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Integration of energy storage system and renewable energy sources based on artificial intelligence: An overview

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ABSTRACT

Energy storage technology plays a role in improving new energy consumption capacities, ensuring the stable and economic operation of power systems, and promoting the widespread application of renewable energy technologies. Several new developments, ideas, approaches, and technologies have been introduced into this area from fields including materials, knowledge manage, electricity, control, and artificial intelligence. Based on the technical characteristics of renewable energy, this study reviews the roles, classifications, design optimisation methods, and applications of energy storage systems in power systems. First, we introduce the different types of energy storage technologies and applications, e.g. for utility-based power generation, transportation, heating, and cooling. Second, we briefly introduce the states of an energy storage system, along with its operation processes and energy storage capacity. Third, a comprehensive review is conducted on artificial intelligence applications in regards to optimisation system configuration, and energy control strategy, along with the applicability of different energy storage technologies. Finally, several issues and insights are discussed, offering new inspiration and concepts for the future study of integrated energy storage systems.

1. Introduction

In recent years, with increasing pressures from both energy consumption and environmental governance, the demand for energy systems in human society has been constantly increasing [1,2]. Controlling the cost of electricity, replacing aging infrastructure, improving the flexibility and reliability of power systems, reducing carbon dioxide emissions, mitigating changes in the atmospheric environment, and providing reliable power support to remote areas with increasingly higher power requirements have become the keys to this energy revolution [1,3]. An energy storage system (ESS) adopts clean energy to meet requirements for energy-saving and emissions reductions, and therefore has been developed vigorously in recent years. As ESSs have certain randomness and intermittency issues (regardless of whether using grid-connected or island operation), there will be voltage and frequency fluctuations [4,5]. In the process of vigorously developing renewable energy sources (RESs), these adverse effects have gradually become more prominent [6]. The renewable energy output has volatility and intermittency [7], which is not conducive to the stable operation of the power grid, and seriously affects the integration of wind and solar power generation. Nevertheless, the installed capacity of renewable energy and distributed energy storage has continued to increase [8,9].

Researchers have studied the integration of renewable energy with ESSs [10], wind-solar hybrid power generation systems, wind-storage access power systems [11], and optical storage distribution networks [10]. The emergence of new technologies has brought greater challenges to the consumption of renewable energy and the frequency and peak regulation of the power grid, and the operation of the power grid has become more complicated. Energy storage technology can quickly and flexibly adjust the system power and apply various energy storage devices to the power system, thereby providing an effective means for solving the above problems. Research has been conducted on the reliability of wind, solar, storage, and distribution networks [12,13]. According to the International Renewable Energy Agency, by 2030, the installed capacity of energy storage in the world will increase by 42% to 68% (based on values from 2017). By 2025, India and China will become the fastest-growing countries for energy storage installations, and Japan

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Nomenclature

AI	Artificial Intelligence
ANFIS	adaptive neuro-fuzzy inference systems
CSP	concentrating solar thermal
ESS	energy storage system
GA	genetic algorithm
HESS	hybrid energy storage system
IRENA	International Renewable Energy Agency
NSGA	non-dominated sorting genetic algorithm
PSO	particle swarm optimization algorithm
PV	Photovoltaic
RESs	renewable energy sources
SOC	State of charge

Symbols

Symbols	Description Unit
Δt	Step of charging (or discharging) time; s
η_c	Energy storage efficiency of the ESS %
η_d	Distributed energy efficiency of the ESS %
E_f	Flywheel stores energy J
E_{SC}	Superconductor energy stored per coil volume J/m^3
E_{ca}	Supercapacitor stored energy J
E_{com}	Compressed air energy kPa.mol^{-1}
E_p	Stored pump energy J
P_{FC}	Fuel cell electric power output W
P_i	Distributed power output power W
P_p	Pump output power W
P_{ref}	Load demand W
Q_w	Flow rate volume passing the turbine m^3/s
V_A and V_B	Volumes of the compressed gas mol
V_q	Voltage across the capacitor Volt
m_f	Flywheel mass kg
m_p	Pump mass kg
p_A and p_B	Pressures outside of the vessel kPa
η_{FC}	Fuel cell efficiency %
η_p	Hydraulic turbine efficiency %
ΔP	Power shortage W
h	Height m
C	Capacitance Frad
E	Stored or released electricity energy kWh
PES	the operating ESS (charge/discharge) power W
Q	Charge stored in the capacitor C
g	Gravitational acceleration m/s^2
r	the radius of the flywheel m
β	Magnetic flux density T
μ	Permeability H/m
ρ	Water density kg/m^3
ω	the angular velocity rad/s

and Australia will become the countries with the largest shares of energy storage installations [14]. The application of energy storage technology can help distribute energy peaks and modulate frequency, smooth fluctuations, and help output high-quality electrical energy. In addition, energy storage technology can provide a short-term energy supply that can be seamlessly switched off-grid, and the economic benefits are also considerable [15–17]. Therefore, it is expected that renewable energy (such as wind and solar energy) will gradually replace fossil-based energy, and will continuously increase its proportion of energy consumption [5,18,19]. However, the large-scale deployment of intermittent renewable energy with multiple time scales can not only profoundly affect the prediction and scheduling accuracy of the power system, but may also cause operational safety and power quality problems when power is exchanged with the power grid, leading to the need for traditional distribution [20–22]. Therefore, a control technology that considers both the sufficiency of the power generation capacity and flexibility of the power generation is urgently required for renewable energy to be used in operation control and energy management [23]. The use of an ESS complements the renewable energy generator set, ensures that it can work over a larger power range, maintains the system's efficient and stable operation in both grid-connected and island modes, and slows down the intermittent output of renewable energy that results in power fluctuations [23,24]. To further improve the economic and environmental benefits of ESSs, their use has been further expanded, such as in solar photovoltaic (PV), concentrated solar thermal, and thermal energy systems [25,26].

Planning, monitoring, and optimisation have been leading strategies for the construction and systematic study of power systems [26,27]. A variety of artificial intelligence (AI) approaches are used for the modelling, optimisation, and enhancement of hybrid systems [28]. Neural network, Fuzzy logic control, and concurrent computation algorithms comprise a major branch of AI [28,29]. In [28], evaluates the performance of four well-known heuristic algorithms for optimizing the size of a PV/wind/FC hybrid system to continuously satisfy the load demand with the minimal total annual cost. In [29], introduced economic analysis of renewable energy to improve functionality of the hybrid system elements to provide more economical and dependable electricity, as well as environmentally friendly sources. The formulation and solution of a design and optimisation strategy can be limited by resource supplies, infrastructure, performance, and/or mathematical models. Advances in computational science have made it possible to solve optimisation problems using a variety of optimisation and simulation methods [30]. Russell and Norvig [31] offered a view of the AI enterprise based around the idea of intelligent agents systems, where introduces analyses the past and future of AI, and provides some light amusement. Intelligent methods have shown effectiveness in regards to enhancing machine performance and providing economic advantages, along with other benefits that cannot be obtained from conventional approaches [32,33]. In [32], investigate the role of AI algorithms in modelling, sizing, control, and estimation of renewable energy specifically PV system output.

