Renewable and Sustainable Energy Reviews 162 (2022) 112440

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

A review on the integration and optimization of distributed energy systems

Fukang Ren, Ziqing Wei, Xiaoqiang Zhai *

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai, 200240, PR China

ARTICLE INFO

Keywords:
Combined cooling heating and power
Renewable energy
Energy storage
Hybrid energy system
Optimal planning
Performance analysis

ABSTRACT

The depletion of fossil fuels and climate change pose huge challenges to sustainable development. How to meet the increasing energy demands in an efficient and environmentally friendly manner has become the focus of attention all around the world. The hybrid combined cooling, heating and power (CCHP) systems that combine fuel powered CCHP systems with high energy efficiency and renewable energy technologies with zero emissions are attractive. Hence, this paper reviews various studies on such systems. Firstly, the possible integration forms of available technologies are summarized, which include combined heating and power systems, waste heat recovery systems, solar energy systems, geothermal energy systems, wind energy systems as well as energy storage systems. Secondly, the different application scenarios such as neighborhood level, district level and city level are summed up. The primary concern at the neighborhood level is whether the allocation of benefits needs to be considered. The core of the district level is how to properly decompose the district into multiple sub-districts. Research on the city level is to provide valuable guidance for the harmonious development of the city. Finally, on the basis of the above review, several perspectives that require further efforts are put forward.

1. Introduction

With the modernization of society, the consumption of fossil fuels is on the rise while the emissions of greenhouse gases are also constantly increasing. It is estimated that the energy demand in 2040 will be nearly 50% higher than that at present time [1]. How to achieve sustainable development and meet the growing energy demand has aroused widespread concern. Distributed energy systems are considered as a potential alternative to conventional power and heating production mode due to the following advantages: (1) fully utilize local resources; (2) low energy transmission loss; (3) small environmental impact [2]. Among them, the CCHP systems driven by natural gas have been well developed, which can not only provide electricity through the prime mover, but also provide heating and cooling through the waste heat activated equipment. Thanks to the cascade utilization of energy, the fuel utilization efficiency is significantly improved, reaching more than 90% and the fuel consumption is dramatically reduced [3]. Although the CCHP systems can reduce the usage of fossil fuels, there are still carbon dioxide emissions, which is a key factor in global warming.

In addition, renewable energy technologies which are driven by solar energy, wind energy and geothermal energy are characterized by zero energy consumption and zero emissions, and they have been widely used around the world. It is reported that more than 100 cities in the world get at least 70% of their electricity from renewable energy resources [4]. The development and utilization of renewable energy sources is the key to alleviating emissions and fighting against climate change. However, the instability and intermittence of solar radiation and wind speed raises challenges with their use. The relatively long self-recovery period to maintain the stability of temperature field is a key factor that restricts the application of geothermal energy.

To ensure continuous operation, the hybrid CCHP systems that integrate renewable technologies with fuel driven CCHP systems are an effective option to provide low-carbon energy and promote sustainable development. Simultaneously, the incorporation of two systems with different characteristics complicates the operation management and control strategy. Therefore, the correct planning is essential to identify the optimal capacity and hourly operation strategy of the components for the maximum or minimum objective functions under certain constraints. The objective functions mainly include economic, energetic, environmental aspects. Thereinto, the economic indicators mainly consist of simple payback period [5], net present value [6] and annual total cost saving ratio [7]. The energetic indicators generally involve energy efficiency [8], exergy efficiency [9], primary energy saving ratio [5], net solar-to-electricity efficiency [10], net solar-to-product efficiency [11] and solar fraction [12]. As for the environmental indicators, they include carbon dioxide emission reduction ratio [13], total greenhouse gasses reduction [14] and relative greenhouse gasses reduction

* Corresponding author.
E-mail address: zxqzhai@163.com (X. Zhai).

https://doi.org/10.1016/j.rser.2022.112440
Received 28 March 2021; Received in revised form 31 January 2022; Accepted 4 April 2022
Available online 8 April 2022

Nomenclature

ABS	absorption chiller
AC	alternating current
ADS	adsorption chiller
CAES	compressed air energy storage
CCHP	combined cooling heating and power
CPC	compound parabolic collector
DC	direct current
DEMO	differential evolution based multi-objective optimization
EB	battery
EC	compression chiller
ETC	evacuated tube collector
FC	fuel cell
FPC	flat plate collector
GA	genetic algorithm
GAMS	general algebraic modeling system
GB	gas boiler
GSHP	ground source heat pump
GT	gas turbine
HE	heat exchanger
HFC	heliostat field collector
HP	heat pump
HRSG	heat recovery steam generators
ICE	internal combustion engine
LFC	linear Fresnel collector
LINGO	linear interactive and general optimizer
MCFC	molten carbonate fuel cell
MOPSO	multi-objective particle swarm optimization
MOSFA	multiobjective strength firefly algorithm
MT	micro turbine
NSGA-II	non-dominated sorting genetic algorithm-II
ORC	organic Rankine cycle
PEMFC	proton exchange membrane fuel cell
PDC	parabolic dish collector
PSO	particle swarm optimization
PTC	parabolic trough collector
PV	photovoltaic
PVT	photovoltaic-thermal
SE	stirling engine
SOFC	solid oxide fuel cell
ST	steam turbine
STC	solar thermal collector
WST	water tank
WT	wind turbine

[14]. Moreover, in order to quickly and accurately optimize the aforementioned indexes, a variety of tools have been adopted, which include single-objective optimization algorithms [15] (CPLEX, YALMIP, GAMS, GUROBI, LINGO, PSO, GA), multi-objective optimization algorithms (NSGA-II [13], MOPSO [16], MOSFA [17], DEMO [18]) and sensitivity analysis [19–21]. Azaza and Wallin [16] constructed a multi-objective optimization model for configuring and operating an integrated energy system, in which reliability, unit cost and renewable factor are considered. Wang et al. [17] developed a novel multi-criteria evaluation method, which considers the impacts on utility grid. Mebarek-Oudina et al. [19] carried out a sensitivity study on the operating parameters of a zigzag-shaped trapezoidal cavity filled with nano-liquid and porous media and identified the most reasonable values. Abusorrah et al. [21] utilized sensitivity analysis to determine optimal design parameters that affect the energy and exergy performance of desalination system. Chen et al. proposed a hybrid solar and geothermal system and optimized the inlet temperatures of solar collector and thermal storage thank [22] and the photovoltaic coverage ratio [23] based on sensitivity analysis.

Given the rapid development of distributed energy systems, some researchers have reviewed such systems from various aspects. For instance, Al Moussawi et al. [24] explained the strengths and weaknesses of the available primer movers, heat recovery components and thermal energy storage. Mohammadi et al. [25] and Kasaeian et al. [26] grouped the cited literatures according to the solar energy technology used. Gao et al. [15] outlined the optimization techniques involved in the planning process. Wen et al. [27] provided an overview of incentive policies in various countries. However, to our knowledge, neither the specific integration forms of different energy technologies, especially solar and geothermal technologies, nor the planning methods for distributed energy systems of different scales, are clearly summarized.

The main purpose of this paper is to fill the above-mentioned gaps and thus provide a comprehensive review of the current distributed energy systems. After the introduction, section 2 provides potential integration forms of different technologies including combined heat and power units, waste heat recovery units, renewable energy units and energy storage units. Section 3 summarizes various application scenarios, which include neighborhood level, district level and city level. Section 4 offers some useful insights and possible challenges.

2. Available energy technologies in hybrid CCHP systems

Different energy technologies have been integrated and employed in multiple generation systems to meet diverse demands including space cooling load, space heating load, domestic hot water load and electricity load. These can be categorized as (i) combined heat and power systems driven by various fuels; (ii) waste heat recovery systems driven by exhaust heat from prime movers; (iii) renewable energy-based systems including solar energy, geothermal energy and wind energy; (iiii) energy storage systems. The following sections summarize the previous research works in the above four aspects.

