space, the states of the system are randomly sampled by non-sequential MCS. Vitorino et al. [25] used a non-sequential MCS based on the branch reliability to evaluate the reliability of network configurations. In non-sequential MCS, the states of the system are obtained by sampling the states space of components according to its forced outage rate, which are not relevant to the chronology of the events and the state transition of the components [9,26].

The conventional simulation methods are further refined to simulate hourly wind speed of WTG and solar radiation of PV. Table 3 shows several improved algorithms which are more flexible to accommodate the complex and diverse power system with renewables. Accordingly, new indicators are also developed to compute the system reliability. For instance, the indicators EWES and ESWE are developed for evaluating the reliability of wind power system [28].

2.2.3. Hybrid method

The hybrid method for evaluating power system reliability integrates the high computational accuracy in the analytical method with the stochastic characteristics embedded in the simulation method. It can efficiently deal with most of the reliability problem. It was firstly proposed by Clancy [30] to evaluate the reliability of multiple area power systems. Billinton and Li [31] then combined normal distribution sampling technique with linear programming model to estimate system state. Pereira and Pinto [32] showed that the hybrid method helps to reduce the variance of Monte Carlo simulation. Billinton and Chu [33] calculated the reliability indicators of power system by simulation method and estimate the system state by analytical method simultaneously.

In recent years, some new hybrid methods, which combines probabilistic model/linear apportioning technique with MCS/Neuro-Fuzzy/Genetic algorithm, are applied to the reliability evaluation of renewable power system. The simulation methods are used to sample the state of components and compute the renewable power output, and the analytical methods are used for ensuring the computational accuracy [34–39]. Table 4 summarizes several relevant studies. Since the hybrid method overcomes the limitations of analytical and simulation methods and provide higher flexibility of renewable power system, it is likely to gain more popularity in the future.

3. Economic evaluation

3.1. Relationship between reliability and economics

Economic benefit is another crucial problem to be considered when electricity generated from renewable energy is on grid. Inadequate reliability of electric power supply ultimately costs

Table 4
Studies on the hybrid method with renewable power generation.

Study	Renewable energy	Algorithm	Reliability indicators	Result/findings
Rajkumar et al. [34]	Solar&Wind	Neuro-Fuzzy, Genetic, PSCAD simulation	LPSP	The optimized system can supply power to the load with low excess energy
Xie and Billinton [35]	Wind	Analytical, Monte carlo simulation	ECR	The ECR is a useful index for a WTG to the relative reliability performance
Lujano-Rojas et al. [36]	Solar&Wind	Probabilistic model, Monte carlo simulation,Artificial neural network	ENS	ANN-based model could represent the main characteristics of hybrid system under high reliability
Nikhil and Subhakar [37]	Solar	Analytical, Simulation	AHL	Combine analytical sizing equation with simulation can optimize the design of PV system
Chattopadhyay [38]	Solar&Wind	Climate model, Analytical, Monte carlo simulation	EUE	A balanced development of renewable and conventional power generation capacity should consider system economics and security
Chen et al. [39]	Wind	Linear apportioning technique, Monte carlo simulation	LOLE, LOEE	The value differences of LOLE and LOEE will increase if the correlation of WTG outages grows

ECR-equivalent capacity ratio, AHL-ampere hours lost, EUE-expected unserved energy.

customers much more than adequate reliability [40]. Fig. 1 shows the relationship between reliability and economic cost. System reliability normally increases with investment cost. In other words, maintain cost and customer damage cost decrease as the reliability level increases. Customer satisfaction, which is mainly determined by reliability, has an influence on customer demand. With the increase of customer demand, the total cost decreases and the benefit increases.