To encourage the AI energy industry to update and aggressively support the production of sustainable energy sources, this study initially presents energy storage technologies, and then outlines the present states of energy storage applications. As an important and regulated tool in the grid, energy storage is a significant element in the promotion of renewable energy absorption, enhancement of power grid control capacities, and assurance of safe and cost-effective grid services. The details of AI applications cover many aspects concerning the integration of energy storage and renewable energy in terms of the parameter estimation, optimal design, and operation control. Finally, a comprehensive analysis addresses the prospects for problems existing in the integration system, and considers future research directions.

2. Energy storage system types and characteristics

Owing to its continuous development and maturity, energy storage technology has been applied in various fields, such as those concerning electric vehicles, renewable energy power stations, RESs, distribution networks, and transmission grids [34]. Fig. 1 shows the characteristics of some common forms of energy storage [35], in which different forms of energy storage exhibit different technical characteristics, especially in terms of energy characteristics [36].

The specific technical characteristics of these forms are as follows.

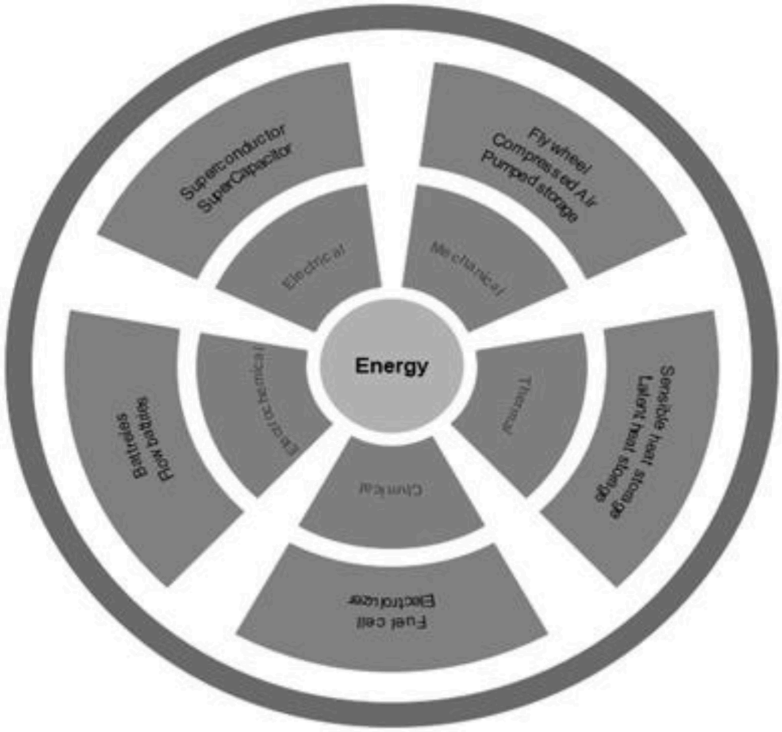

Fig. 1. Classification of energy storage systems (ESSs).

2.1. Mechanical energy

Mechanical energy storage realises energy storage and release through a conversion between mechanical energy and electrical energy i.e. the electrical energy stored in the form of mechanical energy. The main storage types are pumped energy storage, compressed air energy storage, and flywheel energy storage [37].

(a) Pumped storage: Pumped storage is currently the most mature technology, with the largest cumulative installed capacity and longest life cycle. Its working principle is to pump water from a downstream reservoir to an upstream reservoir when storing energy, and to use the water level difference between the upstream and downstream reservoirs for hydropower generation when releasing energy, so as to flexibly realise the flexible conversion between the potential energy of the water and electrical energy [38,39]. The stored pump energy (E_p) can be calculated as follows [38]:

$$E_p = m_p g h \tag{1}$$

In the above, m_p is the pump's total mass (kg); g is the gravitational acceleration (m/s^2); and h is the height (m).

The pump output power can be calculated as follows:

$$P_p = Q_w h \eta_p \rho g \tag{2}$$

Here, ρ is the water density (kg/m^3); Q_w is the volume flow rate passing the turbine (m^3/s); and $\eta_p$is the hydraulic efficiency of the turbine (%).

The advantages of pumped storage are its large capacity, long life, and low cost; it is a widely used energy storage technology that uses electrical energy to drive water resources to store potential energy, and then to convert the potential energy into electrical energy [40]. The cycle efficiency can reach 75%, which is mainly used for regulating peak energy frequency and phase modulations, and providing spare capacity. However, it is not universally applicable, owing to constraints regarding the geological and geographical conditions and construction period.

(a) Compressed air: Compressed air energy storage uses excess electrical energy to compress air in a large storage space, and then releases the air to push a steam turbine to generate electricity when needed [41,42]. According to the different operating principles of the above process, compressed air ESSs can be divided into supplementary combustion and non-combustion types [43]. Compressed air energy storage is driven by compressed air and a motor; the compressed air is released to push the turbine to generate electricity, thereby realising the conversion between internal energy and electrical energy. The compressed air energy stored in the storage vessel can be calculated as follows:

$$E_{com} = p_B V_B lin \frac{p_A}{p_B} + (p_B - p_A) V_B \tag{3}$$

Where, p_A and p_B are constant pressures outside of the vessel; V_A and V_B are the volumes (mol) of the compressed gas, and correspond to the start and end of compression, respectively. In addition, $\frac{p_A}{p_B} = \frac{V_A}{V_B}$.

The advantages of compressed air energy storage are its large energy storage capacity, long cycles, high efficiency, and is mostly used in peak shaving, frequency control, distributed energy storage, and power generation equipment. In addition, highlights the need of various types of store energy in order to strengthen power networks and maintain load levels (permanent or portable, long- or short-term storage, maximum power required, etc.) [44]. The disadvantage is that it has high requirements for the geographical conditions of the construction site; moreover, the supplementary combustion type still requires fossil fuels, and there are gas pollution emission problems [45].