2.1. Combined heat and power systems

The combined heat and power systems (prime movers) are the core components of the hybrid CCHP systems, which can provide electricity and heat at the same time. The prime movers mainly used can be divided into two classes according to their working principles, namely mechanical prime movers including internal combustion engines (ICEs), gas turbines (GTs), micro turbines (MTs) and stirling engines (SEs) [28] and electrochemical prime movers including solid oxide fuel cells (SOFCs), molten carbonate fuel cells (MCFCs) and proton exchange membrane fuel cells (PEMFCs) [29]. Table 1 lists the comparisons of different prime movers. It is observed that the waste heat temperature of different prime movers is between 50 °C and 1000 °C. The highest temperature waste heat comes from SOFCs, which ranges from 800 °C to 1000 °C. The residual heat forms of ICEs and SEs include exhaust gas and jacket water, and usually the temperature of the waste heat of SEs is lower than that of ICEs. The residual heat generated by GTs and MTs is only exhaust gas. As for fuel cells, PEMFCs operate at low temperature, while the other fuel cells operate under higher temperature. Notably, the temperature and form of exhaust heat have a great influence on the design of subsequent thermal utilization method.

Considering their respective characteristics, the optimal prime mover integrated into a hybrid CCHP system necessitates appropriate selection. The most basic criteria include the following four aspects: technical standards including efficiency, maturity, reliability and adjustability; economic standards including investment, operation and maintenance; environmental standards including emissions and noise;

Table 1
Comparisons of different prime movers.

Prime movers	Waste heat temperature	Electrical efficiency	Advantages	Disadvantages
ICE	80~550 °C [40]	25~40% [33]	.short start-up time [31] .high part-load efficiency [24] .good reliability [34] .low investment cost [31]	.high maintenance cost [24] .large noise [24] .high emissions [24] .high heat loss [28]
GT	450~650 °C [40]	21~36% [33]	.good reliability [34] .less floor area [32] .high exhaust temperature [31] .low maintenance cost [32]	.high investment cost [41] .require premium fuel [24] .environmental sensitivity [24] .poor part-load efficiency [28]
MT	200~300 °C [40]	15~30% [32]	.lightweight and compact [34] .easy connection [34] .low noise [34] .low emissions [31]	.high investment cost [32] .low electrical efficiency [32] .environmental sensitivity [24]
SE	65~450 °C [40]	15~35% [42]	.control combustion easily [32] .low noise [32] .low emissions [32] .low maintenance cost [41]	.high investment cost [32] .low electrical efficiency [31] .long start-up time [41] .environmental sensitivity [31]
SOFC	800~1000 °C [34]	50~60% [32]	.quiet operation [34] .good reliability [32] .low emissions [28] .not require catalyst [32]	.long start-up time [32] .require expensive alloys [32] .high investment cost [32]
MCFC	600–700 °C [32]	45~60% [41]	.quiet operation [34] .low emissions [28]	.high investment cost [32] .long start-up time [32] .relatively fixed output [32]
PEMFC	50~100 °C [41]	30~50% [32]	.quite simple [32] .not easy to corrosion [32] .quiet operation [34] .low emissions [28] .short start-up time [41]	.require expensive catalyst [32] .require premium fuel [32]

social standards including acceptability and footprint [30]. Generally speaking, due to the need for regular maintenance, ICEs are widely used in multigeneration plants with a capacity of less than 5 MW [31]. Moreover, ICEs are classified according to its ignition method, either compression ignition engines used in large scale plants or spark ignition engines used in smaller scale plants [32]. GTs are commonly used in larger multigeneration plants with capacities ranging from a few MW to several hundred MW [33]. When the capacity is less than 1 MW, it is not cost-effective because of the low electrical efficiency [32]. MTs are similar in design and structure to GTs [34], but it is more suitable for small multigeneration plants from several kW to hundreds of kW. Different from the above internal combustion equipment, SEs belong to external combustion device. Besides, SEs are considered to be less competitive when considering the investment cost, so this technology has not been extensively explored in recent studies [35]. In comparison with traditional combustion-based technologies, fuel cells with low emissions and high electrical efficiency are the most promising prime movers [36]. At present, the main obstacle to promote the usage of fuel cells is that their cost is still higher than that of combustion-based technologies [37].

In addition, here are some cases which focus on the selection of prime mover. Roman and Alvey [38] optimized the trigeneration systems with different prime movers from the aspects of economy, energy and emissions, and found that the system with ICE has higher comprehensive efficiency. Ebrahimi and Keshavarz [39] evaluated different prime movers with the assistance of fuzzy logic and grey incidence method, and concluded that the optimal prime mover is ICE, followed by SE and MT.

2.2. Waste heat recovery systems

The heat discharged from the prime movers can be captured by various waste heat recovery systems to output products for end users. The ultimate products mainly include electricity, cooling and heating. The core concept of electricity generation technology is the thermodynamic Rankine cycle. According to the working fluid used, Rankine engines are divided into steam turbines (STs) and organic Rankine cycles (ORCs) [42]. Table 2 presents the comparisons of different Rankine engines. Generally, STs are utilized with heat recovery steam generators (HRSGs), which absorb heat to produce steam. In addition, based on the steam pressure at the outlet of the steam turbines, the steam turbines are classified into back pressure steam turbines whose outlet pressure is higher than atmospheric pressure and condensing steam turbines whose outlet pressure is lower than atmospheric pressure [34]. The low-pressure steam at the outlet can also be used for equipment that requires low-grade heat, such as heat exchangers. As for ORCs, the organic working fluid with a lower boiling point is used instead of water. Therefore, the selection of suitable working fluid is an important issue for ORC design [43].

On the other hand, the waste heat can also be converted into heating through heat exchangers, or into cooling through sorption chillers (absorption or adsorption) and desiccant chillers. The main differences between the two kinds of sorption chillers lie in the used sorbent and the duration of the sorption cycle [45]. Moreover, absorption chillers (ABS) are more popular than adsorption chillers (ADS) because of their low investment cost and high efficiency [28]. Besides, it is worth noting that desiccant chillers have attracted much attention because they can handle sensible heat and latent heat separately [45].

Table 2
Comparisons of different Rankine engines.

Types	Operational temperature	Electrical efficiency	Advantages	Disadvantages
ST	Up to 540 [32]	10.7~20% [33]	.long service life [24] .good reliability [32]	.long start-up time [32] .high investment cost [24] .poor part-load efficiency [32]
ORC	90~400 °C [41]	8~23% [41]	.low operational temperature [42] .simple structure [42] .high part-load efficiency [28]	.low electrical efficiency [44] .high investment cost [44]

2.3. Solar energy systems

Solar energy is the most promising renewable energy and has been widely used in hybrid CCHP systems. There are different types of solar collectors, including photovoltaic panels (PVs) for electricity, solar thermal collectors (STCs) for heating and photovoltaic-thermal collectors (PVTs) for electricity and heating. The various applications of the above-mentioned collectors in hybrid CCHP systems are discussed in detail below.

2.3.1. Solar thermal collectors

As shown in Table 3, solar thermal collectors are mainly divided into concentrating collectors, which focus sunlight through mirrors or lenses, and non-concentrating collectors [46]. Due to the differences in the structure of collectors and the properties of working fluids, the operating temperature of solar thermal collectors varies greatly from 25 °C to 2000 °C. The fluid temperature of the concentrating collectors is higher than that of the non-concentrating collectors. In terms of their integration methods, they can be integrated into different locations in hybrid CCHP systems and provide various forms of energy for the coupling devices [40].

Considering the quality matching principle of energy sources and energy demands, low-temperature solar heat can be directly used to provide domestic hot water. For example, Di Somma et al. [47] employed the heat flow generated by ETCs at 353.15 K to produce hot water for end-users. Similarly, Luo et al. [48] built a commercial energy system, as shown in Fig. 1, in which solar thermal collectors are combined with heat exchangers to meet the hot water load. It is recommended that the partial load efficiency of the equipment must be considered in the optimization process. Besides, solar thermal collectors can also be utilized to assist double-effect absorption heat pump to produce chilled water or hot water. Wang et al. [49] designed a hybrid CCHP system driven by solar energy and natural gas shown in Fig. 2, in which the solar hot water is mixed with the jacket water of internal combustion engine. The mixed hot water is sent to the low-pressure generator in summer or to the evaporator and low-pressure generator in winter. The assistance of solar energy makes the system achieve 11.3% fuel saving.