In view of the relationship between reliability and economics, it is important to determine the optimal reliability level at which the investment on improving system reliability is most cost effective in reducing the customer damage costs due to power supply interruptions. Several studies have empirically examined the relationship between reliability and economics. For instance, Ghajar and Billinton [41] assessed the reliability worth of power system by a consistent dataset of interruption cost. Kleyner and Sandborn [42] incorporated several reliability-related factors into a comprehensive probabilistic cost model. Georgilakis and Katsigiannis [43] implemented a complete reliability cost and worth analysis for small autonomous power systems. Hamdan et al. [44] utilized the Load Modification Technique to assess the impact of policy implementation on energy production, overall cost, commercial losses and reliability. Röpke [45] compared the value of supply security with its provision costs.

3.2. Economic evaluation models

In order to make a consistent appraisal of economics and reliability, it is necessary to assess the economic value for achieving a specified reliability level of system. Traditional cost evaluation techniques include cost-benefit analysis (CBA) and life-cycle energy cost (LCC) models. In economic evaluation of power system, CBA is often used to calculate and compare the benefits and costs of a given service area, while LCC model can be used to evaluate the cost sensitivity of power system with respect to the variation of component reliability.

3.2.1. Cost-benefit function

Evaluation of the costs and reliability associated with different system configurations is generally designated as reliability cost-benefit assessment. Reliability cost-benefit studies can be performed through incorporating economics factors into decision-making process of reliability evaluation.

The costs can be classified into investment, maintenance and operation costs. The benefits are comprised of gains from selling electricity, environmental and social benefits due to the adoption of renewable power generation technologies, etc. However, customer damage costs resulting from power supply interruptions are uncertain, which may be estimated by the traditional models such as customer damage function (CDF) or composite customer damage function (CCDF). A CDF provides the interruption cost versus interruption duration for a specific group of customers. The CCDF represents the total interruption cost as a function of the interruption duration in a particular service area or at a specific bus [6].

In CCDF, it is necessary to predict future interruption costs with data collected through estimating the system reliability indicators such as expected energy not supplied (*EENS*) and expected customer damage cost (*ECOST*). Eqs. (10) and (11) show the mathematical expressions of the two indicators [6].

$$EENS = \sum_{i=1}^{N} m_i f_i d_i (\text{kW h/period}) \tag{10}$$

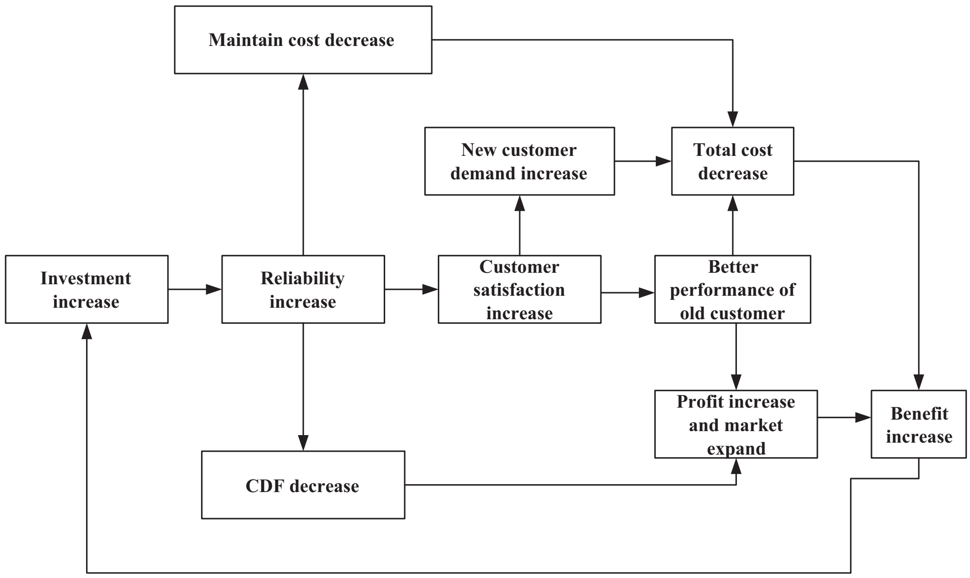

Fig. 1. Relationship between reliability and economics.