(a) Flywheel: A flywheel stores energy in the form of kinetic energy by accelerating a rotor (flywheel) [46]. Power electronic devices are used to switch the flywheel between generator and motor working modes to achieve the conversion between mechanical energy and electrical energy [47]. The stored flywheel energy (E_f) can be calculated as follows:

$$E_f = \frac{1}{2} m_f r^2 \omega^2 \quad (4)$$

Where, m_f represents the total flywheel mass (kg); r is the radius of the flywheel (m); and ω is the angular velocity (rad/s).

The evident advantages of flywheel energy storage are its high instantaneous power, high conversion efficiency, and fast response speed. It is more suitable for application scenarios with higher instantaneous power requirements [48]. At present, low-speed flywheel energy storage technology is relatively mature; in contrast, high-speed flywheel energy storage has more key technologies that require further breakthroughs, such as composite material structure technology, high-temperature superconducting magnetic bearing technology, and high-speed motor technology [49].

2.2. Electrical energy

Electrical energy is stored in the form of an electric or magnetic field in superconductor and supercapacitor storage units, which are presently relatively common [50,51]. Application of electrical energy storage, one sentence EES has numerous applications including portable devices, transport vehicles and stationary energy resources [51]

(1) Superconductor: Superconducting energy storage stores or releases electromagnetic energy directly through superconducting magnets. The superconductor (E_{sc}) energy stored per coil volume (J/m^3) can be calculated [52] as follows: find exact reference

$$E_{sc} = \frac{\beta^2}{2\mu} \quad (5)$$

Where, β is the magnetic flux density (T), and μ is the permeability (H/m).

The advantages of superconductors are their high energy storage efficiency, large energy and power density, and long service life. However, they are currently in the stages of technological research and development, and require higher manufacturing costs. Key technologies such as the superconducting strip technology, large-capacity power conversion systems, low-temperature systems, and current leads require further breakthroughs [53].

(1) Supercapacitor: Supercapacitors can be divided into electric double-layer capacitors and faraday capacitors, according to the different electrode materials and charging and discharging working principles [54]. The device uses an interface double layer formed between an electrode made of a special material and an electrolyte to store energy. The supercapacitor energy stored (E_{ca}) can be calculated as follows:

$$E_{ca} = \int_0^Q V_q dq = \frac{CV^2}{2} \quad (6)$$

In the above, V_q is the voltage across the capacitor (Volt), C is the capacitance (Frad), and Q is the charge stored in the capacitor (C).

The advantages of supercapacitor energy storage include its high charge and discharge efficiency, long service life, high power density, and wide application temperature range [55]. It has broad application prospects for scenarios with high power requirements, but its main shortcoming is its low energy density. It is difficult to apply in scenarios with high energy demand, as the self-discharge energy from this method is approximately 5% per day [56].

2.3. Electrochemical energy

Electrochemical energy realises a conversion between electrical and chemical energy based on a battery electrochemical reaction principle [57]. The most prominent advantages of electrochemical energy storage are its fast response, flexible installation, and short construction period, which provide broad development prospects for the future energy field. Electrochemical energy storage approaches mainly include lithium-ion batteries, lead-acid batteries, flow batteries, and sodium-sulphur batteries [58].

(a) Lithium-ion battery technology is relatively mature and has a high energy density, and is considered as one of the most promising electrochemical energy storage approaches. According to the classification of the positive electrode materials, typical representative batteries include lithium iron phosphate batteries, ternary lithium batteries, and lithium manganite batteries [59,60]. Among them, lithium iron phosphate batteries have been widely used in industrial production, owing to their relatively long service life and good economy. For large-capacity lithium-ion battery energy storage, it is necessary to further reduce manufacturing costs and improve the safety performance, which will help promote large-scale commercial applications [59].

(b) The advantages of lead-acid battery technology are its low cost, high safety, recycling options, and high rate, but there are also problems, such as a low energy density and short cycle life [61]. To solve this problem, the carbon materials have been introduced to improve the negative electrodes of lead-acid batteries, aiming to form lead-carbon batteries with better performance. However, lead-carbon batteries contain a large amount of lead, and thus pollute the environment. In addition, there is no clear conclusion regarding the selection and quantification of negative carbon materials [62].

(c) A flow battery is the most mature all-vanadium flow battery. Flow batteries electrochemically react with active substances in positive and negative electrolyte solutions, enabling the storage and release of electrical energy. They use vanadium ions of different valences as active substances, where investigate critical aspects related to interactions between cathode materials and electrolyte solutions in lithium-ion batteries [63]. In addition, flow battery technology has advantages such as high safety, high cycle times, independent energy capacity/power capacity design, and a low self-discharge rate. However, it has low energy density, and high manufacturing costs [64].

(d) A sodium-sulphur battery has the advantages of a high energy density, long service life, and no self-discharge, etc.; however, it has special requirements for operating temperatures, as it needs to run at high temperatures (300–350°C) for safety control, in addition to issues regarding structural design, material selection, etc. Regarding these requirements, the key to the commercial application of sodium-sulphur batteries is the further improvement of their safety, reliability, and economy [65].

(e) Table 1 shows a detailed comparison of electrochemical energy storage in terms of the operating voltage, energy density, cycle life and energy cost, system efficiency, and operating temperature.

Table 1
Comparison of mainstream electrochemical energy storage parameters [66,67].

Performance	Lithium Ion Battery	Lead acid battery	Flow battery All vanadium	Zinc bromide	Sodium sulfur
Operating voltage (V)	3.3~3.7	2	1.5	1.82	1.8~2
Energy density (W. h per kg)	130~200	30~60	15~50	75~85	100~250
Cycle life (minute)	2500~5000	2000~4000	5000~10000	2000~5000	2500
Energy cost ($ per kW.h)	350~370	180~260	640~860	285~500	285~430
Efficiency (%)	85~98	80~90	60~75	65~75	70~85
Operating temperature (°C)	low temperature	15~25	5~40	20~50	300~350-
Other features	Good performance, intolerant to overcharge and discharge	Good performance, low cost, recyclable	Good consistency, high reliability, long cycle life, large scale	Low cost, long life, high power	Instant charging, high energy, power discharge

2.4. Thermal energy

According to the characteristics of the different heat storage materials, thermal energy storage approaches can be divided into sensible heat storage, latent heat storage, and thermochemical heat storage [68].