The medium and high temperature solar collectors are usually used in combination with various thermodynamic cycles that require work input, and the heat collected is used to preheat the transmission fluids, such as water, air and organic working medium. Generally, water absorbs solar heat and then converts into saturated water vapor or superheated water vapor, which can be used to drive the steam cycle. Baghernejad et al. [50] used solar heat as an auxiliary heat source and combined it with gas turbine exhaust gas to heat the circulating water, thereby providing superheated steam for the steam cycle including steam turbine, heat exchanger and absorption chiller. The optimal design parameters reduce the unit product cost by 11.5% and increase the exergy efficiency by 11.69%. Based on the cascade utilization of solar energy, Saini et al. [51] constructed a novel solar-driven trigeneration system shown in Fig. 3, in which the heat generated by the evacuated tube collectors is applied to generate high-pressure steam through the vapor generator and heating effect through heat exchange in turn. The exergy efficiency and carbon dioxide emission reduction are 3.159% and 13.10 tonnes, respectively. To further increase the share of solar energy, Li and Yang [52] developed a two-stage integrated solar combined cycle system to produce more steam, so that more electricity can be generated. This leads to an improvement of 1.2% and 2.5% in net solar-to-electricity and exergy efficiencies, respectively.

Table 3
Different types of solar thermal collectors [40].

Types	Collectors	Temperature
non-concentrating ones	unglazed flat plate collector (unglazed FPC)	25–50 °C
	glazed flat plate collector (glazed FPC)	50–100 °C
	evacuated tube collector (ETC)	50–200 °C
concentrating ones	linear Fresnel collector (LFC)	60–250 °C
	compound parabolic collector (CPC)	60–300 °C
	parabolic trough collector (PTC)	60–400 °C
	parabolic dish collector (PDC)	100–1500 °C
	heliostat field collector (HFC)	150–2000 °C

Moreover, in order to improve combustion efficiency, solar thermal energy with high-enthalpy can be used to preheat the air before it enters the combustor chamber or drives the air turbine. Wang et al. [53] integrated the parabolic trough collector into a hybrid CCHP system to preheat the compressed air at the outlet of the air compressor of the GT from 574 K to 846.3 K as shown in Fig. 4 and analyzed the thermodynamic and environmental efficiencies of the system. It is concluded that the integration of solar energy leads to a 41% reduction of carbon emissions. Adopting the same collectors in Ref. [53], Behar [54] compared the influences of different heat transfer fluids used in the collectors on the performances of the system. The solar-to-electric efficiency and fuel saving ratio of solar salt are 17% and 5.75% respectively, which are both higher than 15% and 5% of Therminol VP-1 oil. Colakoglu and Durmayaz [55] designed a solar driven multiple generation system, in which the heat generated by the heliostat field collectors is used to heat the preheated compressed air to 1000 °C to provide power for the air turbine, and optimized the system parameters taking into account energy, exergy and environmental factors. Yang et al. [56] employed the thermal energy from parabolic trough collectors to raise the temperature of the high-pressure air from the compressed air energy storage (CAES), which is then sent to the air turbine to generate electricity. Wang et al. [57] proposed a natural gas and solar driven hybrid CCHP system coupled with CAES and ORC shown in Fig. 5. The high-pressure air from CAES is heated by thermal oil and then used by air turbine and ORC for producing electricity. It is found that the average energy efficiency increased by 3.61% in winter, 1.47% in transition season and 7.72% in summer, respectively.

Besides, the medium and high temperature solar heat can be used as the high temperature side heat source of the thermal cycle to supplement heat, such as absorption chiller and ORC. Wang and Fu [58] designed a hybrid trigeneration plant fueled by dimethyl ether and solar as shown in Fig. 6, in which the exhaust gas from the prime mover is recovered through ORC and the absorbed solar energy is used to heat 358 K cooling water for running absorption chiller and heat exchanger. The reduced CO_2 emissions are 358.7 kg/day and 778.7 kg/day in typical winter and summer days, respectively. Eisavi et al. [59] proposed a solar heat-powered combined cycle composed of ORC, absorption chiller (double-effect or single-effect) and heat exchangers. The energy and exergy analysis indicated that the cycle coupled with double-effect absorption chiller had more advantages than the cycle coupled with single-effect absorption chiller. Although it results in a 27% reduction in electrical output, the cooling and heating outputs are fairly better. Khaliq et al. [60] proposed a multi-generation system based on solar energy, as shown in Fig. 7, which consists of a small heliostat field that provides the primary energy input of the system, an ORC that generates electricity, a heat exchanger that produces heating and an ejector-absorption chiller that produces cooling. It is indicated that the change of solar intensity has great influence on the energy and exergy outputs, but has little influence on the energy and exergy efficiencies.

In addition, different from the above-mentioned physical-level utilization methods, solar thermochemical utilization technology is a novel and efficient integration form to utilize medium and high temperature solar energy. The solar heat is utilized to facilitate fuel transformation and syngas production through an endothermic chemical reaction, thereby converting low-grade solar energy into syngas chemical energy and improving fuel heating value [61]. Su et al. [62] designed a distributed energy system based on the dry reforming of biogas, in which the collected solar heat promotes the conversion of biogas into syngas to drive ICE. The results indicated that the heat value of syngas is 19.06%

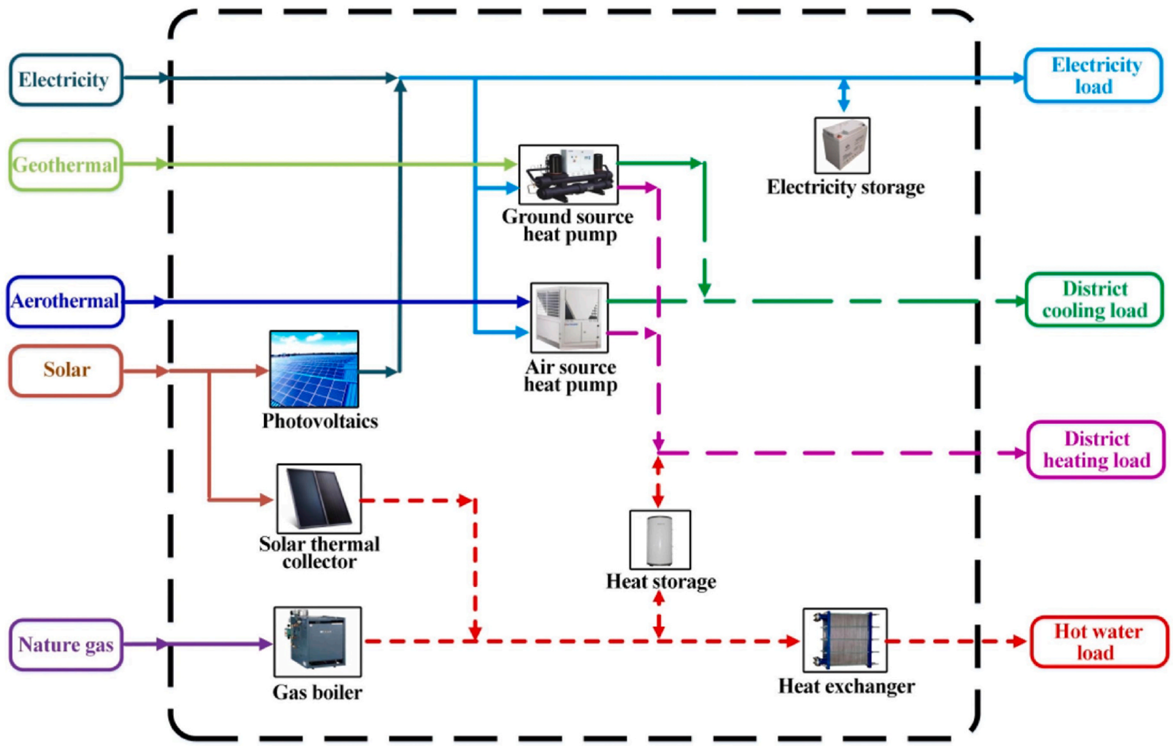

Fig. 1. Schematic diagram of hybrid CCHP system in Ref. [48].