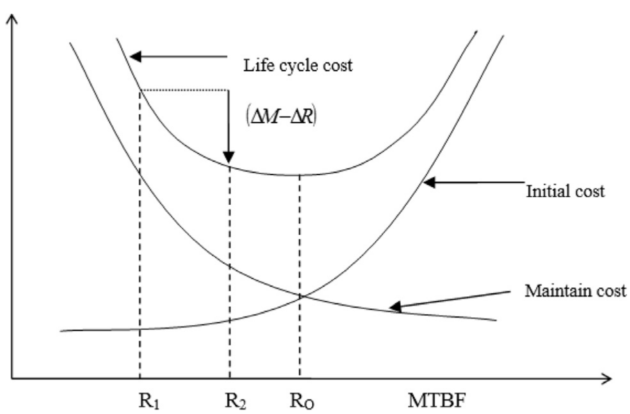

Fig. 2. Optimization of life cycle cost [19].

$$ECOST = \sum_{i=1}^{N} c_i(d_i) f_i m_i (\$/\text{period}) \quad (11)$$

where m_i is load curtailed (kW) due to capacity shortfall, f_i is the frequency of outage event i, d_i is duration of outage event i, $c_i(d_i)$ is the cost in \$/kW of outage duration d_i using the cost function CCDF, and N is the total number of load outage events.

IEAR, an indicator in reliability cost analysis, is defined as the ratio of *ECOST* to *EENS* at either the load buses or for the overall system, as shown in Eq. (12). It is a convenient and understandable indicator, which provides a monetary evaluation of energy deficiencies at the load buses and for the overall system from the point of view of customer damage cost.

$$IEAR = \frac{ECOST}{EENS} (\$/\text{kW h}) \quad (12)$$

3.2.2. Life-cycle energy cost model

The life-cycle cost of a power system can be expressed by

$$LCC = C_o + \sum_{i=1}^{L} \left[\sum_{j=1}^{N} (R_{ij} + P_{ij}) \right] \left[\frac{(1+e)^i}{(1+k)^i} \right] \quad (13)$$

where *LCC* is system life-cycle cost, C_o is initial system cost, L is mean system lifetime, N is the number of components, R_{ij} is the repair cost for component j in year i, P_{ij} is the preventive maintenance cost for component j in year i, e is the repair cost escalation rate, and K is cost-of-capital rate.

The optimal system is with low initial cost but high reliability, which can easily maintain the system with minimum life-cycle cost per unit of energy delivered. As shown in Fig. 2, the optimal life-cycle cost is a function of the mean time between failure (MTBF). $(\Delta M - \Delta R)$ denotes the value of life cycle cost decreased when system reliability increases from R_1 to R_2. The minimum of the U-shaped life cycle cost is achieved at R_o, where the system reliability also reaches an optimal level relatively. If the value of system reliability is higher than R_o, the MTBF will be higher while the life cycle cost will also increase.

When renewable power generation is considered, it is required to evaluate the system in terms of economics again. However, the basic methods are still CBA and LCC. In economics evaluation, parameters like NPC [36], EPBP [46] and ACS [21] are always the objectives to minimize, and the correlative constraints contain installation cost, maintenance cost, penalty costs for emissions, conventional unit operation cost, investment cost, battery cost and incomes [47,48]. Because of the specificity of renewable power generation, cost becomes a common concern of many studies. Table 5 shows a summary of the studies on economic evaluation of renewable power generation.

4. Main features of past studies

4.1. Methodology aspect

Table 6 provides a summary of the studies on reliability and economic evaluation of power system with renewables according to the following attributes: type of renewables, method, application area, level of study, country involved, and positive correlation between economics/management and reliability. Fig. 3 shows the shares of different methods used in the studies given in Table 6. It is found that the analytical method accounts for 23 percent while nearly 47 percent of the studies use simulation method. Due to the stochastic and intermittent characteristics of renewables, the reliability evaluation of power system with renewables requires the simulation of renewable energy power output. With the simulation method, researchers can obtain the data through stochastically sampling without historical data. Owing to these merits, the simulation method will continuously play an important

Table 5
Studies based on economic evaluation of renewable power generation.