(a) Sensible heat storage materials use their own specific heat capacity characteristics to store and release heat through temperature changes. Liquid sensible heat storage materials such as water and solid sensible heat storage materials such as crushed stone and soil are widely used in areas where a heat storage temperature is not required, such as in solar air conditioners [69,70]. Their common features are their large heat storage per unit mass or volume, stable physical and chemical properties, and good thermal conductivity. However, because of the large volume required, such approaches cannot be used on a large scale. Materials such as molten salts, liquid metals, and organics can be used as sensible materials [71]. Molten salt has the advantages of a high heat capacity, wide temperature range, and low viscosity, making it a typical medium-and high-temperature heat transfer and heat storage material.

(b) The basic principle of latent heat storage is that two phases of a material are in a state of equilibrium and coexistence. When one phase is transformed into another phase, heat is absorbed or released. The heat absorbed per unit mass of material during the phase transition process is called the latent heat [72]. Latent heat storage is currently the most researched heat storage technology, mainly because the energy storage density of latent heat storage materials is significantly greater than that of sensible heat storage materials, and it has good practical research and development prospects. According to the phase change temperature of the materials, latent heat storage materials can be divided into low-temperature phase change materials and high-temperature phase change materials. Low-temperature phase change heat storage materials are mainly used for waste heat recovery in industry, solar energy storage and utilisation, and heating and air conditioning systems [73]. Ionic liquids and ionic liquids have great potential for becoming excellent medium-and low--temperature latent heat storage materials. High-temperature phase-change heat storage materials include high-temperature molten salts, mixed salts, metals, and alloys, which are mainly used in aerospace systems, power plants, and other fields [74].

2.5. Chemical energy

Chemical energy approaches, also known as thermochemical approaches, convert chemical energy into electrical or thermal energy [75]. An appropriate chemical reaction system is the key to this type of storage technology. However, the safety, economy, efficiency, and other issues need to be resolved, and most thermochemical thermal energy systems are in the technological research and development stage [76].

2.5.1. Fuel cell

Fuel cells are a new type of energy conversion unit for directly converting the energy in natural gas and oxidants into electrical energy [77]. The power generation efficiency can reach more than 65%, with a high energy efficiency. The conversion efficiency of a fuel cell is high, and the waste heat generated during the power generation process is small [78].

Fuel cell electrolyte materials include solid oxides, proton exchange membranes, and acidic or alkaline materials. According to the differences in the materials, the operating characteristics of the fuel cells are also different. For example, when natural gas is used as a fuel to generate electricity, it must first be converted into hydrogen by processes such as catalytic hydrogen production, and must undergo impurity removal [79]. The produced hydrogen then enters an anode through a fuel port, where it undergoes an oxidation reaction to ionise the hydrogen ions. Finally, under the action of the catalyst, the oxygen undergoes a reduction reaction with the hydrogen ions of the anode, and produces water.

The mathematical models for the efficiency and output electric power are as follows:

$$V_{FC}(t) = \frac{P_{FC}(t)}{\eta_{FC}(t) L_{NG}} \Delta t \tag{7}$$

$$\eta_{FC}(t) = -0.0023 P_{FC}(t) + 0.674 \tag{8}$$

In the above, $V_{FC}(t)$ is the fuel consumption during the period t;$P_{FC}(t)$ and $\eta_{FC}(t)$ are the output electric power and efficiency of the fuel cell during the period, respectively.

2.5.2. Hydrogen energy storage

Hydrogen energy is expected to comprise one of the most important sources of energy in the future. The working theory of hydrogen energy storage is to transform electrical power into hydrogen fuel based on core technologies, such as those concerning the manufacture of hydrogen, storage of hydrogen, and supply of hydrogen fuel [80]. Hydrogen energy storage has been shown to useful for a modern high-capacity ESS and has shown tremendous growth potential, owing to its excellent advantages such as its high energy density, low operational and maintenance costs, and environmental protection advantages [81]. Currently, hydrogen energy storage technologies still face challenges such as low energy conversion efficiencies and high production costs. Nevertheless, ongoing breakthroughs in materials and core innovations for the industrial use of hydrogen energy storage appear to be imminent [82].

2.6. Comparison of performance indicators for energy storage technologies

The selection of an appropriate type of energy storage must consider the application requirements, e.g. the characteristics of the application presented in Fig. 2. This is conducive to increasing the application value of energy storage technology in power generation, transportation, heating, and cooling [83].

Table 2 displays different energy transfer parameters and features. ESSs can be broken down into mechanical energy storage, electromagnetic energy storage, electrochemical energy saving, and hydrogen energy storage [84]. The response time of electrochemical energy storage is on the order of milliseconds, the rated power can reach the megawatt level, and the cycle efficiency is the highest (reaching more than 80%); however, the service life is limited [85]. EES has numerous applications including portable devices, transport vehicles and stationary energy resources. Pumped storage and compressed air ESSs have long lives and large rated power, but also have long response times and strict site selection requirements, and require large-scale promotion in areas with high electricity loads [86]. If combined with lithium batteries, heat pumps, and other technologies, the cycle efficiency can be increased to 60%. Therefore, we should give full play to its advantages, so as to realise the thermoelectric coupling of the power supply unit, realise the peak shaving of the power grid, and ensure the safe and stable operation of the power grid [87].

3. Energy storage system evaluation

The ESS capacity has a great impact on the overall economics and operational safety of RESs, and must be optimised during the RES planning and design phase [90]. An ESS that is excessively small cannot improve the power quality and overall operating performance of a RES, whereas an ESS that is excessively large imposes higher investment and maintenance costs on the RES [91]. The types, quantities, and structures of power sources in RESs are diverse, and the equipment functions are also different. The load can be either an electric load or thermal load. Therefore, capacity planning for an ESS is closely related to the operation strategy for the RES. Comparison operation strategy of different energy storage technologies including the operation timing and start-stop duration of the distributed units in the RES system, as well as important advances and affects the ESS behaviours [92].

3.1. Energy storage system operation process

The power system energy shortage is owing to the large difference in the time sequence between the load curve and output curve of the renewable energy [93]. The ESS operation process should consider influencing factors such as the response rate, life limit, application cost, and locations (such as for the power generation side, distribution side, and load side) for economic and stable operation. Therefore, the power shortage can be expressed as follows:

$$\Delta P(t) = \sum_{i=1}^{n} [P_i(t)] - P_{ref}(t), n < m \quad (9)$$

In the above, $P_i(t)$ is the output power of the distributed power supply i in the RES at time t, and $P_{ref}(t)$ represents the load demand of the RES at time t. When $\Delta P(t) > 0$, the ESS considers whether to store energy; when $\Delta P(t) < 0$, the ESS considers whether to release energy.

The behaviour of the load consumption should be as close as possible to the output of renewable energy, and a certain proportion of the load is considered to be flexible or transferable within a certain period of time [94].