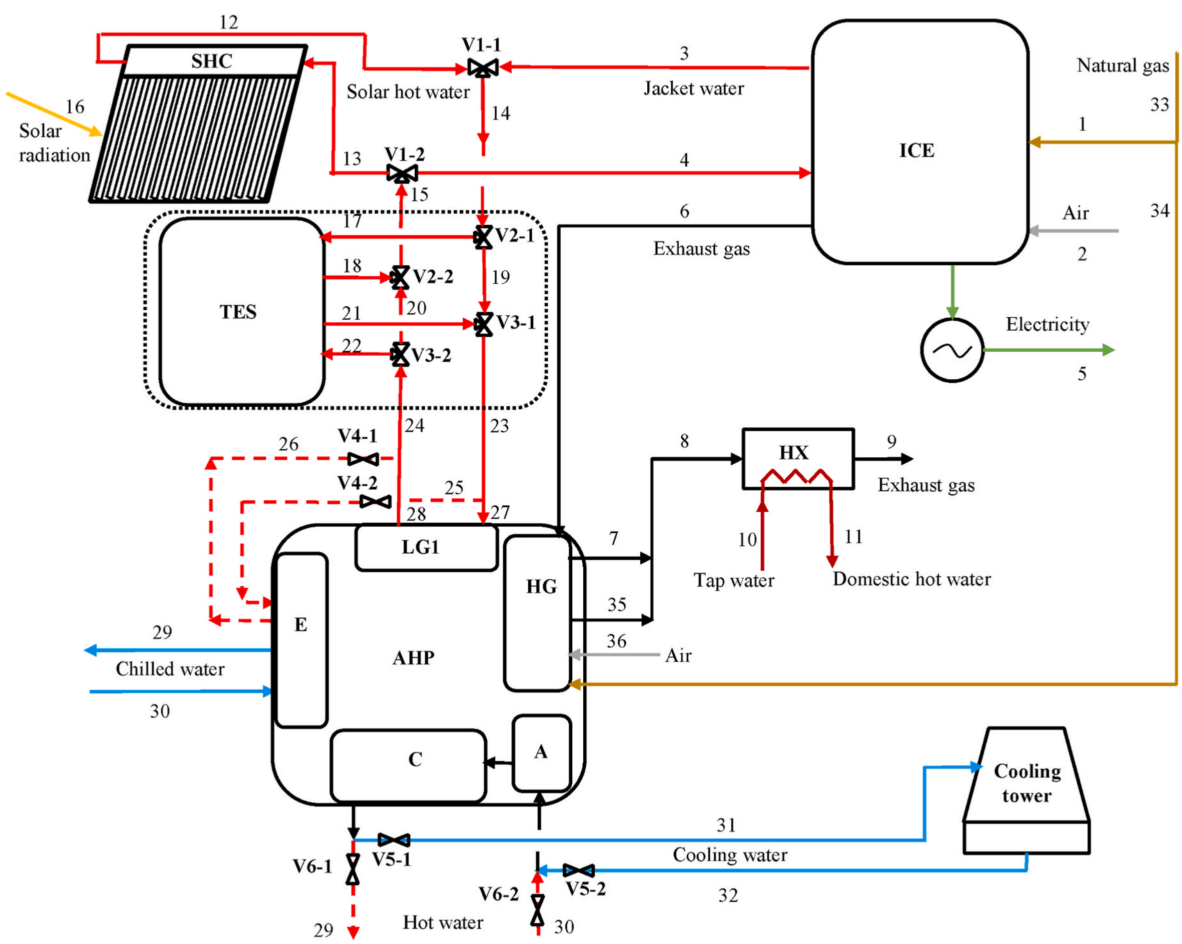

Fig. 2. Schematic diagram of hybrid CCHP system in Ref. [49].

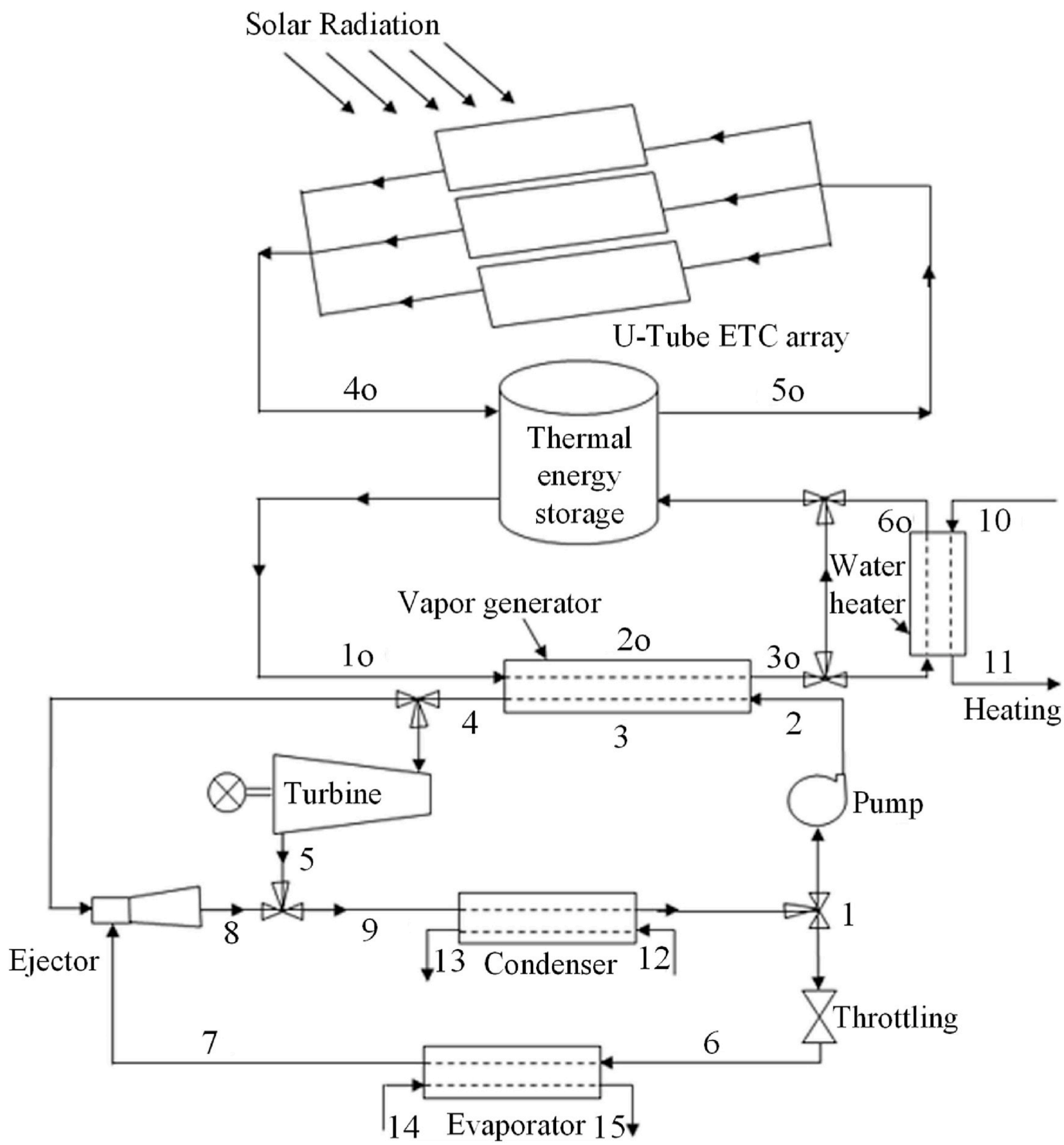

Fig. 3. Schematic diagram of hybrid CCHP system in Ref. [51].