Study	Renewable energy	Method	Objective	Variables	Result/findings
Karki and Billinton [35]	Wind	Cost-benefit	Minimum total investment cost	installations, maintenance cost, penalty costs for emissions, conventional unit operation cost	Capacity expansion should be determined by both the reliability and economics advantages
Kaviani et al. [21]	Solar & Wind	Cost analysis	Minimum of ACS	investments, replacement, operation,maintenance and loss of load costs	Costs of the system depend on its components reliability
Kaldellis et al. [46]	Solar	Life-Cycle Energy Analysis	Minimum EPBP	annual energy losses of the system, energy content of the PV modules	The contribution of the battery component exceeds 27% for the system life-cycle energy requirements
Dufo-Lopez et al. [47]	Solar&Wind	Cost-benefit	Maximum NPV	total initial investment cost, incomes	The selling price of hydrogen should be with strong wind in order to get economically viable systems
Lujano-Rojas et al. [36]	Solar&Wind	Cost analysis	Minimum expected value of NPC	capital, replacement, operation,maintenance costs	A determined reliability level, and the estimation of expected value of NPC show the advantages of the hybrid model
Xu et al. [48]	Wind	Cost analysis	Minimum payment cost	installations, operation cost, bid price of traditional generator	Provide a benchmark for works on PCM considering wind power

Note: NPV-net present value, ACS-annualized cost, NPC-net present cost, PCM-payment cost, EPBP-energy pay-back period

role in the future research. Fig. 3 also shows that the hybrid methods are used in 24 percent of the studies, which were mainly published in recent years. It indicates that scholars tend to combine the analytical model with the simulation method, which helps improve the accuracy and efficiency in the reliability evaluation of renewable power system.

As shown in Table 6, the optimization level of a study may be classified into technical and non-technical levels. At technical level, domain knowledge of renewable power system is needed and the system can be optimized by technological innovation. For example, Chaudhry and Hughes [49] proposed a most-likely Resistance–Load scenario as risk and reliability analysis techniques for wind power generation. Zhang et al. [50] evaluated the reliability of large-scale photovoltaic systems through the state-of-the-art technologies. At non-technical level, some operational and strategic approaches are often used to optimize the reliability of renewable power system from the perspectives of investment growth, policy incentives, battery optimization and micro-grid application. For instance, Bouhouras et al. [7] improved the reliability and reduced the loss of urban distribution system with artificial intelligence technique. Nottrott et al. [52] developed a linear programming model for load management in the photovoltaic battery storage system to gain financial benefits.

4.2. Application scheme

Fig. 4 shows the shares of different renewable energy types dealt with by the studies reviewed. It can be observed that solar energy is least examined, which takes account of 15 percent of the previous studies. It might be explained by the high investment cost and intermittent characteristics of solar energy. In contrast, wind energy with more mature technology is more continuous than solar energy. It can also be seen from Fig. 4 that over 35 percent of studies consider renewables in general but only 18 percent of studies deal with both solar and wind energy. In Section 5, we shall analyze the impacts of utilizing different renewable energy on system reliability and economics through a case study.

As shown in Table 6, the application area covers the generation, transmission, distribution and storage systems. And over 70 percent of the studies deal with renewable generation, which might be a result of the rapid increase in the installed capacity of renewable power generation in the past twenty years. Table 6 also shows that the types of renewable energy resources are also relevant to the regions examined. The countries examined mainly developed countries with sufficient wind energy, low latitude countries with adequate solar energy and the major developing countries with huge energy consumption such as China and India. For instance, Malaysia has abundant solar with the average daily solar irradiance of 5.5 kW/m^2 but low wind speed ranging from 2 m/s to 4 m/s [69]. It is therefore suitable for Malaysia to develop solar energy generation or hybrid system with wind energy. In addition, some countries and regions have implemented a number of policy measures which promoted the use of renewable energy. For example, China announced the Long term development plan for renewable energy and the Research Report of Chinese new energy power development in 2007 and 2012, respectively. Such policies accelerated the development of renewable generation, which evolve researchers' enthusiasm in evaluating the reliability and economics of renewable generation in these countries/regions.