3.2. State of the energy storage system

To introduce an ESS on the power supply side to improve the practicability and operation of the system, a demand response is used the inherent power consumption mode of the user side, thereby providing the user's energy consumption [95].

The charging [96] can be represented as follows:

$$SOC(t) = SOC(t-1) + \frac{P_{ES}(t).\eta_c.\Delta t}{E_{ES}(t-1)} \quad (10)$$

The discharge can be represented as follows:

$$SOC(t) = SOC(t-1) + \frac{P_{ES}(t).\Delta t}{\eta_d.\ E_{ES}(t-1)} \quad (11)$$

Here, $PES(t)$ is the operating (charge/discharge) power of the ESS at t; $SOC(t)$ is the state of charge of the ESS at t; Δt is the charging (or discharging) time; η_c is the energy storage efficiency of the ESS; and η_d is the energy efficiency of the ESS. Notably, the self-discharge rate of the energy storage device is not considered here.

3.3. Energy storage capacity

The difference between the output power of the power supply device and planned output in the system $\Delta P(t)$ determines the charging and discharging operation mode of the ESS, and the area enclosed by ΔP(t) and the coordinate axis is recorded as a parameter $\Delta E(t)$. Its positive and negative values indicate that the ESS is in the charged state and discharged state, respectively [97]., the total amount of electricity that the

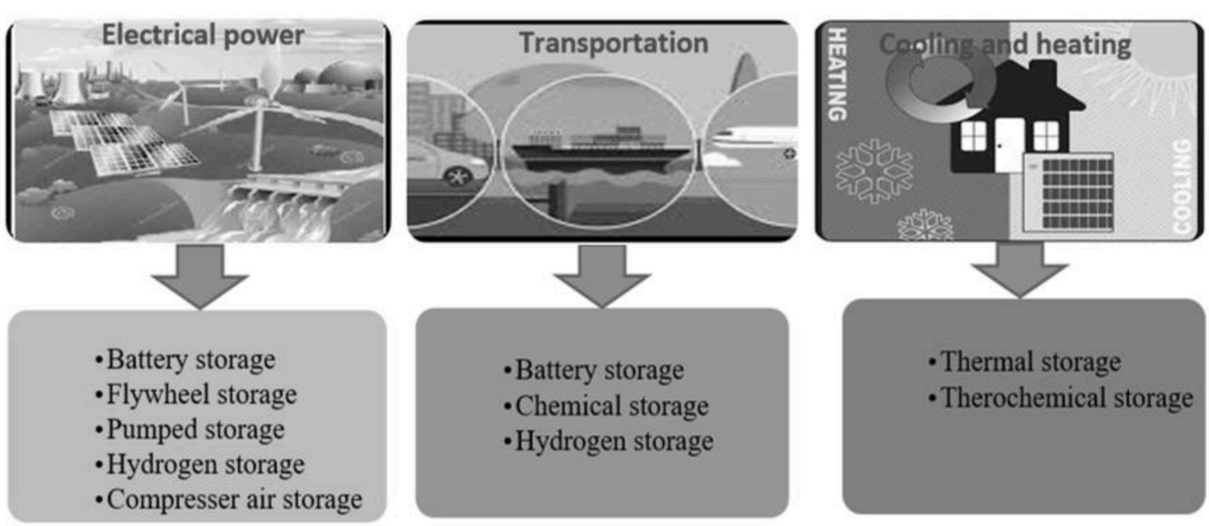

Fig. 2. Applications and possible hybrid approaches for common energy storage.

Table 2
Comparison of performance indicators for energy storage technologies [88,89].

Energy	Energy storage category	Energy density (W.h per kg)	System lifecycle (time)	Efficiency (%)	Response time	Rated power
Mechanical	Pumped storage	0.5-3	Unlimited usage	70~85	4~10h	100~2000MW
	Compressed air	34	Unlimited usage	>70	6~20h	10~300MW
	Flywheel	100-130	10^5~10^7	70~90	> 15 min.	1-20MW
Electrical	Super capacitor		>50000	95	1~30s	10kW~1MW
	Superconductor	90000-100000	Unlimited usage	Upto 100		2~200 MW
Electrochemical	Lead-acid batteries	25~42	500~1200	75	20ms above	kW~MW
	Nickel-cadmium batteries	35~57	1000~3500	80	-	10MW
	Lithium Ion Battery	60~130	7000~10000	90	20ms above	kW~MW
	Sodium-sulfur battery	130	2500~4500	85		10MW
	NiMH batteries	50~60	>2500	85		100kW
	All vanadium liquid battery	50	1000~2500	80	20ms above	kW~MW
Thermal	Sensible heat storage	21	>10a	30~40	5%/min	7h Heat storage capacity
	The latent heat storage	0.3	Unlimited usage		-	
Chemical	Hydrogen storage	2.8~3.3	>2000h	25~45		30kW~100MW
	Fuel cell	150	>2000h	40~60		8~30kW

ESS needs to store (or release) in the time interval T is $E(T)$, and the expression of $E(T)$ is as follows:

$$E(T) = \int_{t}^{t+T} \Delta E(t)dt \tag{12}$$

In addition to electricity, the stored energy forms also include cold/heat and gas storage, where cold/heat and gas reserves can be converted from power to volume according to usage.

4. Artificial intelligence technology

Researchers have introduced many algorithms and methods for optimisation modelling, state estimations, and behaviour expressions for the integration of renewable energy and ESSs. These can be summarised by three aspects, as shown in Fig. 3.

(1) Optimisation system configuration

This form of work aims to determine the optimum battery and ultracapacitor configurations by considering the correlation of the energy management algorithm with the power matching during device operation, as well as the combined optimisation of power matching and energy management algorithms [98]. Particle swarm optimisation (PSO) algorithm, Harmony search algorithm, Artificial bee colony optimization, and hybrid optimisation methods are widely employed [99].