higher than that of unreacted biogas under the design condition. After that, Su et al. [11] constructed a hybrid CCHP system based on the steam reforming of biogas driven by parabolic dish collectors. The net solar-to-product exergy and thermal efficiency are up to 26.49% and 46.80%, respectively. Xu et al. [63] established a numerical model for solar based combined cycle system, in which solar thermal energy is integrated into the methanol decomposition process to produce H_2 and CO for micro-gas turbine. The thermodynamic analysis showed that the primary energy ratio and exergy efficiency were 76.4% and 48.81%, respectively. Adopting the same solar energy utilization mode in Ref. [63], Hou et al. [37] analyzed the performance benefits of the decomposition reaction compared with direct combustion of methanol, and concluded that the thermal and power output efficiencies are increased by 3.6% and 13.8%, respectively. Liu et al. [64] employed different solar energy collectors to power a hybrid plant based on the raw lignite decomposition, in which the parabolic trough collector is used for drying and the heliostat field is used for pyrolysis and gasification. With the introduction of solar energy, the energy saving ratio reaches 63.84%. Bai et al. [65] designed a solar-biomass hybrid system consisting of a parabolic trough collector to drive biomass pyrolysis, a point-focus collector to drive biomass gasification and a gas turbine to generate electricity. The two-stage gasifier reduces the exergy destruction by 23.25% and increases the energy level upgrade ratio by 10.73%. Wu et al. [66] adopted the dish parabolic collector to generate superheated steam that is used to assist the biomass gasification shown in Fig. 8. They found that the proposed hybrid system improves the primary energy efficiency by 5.98% and shortens the payback period by 59.3%. Zhang et al. [10] combined the solar collector with the evaporator to produce saturated steam, which is used in the natural gas reforming process driven by the high temperature exhaust gas from the gas turbine. The study demonstrated that it can save 30.4% of fossil fuel consumption.

Based on the above different forms of solar energy utilization, Liu et al. [67] compared the benefits of the integrated system under the following two modes: solar energy is fed to drive biomass gasification or to increase the temperature of compressed air. They found that the energy efficiency of the former (29.36%) is higher than that of the latter (28.03%). To compare the performances of hybrid system with different types of solar collectors, Asadi et al. [68] investigated the effects of four kinds of collectors including FPCs, ETCs, CPCs and PTCs, and optimized

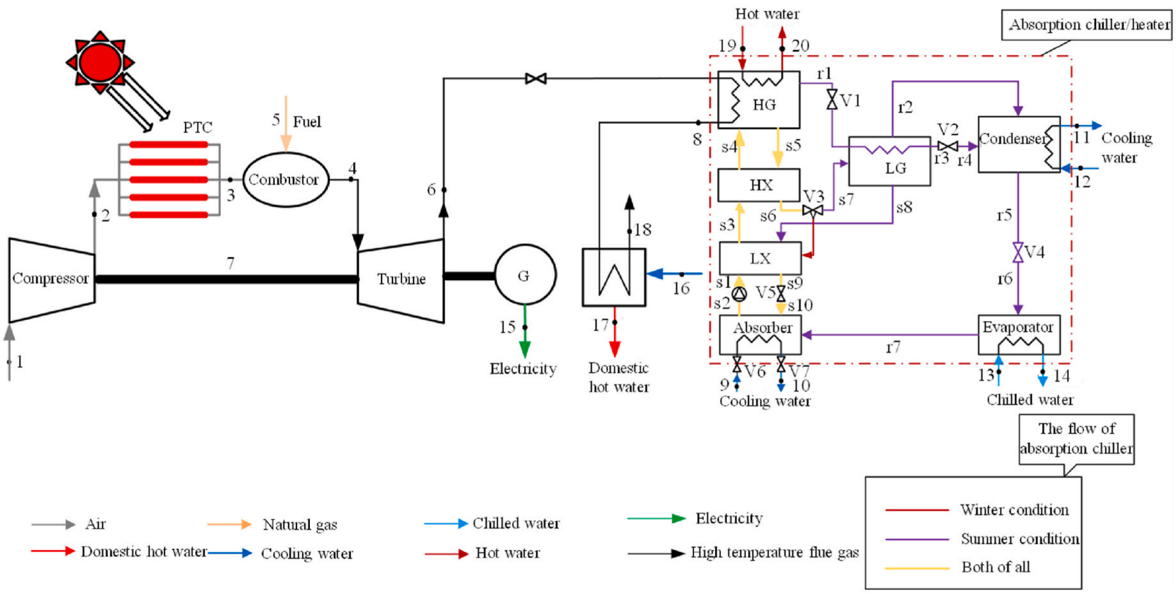

Fig. 4. Schematic diagram of hybrid CCHP system in Ref. [53].

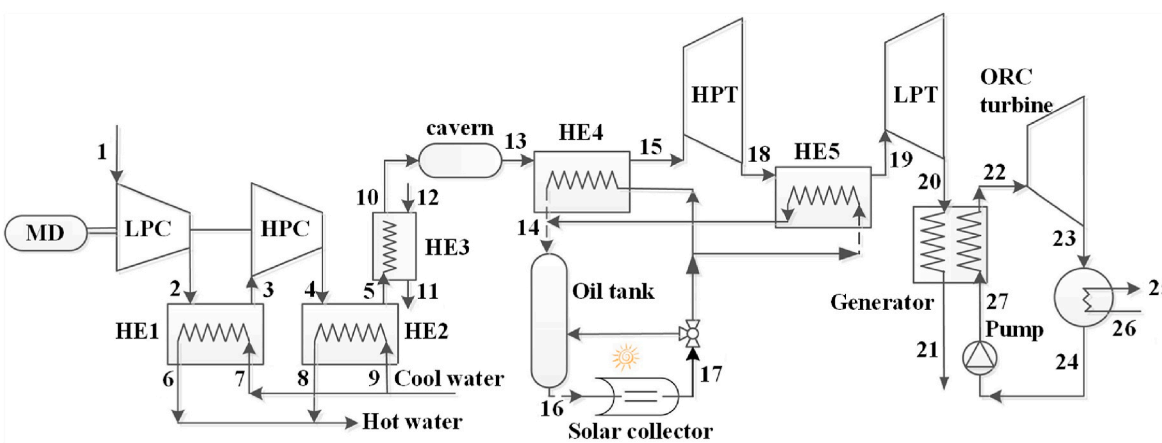

Fig. 5. Schematic diagram of hybrid CCHP system in Ref. [57].

the system configuration in consideration of energy, exergy and economy. The obtained results indicated that the PTCs have obvious advantageous in exergy efficiency, while the ETCs have higher economic efficiency.

The aforementioned researches explored the feasibility of solar thermal utilization, and they can be classified into the following types: hot water type, steam type, air type, organic working medium type, thermochemical reaction type. Table 4 presents the results of some cases conducted on solar thermal utilization.

2.3.2. Photovoltaic panels

Different to solar thermal collectors that can produce thermal energy with different temperature levels, the output of PVs is direct current (DC) electricity, which can be easily integrated into hybrid CCHP systems to satisfy the electricity demand of components or users [13]. For instance, Guo et al. [69] proposed a two-stage multi-objective optimization model to optimize the capacity and operation strategy of the equipment to achieve the lowest cost and CO_2 emissions. They found that PV panels are installed at the maximum capacity because of its zero emissions and relatively low investment cost. Gazda and Stanek [14] designed a hybrid solar-biogas-natural gas driven CCHP system consisting of PV panels, gas boiler (GB), ICE and adsorption chiller, as shown in Fig. 9. The analysis indicated that the primary energy saving and carbon dioxide emissions reduction ratios are respectively 54.50% and 67.37% through this supplementary utilization method. The commonly used PVs are mainly categorized as crystalline silicon cells and thin film cells as displayed in Table 5, whose electrical efficiencies range from 12% to 25% and from 10% to 16%, respectively. In addition, it must be noted that since the electricity demand of the building are alternating current (AC), the inverter is an essential component in order to realize the conversion from DC to AC.

Moreover, when the electricity generated by PV panels is greater than the electrical demand, the surplus electricity can be stored in the battery (EB) as a backup electrical source, or used as the power source of the electrolyzer to produce hydrogen, which is delivered to fuel cell for electricity production if necessary [71]. Lototskyy et al. [72] proposed a multi-generation system based on PV panels and reversible SOFC, where PV panels are used to cover electrical load and partly used to drive SOFC operating in electrolyser mode. The energy efficiencies of electrolyser mode and fuel cell mode are up to 69.4% and 72.4%, respectively.