Table 6 also shows that reliability assessment is often linked to economic assessment of power systems with renewables in application. Economic policies such as feed-in tariff, financial subsidies, tax policy and other financial means can be used to improve the economic performance of power systems [20,28,52,70]. Management methods including renewable system integration, energy production, system operational mode

Table 6
Classification of studies on reliability and economic evaluation of power systems with renewables.

Study	Type of renewables	Method			Application area				Level of study		Country	Positive correlation	
		An	Si	Hy	Ge	Tr	Di	St	T	Non-T		E&R	M&R
Stember et al. [19]	solar	√	√				√			√	–	√	–
Iniyanet al. [20]	renewable	√			√					√	India	√	√
Kaldellis et al. [53]	solar		√		√					√	Greece	√	–
Karki and Billinton [28]	wind		√		√					√	–	√	–
El-Tamaly and Mohammed [54]	solar&wind		√					√	√		–	–	√
Karki [55]	wind		√		√					√	–	√	√
Diaf et al. [56]	solar&wind		√		√			√		√	France	√	–
Kaviani et al. [21]	solar&wind	√			√					√	–	√	–
Georgilakis and Katsigiannis [43]	renewable		√		√					√	–	√	–
Bouhouraset al. [7]	renewable	√					√		√		Greece	√	√
Moharil and Kulkarni [57]	solar		√		√					√	India	–	√
Rajkumar et al. [34]	solar&wind	√	√	√	√			√	√		Malaysia	√	–
Xie and Billinton [35]	wind	√	√	√	√				√	√	Netherlands	–	√
Abul'Wafa [58]	wind		√			√				√	Egypt	√	√
Kanase-Patil et al. [59]	renewable		√		√					√	India	√	√
Chaudhry and Hughes [49]	wind		√		√				√		Canada	–	√
Wissem et al. [51]	solar		√		√				√		Tunisia	√	–
Borges [9]	renewable	√	√	√			√			√	–	–	√
Chaiamarit and Nuchprayoon [5]	renewable		√		√					√	China	√	–
Igba et al. [60]	wind	√			√				√		–	–	√
Celli et al. [61]	renewable		√				√	√	√	√	–	–	√
Arabali et al. [62]	wind		√					√		√	–	√	–
Nottrottet al. [52]	solar	√						√		√	America	–	√
Cong [63]	renewable	√			√					√	China	√	√
Lujano-Rojas et al. [36]	solar&wind	√	√	√	√			√		√	Spain	√	–
Xu et al. [48]	wind		√		√					√		√	–
Oh et al. [64]	renewable	√	√	√	√					√	Korea	√	–
Li et al. [65]	renewable		√		√				√		Ireland	√	√
Hasan et al. [66]	renewable	√				√				√	Australian	√	–
Lin et al. [7]	wind	√	√	√	√	√				√	–	–	√
Paliwal et al. [67]	solar&wind	√	√					√		√	India	–	√
Chattopadhyay [38]	renewable	√	√	√	√	√				√	India	√	√
Han [68]	wind	√			√				√	√	–	–	√
Chen et al. [39]	wind	√	√	√	√				√	√	–	–	√

An=Analytical, Si=Simulation, Hy=Hybrid, Ge=Generation, Tr=Transmission, Di=Distribution, T=Technical, Non-T=Non-technical, E=Economics, R=Reliability, M=Management, E&R=Correlation between economics and reliability, M&R=Correlation between management and reliability.