(1) Energy control strategy

This form of work focuses on the development of effective and intelligent management mechanisms for enhancing the robustness and reliability of the ESS, and the control system's adaptability under dynamic operational conditions [100]. A hybrid ESS (HESS) control

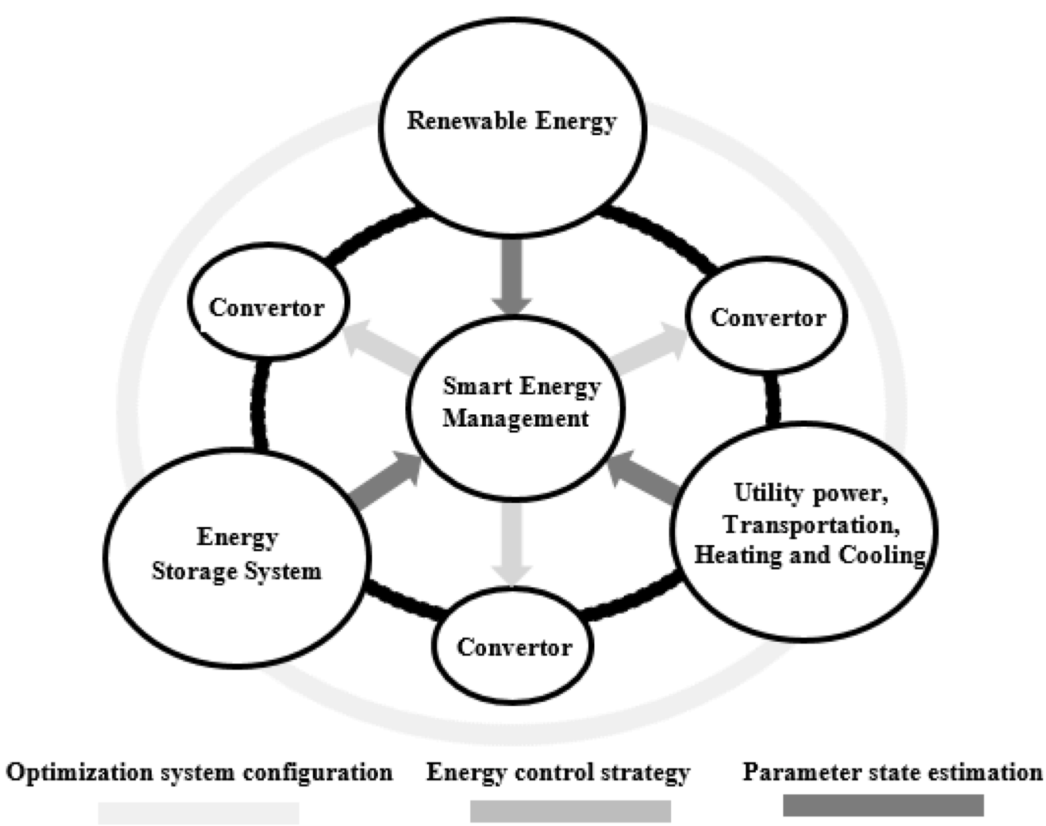

Fig. 3. Application of artificial intelligence (AI) technology based integration of renewable energy sources (RESs) and ESSs.

strategy is important for improving the use of resources and energy efficiency. The monitoring technique is typically complex, and must work constantly as the RE sources are intermittent and must achieve multiple goals. Widely used methods include dynamic programming, variable control, adaptive neuro-fuzzy inference systems control, and predictive control [101].

(1) Parameter state estimation

This type of research aims at developing high-precision, adaptive, and robust methods for system identifications and state assessments [100]. In addition, it is used to study the effects of stress factors on electrode materials and electrolytes from an electrochemical or material science perspective and the aging laws of power supplies based on signal analysis and features of the thermal and electrical behaviours, so as to investigate the connection(s) between the stress factors and aging mechanisms [102]. The most popular approaches include neural networks and Bayesian filters.

4.1. Optimisation system configuration

According to the 2005 energy policy formulated by the US Department of Energy, demand response is a service mechanism for encouraging users to change their demands for energy through methods such as financial incentives or education [103]. In particular, evaluation indicators (reliability, economic, and environmental) used to determine the size of each component of hybrid renewable energy system [104]. In addition, more attention is necessary to understand the current status and development trends of optimal sizing for hybrid renewable energy systems. An important derivative of a power system is the demand-side management [105]. If the ESS is combined with the demand response and fully utilised, the energy consumption mode of the RES can be further optimised. Many studies have different indicators for evaluating ESS performance [106]. For example, electrochemical energy storage is mainly analysed from the perspectives of system efficiency and battery life [107]. Battery life indicators include the maximum charge currents of the battery, maximum discharge currents, and root mean square currents. The battery system efficiency indicators include the power converter and system energy loss [29,105]. In addition, for the optimisation of the RES and ESS capacity, common optimisation algorithms include PSO algorithms, genetic algorithms, and improved non-dominated sorting genetic algorithms, and researchers can choose an algorithm according to the actual situation of the calculation example and the characteristics of the algorithm itself [108,109]. In [108], investigate the strengths and shortcomings of the existing artificial intelligence-based methods for building energy systems. The PSO algorithm has a simple structure, fast convergence, easy implementation, and good intelligence. Table 3 reviews the important works in this field in terms of optimisation algorithms, storage types, RESs, and main evaluation indicators.

Table 3
Previous research on artificial intelligence (AI)-based energy storage optimisation.

Author	AI techniques	Energy storage type	Renewable energy	Factors	Findings
[110]	Agglomerative hierarchical clustering Algorithm	Battery	Solar, wind	Time	The author proposed agglomerative hierarchical clustering algorithm for optimizing integration of Solar/Wind with battery. Results show that time series data of (5–15 days) sufficiently to improve the system performance by 5%. An advantage for AHC compared to other clustering methods is the preservation of time chronology, which is important for energy storage applications.
[111]	Non-dominated sorting GA	Pumped storage, battery	Solar, wind	Cost and emissions	The GA algorithm optimize the integration of photovoltaic, wind, pumped-storage in terms of system economic and environmental performance.
[112]	PSO	battery and hydrogen	PV, Wind	costs, efficiency and lifetime	The PSO algorithm implemented in the energy management system to minimize the operating costs (29.36%) and maximize the system efficiency (27.21%) and improve the lifetime of the devices (43.43%).
[113]	PSO	Battery, thermal energy	PV, Wind	Power output	The proposed multi-objective PSO power optimization Moreover, the solution would increase the performance and the stability of the transmission channel use as comparing to solar, PV, thermal energy storage network, solar-photovoltaic battery and hydro-photovoltaic systems.
[114]	Hybrid PSO and Teaching Learning	Battery	Wind	Emission, time, and cost	A robust multi-target optimization based on a minimum optimization approach to resolve the complexities of REG is suggested. Numerical results indicate that a flexible multi-target dispatch model satisfies the demands of solutions when considering wind turbine instability. In the meantime, the comparable findings indicate the PSO-TLBO method's successful success in addressing the suggested shipping problems.
[115]	Harmony search optimization	Battery	PV	Time-of-use pricing	In case of renewable energy generation facilities such as wind and solar, the harmony algorithm proposed to find optimal ESS scheduling at demand-free time-of-use rates. Research concentrated on the ESS scheduling for retail consumers of PV generation systems under the same energy pricing strategy.
[116]	PSO	Electrochemical Energy Storage	PV	Power output	Ensure the energy storage systems are not overwhelmed and dismantled. Secondly, the voltage fluctuation following the connection of the electrochemical energy storage power station with the calculation of power flow and a discrete reactive power compensation on the bus line for adjustment of voltage fluctuation further.
[117]	Hybrid GA and ANN	Battery	PV	Cost, power output	The ANN / GA formula for optimum size of the solar spectrum and the power of the battery to satisfy demand for load. The average capital cost of the energy storage device must be a minimum and the system stability (usually calculated as load failure probability) is appropriate.
[118]	Bee colony algorithm, PSO	Fuel cell	PV, Wind	Power loss, voltage stability index, and emissions	The findings obtained with the artificial bee colony algorithm with multiple goals are of sufficient consistency and greater variety relative to the updated PSO process.