2.3.3. Photovoltaic-thermal collectors

Aiming to further improve the utilization efficiency of solar irradiance, the hybrid photovoltaic-thermal collectors, which integrate PV

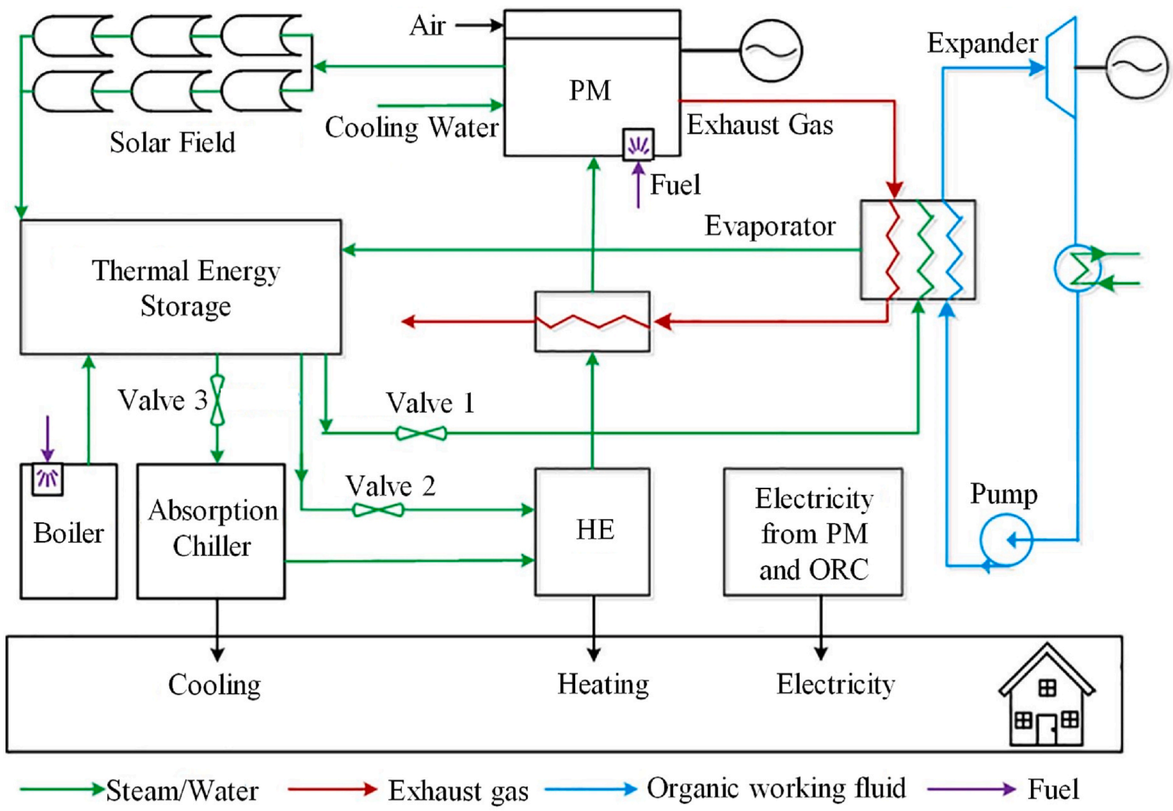

Fig. 6. Schematic diagram of hybrid CCHP system in Ref. [58].

panels into STCs, are developed to provide both electrical and thermal energy simultaneously. The STCs located on the back of the PV panels absorb the available heat through working fluids, thereby cooling the PVs. Therefore, the energy efficiency of PVT panels is higher than that of PV panels due to this cooling technology [73]. The PVT collectors can be roughly classified into non-concentrating type and concentrating type in relation to their structure or air type, liquid type, heat pipe type, phase change material type and thermoelectric type in relation to their heat extraction method [74,75]. The integration methods of PVT collectors are similar to STCs and PV panels, such as heating circulating working fluid [76–80], driving electrolysis reaction [81–83] and satisfying electric load [84,85].

Wang et al. [76] simulated and evaluated the solar-powered electricity generation system, which includes concentrating photovoltaic (CPV) panels that provide electricity and low-temperature heat, chemical heat pump that upgrades the solar heat of CPV from 185 °C to 360 °C, PTCs for providing superheated steam and steam Rankine cycle. Benefitting from the chemical upgrade, its solar-to-electric efficiency is increased by 20.10% and 23.99%, respectively, in comparison to the CPV and the PTC individual systems. Li et al. [77] established a numerical model of a solar-assisted trigeneration system, in which the PVT panels produce hot water to drive the absorption chiller, and performed parameter analysis to obtain the best performance. They concluded that increasing the solar energy utilization area can decrease the payback period, and the best payback period and electricity saving are 11.8 years and 26%, respectively. The CPC-PVT collectors can be integrated into a typical trigeneration unit in Fig. 10 [78–80], in which solar heat water and waste heat from ICE runs the absorption heat exchanger to produce chilled water, heating water and hot water. The proposed hybrid system was evaluated from different perspectives. The thermodynamic analysis (25% PV covered ratio) demonstrated that the energy and exergy efficiencies are respectively 63.3% and 21.8% in cooling mode, and 61.8% and 27.1% in heating mode [78]. To further optimize the system performance, the impacts of different PV covered ratio was also tested. The results indicated that with an ideal PV covered ratio, the exergo-economic efficiency reaches 35.56% [79], and the exergy consumption corresponding to the unit exergy output is 2.36 J/J [80].

Bicer and Dincer [81] proposed a PVT based tri-generation system. The electric energy produced by PVT is used to drive the water electrolysis process, and the thermal energy is used to preheat the water used in electrolysis process and provide energy for heat pump. Reddy et al. [82] studied the advantages of the hybrid solar-biogas driven tri-generation system, as shown in Fig. 11, in which part of the electricity from concentrated PV panels is employed to drive the electrolyzer to produce hydrogen and the mixture of hydrogen and biogas is fed into the electric generator. The experimental results showed that its thermal efficiency and peak power reach 19.50% and 812 W, respectively. Raja and Huang [83] constructed a solar powered multigeneration system, which includes PTC and PVT. The thermal fluid from PTC was first employed to run ORC, and then used to preheat the water for electrolysis reaction. One part of the hot water from PVT was supplied to the electrolyzer and the other part was used to drive the heat pump. The thermodynamic analysis indicated that the energetic and exergetic efficiencies are 12.90% and 54.72%, respectively.

Aste et al. [84] compared the performance when adopting covered and uncovered PVT, and concluded that the primary energy efficiency of the uncovered one is higher than that of the covered one, but the overall efficiency is the same. Su et al. [85] studied a solar powered CCHP system composed of PVT unit, liquid desiccant unit, vapor compression unit and chilled water unit. The heat from PVT drives the desiccant regeneration in summer and is supplied to user in winter. The proposed system can realize the energy consumption saving about 73.28% and greenhouse emissions reduction about 74.55%.