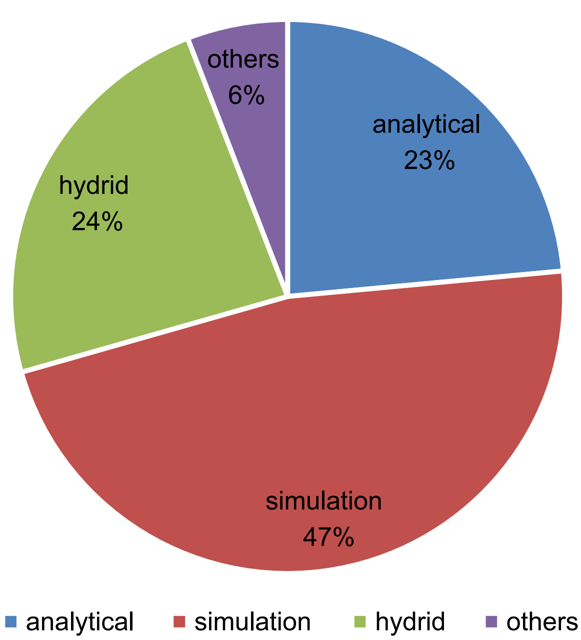

Fig. 3. Share of reliability evaluation methods.

and other configuration optimization have a deep effect on reliability [54,56,59,60]. With the implementation of the economic policies and system management methods, both economics and reliability of power systems with renewables are possibly to improve. Nevertheless, our review finds that past studies mainly focus on different aspects of reliability or economics and it is hard to quantify their specific correlation. An option is to use the EENS indicator [6,22], which is derived from the reliability assessment but can be used to evaluate the economic benefits. The main challenge of reliability and economic evaluation of power system is to achieve an optimal balance. Different criteria of reliability and economics may lead to different optimal result, which can be considered together by using multi-objective programming method.

Table 7
System indicators of reliability.

Indicator	Scenario 1	Scenario 2	Scenario 3	Scenario 4
SAIFI(times/customer · year)	1.8452	0.7812	0.9388	0.4864
SAIDI(hour/customer · year)	3.9358	3.4195	3.7869	1.9534
ASAI(%)	99.9384%	99.9609%	99.9568%	99.9777%
EENS(MW h/year)	55.633	30.562	34.656	16.913

5. Case study

Our review study identifies the necessity of evaluating reliability and economics of power system with renewables

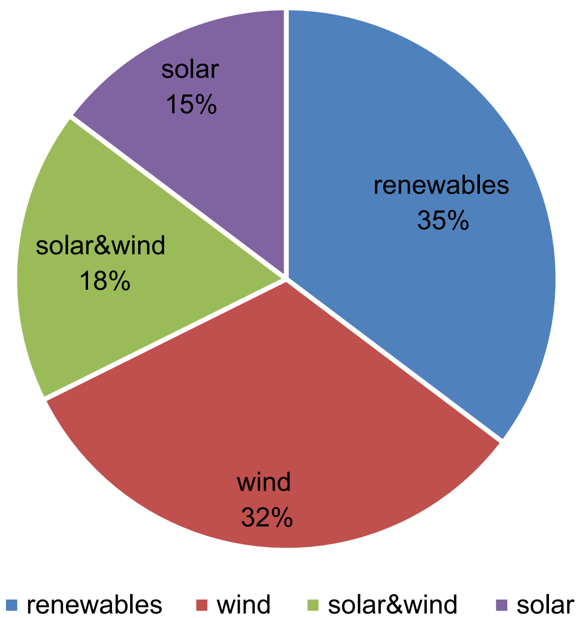

Fig. 4. Share of renewable energy types.

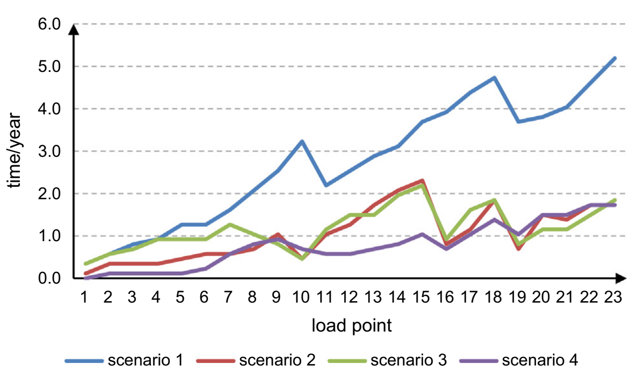

Fig. 5. Failure rate of load point.