4.2. Energy control strategy

Energy storage has the advantage of two-way power regulation, i.e. it can absorb power when renewable power is at a surplus, and release power when the provided power is insufficient [119]. At present, it has been widely used in auxiliary wind power grid-connected power climbing control [120]. For large wind farms, the ESS is connected to the grid connection point of the wind farm, and the energy storage charging and discharging power are dynamically adjusted according to the control strategy, so that the grid connection power of the wind farm efficiently meets the climbing limit index [121]. Many control strategies exist for energy storage-assisted wind power control, including first-order filtering, slope limiters, and model predictive control [122]. In [122], develop heuristic optimization algorithm for maximizing economic profit from integration of RES and thermal power generation with pumped storage to reduce the impact associated with environmental emission and uncertainty.

In [123], an energy storage-assisted wind power climbing control method was based on a slope limiter, which limited the rate of change of the wind power grid-connected power to within a certain range. When the wind power climbing rate exceeded this slope, more or less wind power was stored or released by the energy storage. A wavelet filtering algorithm has good application value for hybrid energy storage-assisted wind power grid-connected power climbing [124,125]. In [124], residual forecast error signal is analysed to optimise the grid-scale energy storage units with wind power and decreasing the wind spillage using the discrete wavelet transform method. It divides the power requiring energy storage compensation into high-frequency and low-frequency parts through a real-time wavelet analysis of the wind power, and then assigns the power command of the high-frequency part to the super capacitor, and the low-frequency part to the lithium battery [126]. A model predictive control algorithm based on roughness penalty factor evaluation indicators has also been proposed; it achieves dual time scale climbing limit indicators, while improving the wind power smoothness of the grid-connected power and reducing the energy storage capacity. In [127], an optimal control strategy was proposed for a hybrid ESS, aiming to improve the power generation capacity of the wind power tracking plan. The strategy included two parts: internal energy coordination control and multi-objective optimisation control, and used appropriate control methods under different ESS charge states to achieve optimised tracking control [128]. In fast frequency modulation and ultra-low frequency oscillation suppression, the energy storage control strategy will affect the energy storage capacity demand and control effects [129]. Therefore, according to the characteristics of the different frequency stability problems, it is necessary to design a reasonable control strategy for energy storage, enabling fast frequency modulation and the suppression of ultra-low frequency oscillations; this is conducive to improving the technical economy of the energy storage, and to improving the frequency modulation capability of the power system. In [130], an energy storage optimisation control method based on a prediction of wind power climbing events was used to classify climbing scenarios. Then a fuzzy logic strategy was used to dynamically adjust the grid-connected power climbing for different climbing scenarios [131]. In [132], the weight coefficient of the objective function is adjusted in real time to obtain the best PV power generation plan tracking effect, in accordance with the grid-connected power and minimum deviation of the power generation plan, and by introducing fuzzy control. In [133] optimize reliability level and operation cost for power management of storage mechanisms using fuzzy logic controllers. The hybrid green power systems consisting of wind turbines, photovoltaic collectors integrated with power storage system including battery stack, supercapacitor, hydrogen tank, and fuel cell. Table 4 introduces important works in terms of control strategies, and the main findings.

Table 4
Previous research on AI technique-based energy storage system control.

Author	Method	Result/Finding
[117]	Hybrid differential evolution optimization and ANN.	On a power network consisting of a synchronous generator, a photovoltaic power and a battery power storage system the effectiveness of this proposed controller is validated. Controller parameters are adjusted online by training of the ANN with the data sets created during the optimization phase of the two controllers using the DEO with low and high disturbance
[130]	Fuzzy logic controller	FLC membership capabilities are designed to mitigate green energy hybrid system operating expense based on weekly and regular data predictions for water, electricity, and environmental parameters, including wind speed, sunshine and air temperature using frog-spring shuffle algorithms. The accounting of power grid costs has been reported to have significant impact on the efficiency of energy storage components for the HRES on-grid service as the configured weekly and frequent FLCs minimize operating hours of fuel cells and electrical gasses and fewer SOC variability in the battery stack.
[133]	PSO	A new ESS control system with a multi-agent configuration was introduced for 100 megawatt, and the control effect was confirmed on the basis of simulation analysis and testing.
[134]	ANN and Dynamic programming	The ESS power flow is balanced by minimizing power loss and increasing battery life by minimizing battery current volume and variations.
[135]	Polyline Fuzzy Neural Network	In terms of the appropriate frequency, the definition of widespread wind storage inertia is evaluated. The PFNN approach suggests adjusting frequency frequencies as the energy storage device input and state as output.
[136]	Hierarchical Control	Through balance regulation the simulated impedance is dynamically balanced to remove the effect of the incorrect line impedance on the exactness of the current portion. Then each power storage unit can adjust current by SoC balance control according to its capacity and charge status (SoC), decrease SoC error, and gradually perform DESU SoC balance during loading and discharge.
[137]	FBC and ANN	A neural network is proposed to manage the SOC battery in the combined wind / PV system operating range. Furthermore, FBC keeps the battery current and the DC voltage smooth.
[138]	FLC/GA	The FLC/GA recommended that wind production fluctuate to energy demand. The configured FLC / GA decreases the voltage fluctuation by 43.46%.
[139]	FLC	The FLC recommended use of Wind and PV hybrid to store battery electricity, depending on the cost of use. The suggested program reduces the overall savings from the traditional conventional approach by 13 %.
[140]	FLC/ANN	The ANFIS system to control hybrid Wind and PV for battery and hydrogen energy storage considering the system efficiency. The system efficiency improved by 0.6% and 0.4% for battery and hybrid battery/ hydrogen respectively.
[141]	ANN	The ANN control hybrid Wind and PV for battery and hydrogen energy storage

(continued on next page)

Table 4 (*continued*)

Author	Method	Result/Finding
		considering the system response. The proposed ANN was response capability is faster as compared to fuzzy logic controller.
[130]	FLC/PSO	The FLC/PSO algorithm to control wind energy with battery and hydrogen energy storage considering the operational cost and battery SOC. The proposed system weekly operation cost reduced by 18.72% and battery SOC improved by 16.89%.
[142]	ANN	The proposed method based on sizing and control approaches for a flow battery energy storage system integrated with large wind farm. The results present that the power flow control strategy does have an important effect on the proper sizing of the rated power and energy of the system.