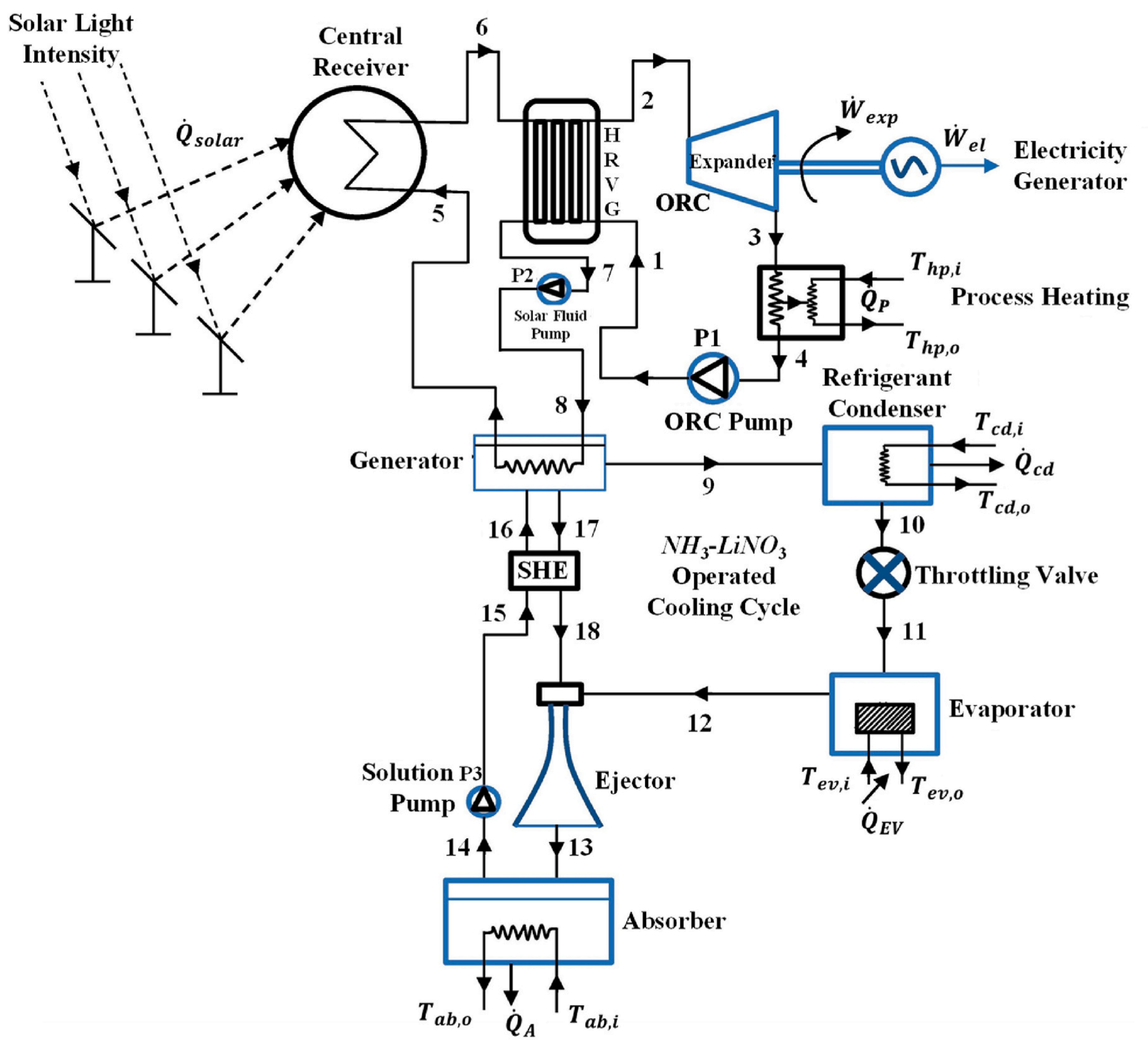

Fig. 7. Schematic diagram of hybrid CCHP system in Ref. [60].

2.4. Geothermal energy systems

Geothermal resource, as an exploitable energy under the surface of the earth, is considered as the most stable source because of its independence to ambient conditions. The available geothermal heat could be divided into three categories, namely shallow geothermal resources (low temperature), hydro-geothermal resources (low-medium temperature) and hot dry rock resources (high temperature). According to the quality of geothermal energy, it can be converted into heating and cooling by heat pumps, or into electricity by various power plants [86]. Table 6 summarizes the results of some cases conducted on geothermal utilization.

Among the various application fields of geothermal resource, geothermal power production is an alternative technology driven by medium and high temperature geothermal resource. Nowadays, there are numerous power plants in use, including dry steam power plants, flash steam power plants and binary cycle power plants [93]. Dry steam power plants use geothermal fluid in the form of steam; it can convert 50%~70% of geothermal energy into electricity. Flash steam power plants are powered by liquid phase geofluid, where the liquid is evaporated through a throttle valve and the vapor-liquid mixture is separated by a separator; its electrical efficiency can reach 21% when single flash one is adopted, and 46% when double flash one is adopted. In addition, as for binary cycle power plants, the geofluid is not used directly to drive the turbine, but as a heat source to evaporate the circulating working fluid; the energy performance is within the range of 7~12% depending on the working fluid. Zhai et al. [87] established a geothermal based ORC model and analyzed the effect of working fluid on system operation to select the most suitable working fluid. Considering the possibility of global warming, they recommended R32, R134a and propylene. Guzović et al. [94] compared the thermodynamic performance of ORC and Kalina cycle driven by geothermal energy, and concluded that ORC has better thermal and exergetic efficiencies and provides more net power under the given heat source. Yu et al. [88] proposed a novel combined system for effective utilization of geothermal energy, which includes a Kalina cycle and a transcritical CO_2 cycle. The net power output reached 2808 kW with the exergy and thermal efficiencies of 44.47% and 8.28%.

In general, the geothermal fluid at the outlet of the geothermal power plant still has sufficient thermodynamic quality, which can be extracted for various applications with lower temperature requirements. Therefore, in order to maximize the utilization of geothermal energy at different temperatures, the integrated energy systems based on the principle of energy cascade utilization have been proposed to obtain

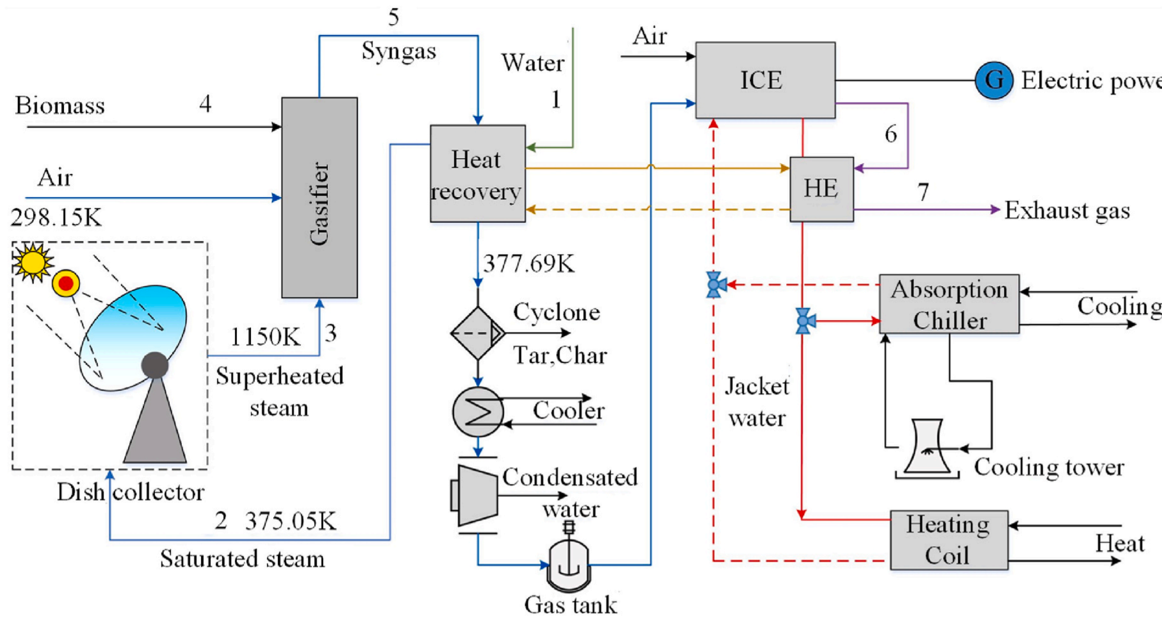

Fig. 8. Schematic diagram of hybrid CCHP system in Ref. [66].

Table 4
Cases of solar thermal utilization.