Table 8
Cost-benefit analysis results.

Scenario	NPV (1000 US$)	Total cost (1000 US$)	Total benefit (1000 US$)
2	442.9	6470.1	6913
3	2739.4	4749.8	7489.1
4	−8808.5	15071.4	6262.9

simultaneously. The system reliability might be improved through adding renewable generation. In addition, the use of different renewable energy leads to different system reliability. In this section, we present a case study for a small reliability test system designated as the IEEE-RBTS [27,29]. The test case is the 4th feeder of IEEE-RBTS Bus 6, which is a typical rural network with agricultural, small industrial, commercial and residential customers. The feeder whose peak load is 10.93 MW contains 23 load point. The failure rates and repair durations of the various components such as transformers, breakers, busbars, and feeder sections follows the same data based on reference [27]. The basic parameters of wind and solar energy is obtained from [71,72]. The economics parameters of the power system such as installment cost, maintenance cost, feed-in tariff of wind power, PV power and coal power, IEAR, penalty and environment value of pollutions, coal cost and subsidy are taken from [73–76]. And the reliability indicators referred in Section 2.1 are calculated with advanced Probabilistic model and MCS method. Economics result is derived from cost-benefit method. These results are obtained using MATLAB program.

In the case, the following four scenarios are considered:

Scenario 1. Evaluate the reliability and economics of the original power system without renewable power generation.

Scenario 2. Evaluate the reliability and economics of a power system with two sets PV-wind power generation. The rated power for PV/WTG is 1.5/3 MW.

Scenario 3. Evaluate the reliability and economics of a power system with two sets WTG. The rated power is 4.5 MW.

Scenario 4. Evaluate the reliability and economics of a power system with two sets PV power generation. The rated power is 4.5 MW.

Fig. 5 shows the failure rates of load point under different scenarios. It is found that the failure rate of load point under scenario 1 is significantly larger than that under scenarios 2, 3 and 4. The result reveals the advantage of renewable power generation, which can decrease the failure time of load point compared to the power system without renewables.

We further compute the values of four indicator described in Section 2.1, i.e. SAIFI, SAIDI, ASAI and EENS, to evaluate the system reliability and the results are displayed in Table 7. All the indicator values show that scenario 1 is inferior to other scenarios in terms of system reliability. Interestingly, we find that the system reliability under scenario 4 is the highest, which is inconsistent with the case of PV power generation (see Fig. 4). The reason we inferred is described in the following.

Table 8 shows the cost-benefit analysis results under different scenarios. Clearly, the cost of PV generation is higher than the cost of wind generation, which could explain why PV generation is not widely used though its reliability is the highest. It also demonstrates the difficulty between reliability and economics while the value of NPV and ASAI is inconsistent in each scenario. We emphasize one more time that evaluate reliability and economics of power system with renewable power generation in application is necessary.

6. Conclusion

This paper provides a literature review of studies on evaluating the reliability and economics of power system with renewables. We first introduce the key indicators and models for assessing the reliability and economics of power systems. Different studies are compared in terms of type of renewables, evaluation method, application area, level of study and country involved. The main features of past studies are summarized. We also propose a case study to illustrate the differences between alternative system setting in reliability and economics.

Our review study shows that among the three types of methods for reliability evaluation of power systems with renewables, the simulation method is most frequently used because of its high computational efficiency. In addition, the components and system states can be obtained through random sampling in the simulation method. Nevertheless, the hybrid methods, which combine the strengths of the analytical and simulation methods, have recently received increasing attention with the development of renewable power generation. In economic evaluation, the cost-benefit analysis and life-cycle energy cost are the conventional models. The relationship between economics and reliability can be connected with the EENS indicator. However, it is rather difficult to determine an optimal tradeoff between reliability and economics that may be resolved by using multi-objective programming method [77]. It is therefore worthwhile exploring the application of advanced multi-objective programming methods with strengths in convergence rate, computation accuracy and solution diversity to simultaneously optimize the reliability and economics of power systems with renewables.

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