5. Conclusion and future trends

With the vigorous developments in clean energy, the environmental pollution problems caused by fossil fuel energy have been effectively suppressed, and energy transformation has become a general trend. However, during the gradual developments in new energy, adverse impacts from such large-scale new energy access have gradually emerged, i.e. regarding the safety and stability of the power grid and its economic operation. An energy storage network adds greatly to the cost of RESs, but is projected to decrease steadily over the next few years [143]. Therefore, the effective use of ESSs is an important topic for making it easier for clean energy to penetrate into industries. Based on the decision matrix, battery, and supercapacitor, the HSS and SMES have shown promising characteristics, even though both technologies are still emerging in terms of their economics, efficiency, and practicality [144]. The ESS is a cost-effective and practical solution for the REPS battery.

Owing to the relative maturity of battery and supercapacitor technology, the costs are quite small, and devices are widely available in various sizes. A battery-supercapacitor system is the most commonly used HESS; the fuel cell-supercapacitor, battery-flywheel, and 'battery-sMC' approaches are less familiar, and can be used to model corresponding configurations in detail. The main benefits of an ESS can be summarised as follows: decreased costs for storage devices, increased storage life, decreased reaction time, increased reliability, increased power efficiency, and improved pulse loads [145]. Several tests indicate that the reliability of the storage is enhanced, and that the construction technique is roughly simple [127,146]. However, the ESS design has not been fully addressed in the context of system stability and/or improvements in power quality. There is a void in the multi-target modelling approach used to scale ESSs for various variables [146,147]. An ESS architecture can be divided into four major areas: the ESS scale, range of topological power converters, control systems, and energy management. Specific methods of ESS capability scaling have been discussed in the literature. To determine the energy storage capacity, different objective functions are used. The lifespan in storage is an important consideration for determining the scales of chemical and electrochemical storage [148].

The latest control strategy development concerns developing new optimisation algorithms for overcoming complex optimisation issues. Multi-target challenges, such as economic and technical constraints, should be considered in optimisation algorithms [149]. Furthermore, as the RES output power is strongly dependent on meteorology and the demand is constantly fluctuating, a predictive control strategy should be integrated in a control approach based on optimisation, so that controls with a higher level of performance and robustness can be achieved [150]. There is minimal research, however, focusing on RESs with ESS optimisation-based control strategies and/or predictive control strategies [122,151]. For an RES, it is essential to provide consumers with high-quality electricity. In action, an RES supplies specific types of loads, for instance, unbalanced loads, non-linear loads, and pulse loads [152,153]. If only the ESS is used in an RES with the above loads, there will be an insufficient dynamic response to the loads, and the lifetime. The use of AI can provide correct contextual solutions under these situations, and improve the lifetimes of storage systems. Thus, predictive management strategies and control strategies focused on AI should be built to further increase the penetration of renewable energy for RESs with ESSs [10]. Giving full play to the advantages of the various types of AI, cooperating with existing ESSs in the power system, and achieving multi-objective power system optimisation control should be the research directions for future energy storage applications [154]. In addition, although real-time control of the energy storage charging and discharging power can be achieved based on the differences between the current new energy actual output and planned output, it is also necessary to consider future new energy outputs, and the remaining power of the ESSs. In [155], the ESS has a certain guiding effect on the practical application of energy storage; however, a single ESS reduces the system economy [156]. In addition, the above energy storage control algorithms are based on wind power history and real-time or ultra-short-term prediction information, aiming to achieve wind power grid-connected power that meets the corresponding climbing limit index, and to improve the friendliness of grid-connected wind power [157,158]. Owing to the lack of prospective consideration of future climbing events, the above method cannot adequately address future severe climbing events, such as rapid wind climbing or large-scale climbing [158,159]. When the corresponding event occurs, the state of charge of the energy storage owing to the large charge or discharge power (or the long duration of the energy storage) can easily reach its upper or lower limit.

At present, the research on the optimization and integration of energy storage system and renewable energy resources are not systematic and deep enough, and the related theories are not mature enough, and there are still many problems to be solved urgently. In view of the research content and the prospects for future research are as follows:

(1) Consider the influence of multiple factors on the operating characteristics in the congested area in the analysis of working conditions. The operation of the congested area is affected by factors such as weather, commuting peaks, weekends and holidays.
(2) The design of a complete energy storage system not only includes research on the technical and theoretical feasibility of the system, but should also requires effective evaluation in terms of engineering economy, environmental impact, and safety to determine the feasibility of the aquifer compressed air energy storage technology.
(3) Refine the energy transmission process of the power supply network and the control strategy model of the wayside energy storage system, for example, consider the change of the impedance of the power supply network with distance, and modify the power control model of the wayside energy storage system to a voltage and current dynamic model, etc.
(4) In the optimization energy storage model, an integer idle speed control strategy is used to reduce the size of the solution space. Considering the restriction on the value range of decision variables, or try different driving strategy optimization methods to analyze its impact on the results of energy-saving optimization.
(5) Adjustment of the operation diagram mainly focuses on energy conservation and considers some safety and service quality constraints. However, the formulation of the actual operation diagram also involves issues such as operational service quality, management costs, etc., usually multi-objective optimization.

(6) Combining the characteristics of the above optimization algorithms, based on the exhaustive search and heuristic search, the relevant intelligent solution algorithm is designed to provide a basis for obtaining the approximate optimal solution of the energy-saving operation and controlling strategy.
(7) The hierarchical energy-saving optimization model for dispatching control combined with energy storage, and formulate the optimization of single train driving strategy, integrated optimization of inter-station operation time and division, and optimization of multi-train operation diagrams under the application conditions of trackside energy storage system.
(8) Finally, AI has helped energy storage technology to assist the power grid more practically in practical engineering applications and the maturity of energy storage technology, improved standard specification systems.

Declaration of Competing Interest

The authors declare no conflict of interest.

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