Ref.	Type	Key findings
[48]	hot water type	.The part load performance of equipment has a great impact on objectives .The optimal parameters increase cost by 13.2%, but reduce emission by 9.5%
[10]	steam type	.The net solar-to-electricity efficiency ranges from 26% to 29% .The hybrid system saves 30.4% energy and 33% emissions
[51]	steam type	.Increasing generator and condenser temperatures and decreasing evaporator temperature can improve exergy efficiency .Increasing the temperatures of generator, condenser and evaporator can reduce unit product cost
[53]	air type	.The energy efficiency and exergy efficiency are 66.0% and 25.7% in winter and 83.6% and 24.9% in summer, respectively .The use of solar energy reduces about 41.0% carbon emissions
[57]	air type	.The energy and exergy efficiencies are 98.30% and 68.94%, respectively .The energy efficiency increases with the increase in compressor pressure ratio, while the exergy efficiency shows an opposite trend
[59]	organic working medium type	.The solar collector and the evaporator of ORC are the main components causing exergy loss .The capital cost can be reduced when ORC operates under lower pressure
[58]	organic working medium type	.The ORC improves 9.87% of efficiency .The payback period changes from 4.0 years to 6.5 years with the reduction of electricity price
[37]	thermochemical reaction type	.The electrical and thermal efficiencies are 59.7% and 81.6%, respectively .The investment payback period raises with the increase of SOFC price
[64]	thermochemical reaction type	.The net energy efficiency increases by 8.30% .The integration of solar energy reduces about 63.84% lignite energy

different products. Ambriz-Díaz et al. [95] carried out an experimental study of a multigeneration system fueled by geothermal heat, and analyzed the system from the perspective of thermodynamics and thermoeconomics. The economic results indicated that the cost of electricity production (8.54$/h) is the highest, followed by cooling production (7.78$/h) and heat production (3.52$/h). Zare [96] compared the thermodynamic performance of two trigeneration systems powered by geothermal energy, which consist of ORC or Kalina cycle, absorption chiller and heat exchanger. The exergy efficiency of the system based on Kalina cycle is higher than that of the system based on ORC. Cao et al. [97] proposed a geothermal-boosted combined cycle consisting of an ORC, an absorption chiller and a heat exchanger in Fig. 12. The dynamic simulation demonstrated that higher heating capacity and cooling capacity can be obtained at high geothermal water temperature. In the same context, a domestic energy system was proposed and analyzed by Nami and Anvari-Moghaddam [90]. It was shown that the second law performance could reach 60% under the optimized state. Zare and Rostamnejad [89] proposed two novel trigeneration systems based on ejector transcritical CO_2 cycle and Rankine cycle, and evaluated the feasibility in terms of the first law and second law efficiencies. The results showed that the system with internal heat exchanger has higher exergy efficiency than the system with gas cooler.

In addition to the above-mentioned cascade cycles driven solely by geothermal energy, other methods to enhance the thermodynamic performance are hybrid systems which combine multiple energy sources. Musharavati et al. [98] proposed a multi-generation system based on basic geothermal driven system including absorption chiller, organic flash cycle and heat exchanger. PVT, thermoelectric unit and reverse osmosis desalination unit are added to the modified system. The optimal energy and exergy efficiencies are respectively 5.46% and 20.16% with net output power of 70.85 kW. Rostamzadeh et al. [99] proposed a geothermal assisted multigeneration system, which is composed of liquefied natural gas unit, absorption refrigeration unit, absorption-compression heat pump unit, Kalina cycles, domestic water heater unit, humidification-dehumidification desalination unit and biogas steam reforming unit. The results demonstrated that the total exergy destruction is 2036.19 kW, and the thermal and exergy efficiencies are respectively 62.28% and 74.9% under the design condition. On this basis, to obtain the optimal operating performance, Rostamzadeh et al. [100] established an optimization model that considers economic, environmental and energetic aspects, and employed genetic algorithm to find out the best design parameters. Its production cost can be reduced up to 3.7%, while the thermal efficiency and exergy

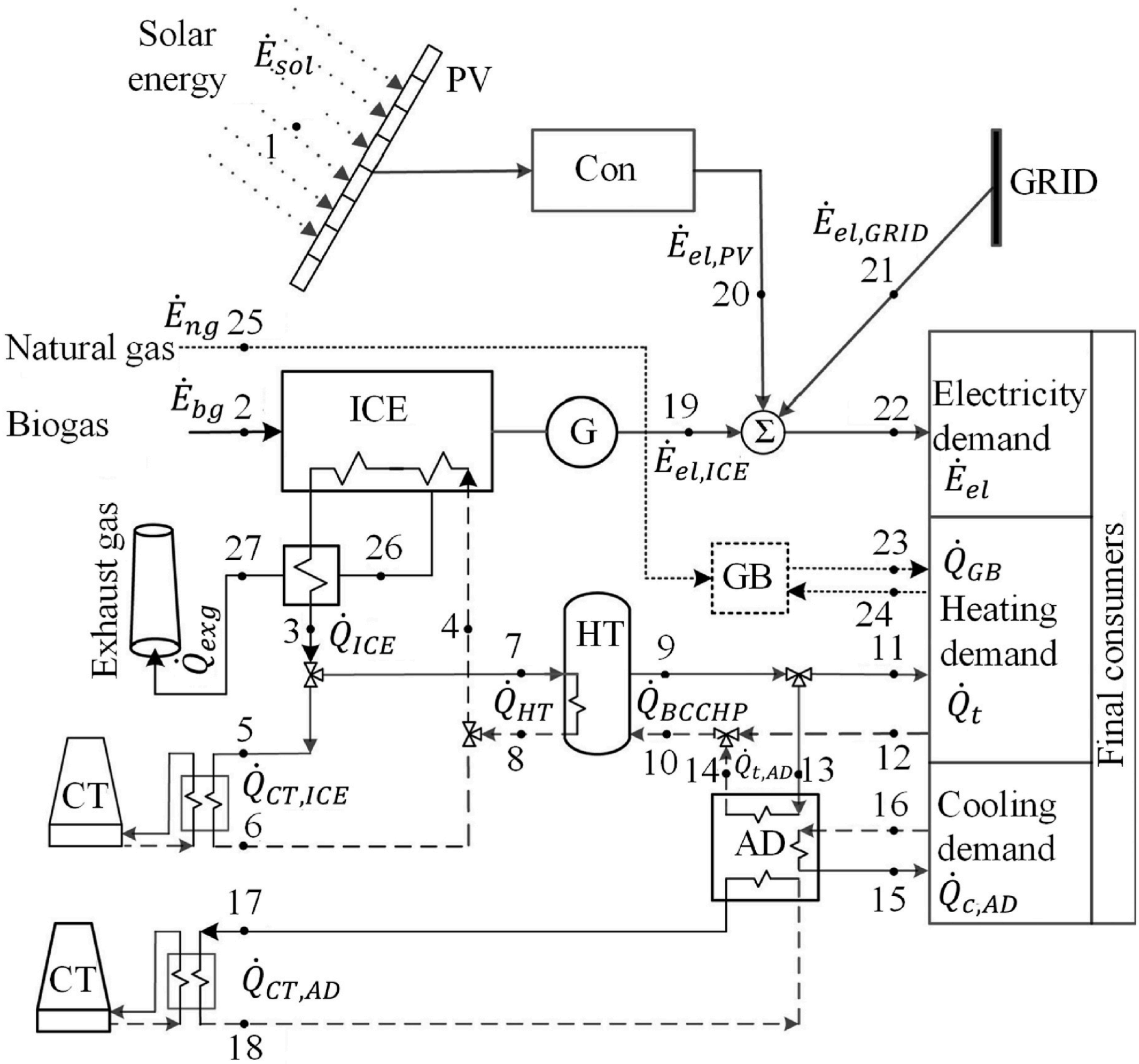

Fig. 9. Schematic diagram of hybrid CCHP system in Ref. [14].

Table 5
Different types of photovoltaic panels [70].

Type	Collector	Efficiency
Crystalline Silicon	Polycrystalline	12–15%
	Monocrystalline	15–25%
	Amorphous	12–15%
Thin Film	Copper-Indium-Selenium	14%
	Copper-Indium-Gallium-Selenium	10–13%
	Cadmium Telluride	16%

efficiency can be improved up to 12.07% and 5.16% respectively. Ansarinasab and Hajabdollahi [101] developed a multigeneration system based on various thermal systems such as ORC, Stirling engine, desalination unit and water heater in Fig. 13, and optimized design parameters to obtain the best integrated performance. The outcomes showed that the exergy efficiency and product cost rate are respectively 52.65% and 4.35$/GJ under the best design.

Besides, ground source heat pump (GSHP) is a fully mature technology and has been widely used in various energy systems. It consists of four units, namely evaporator, compressor, condenser and throttle value, and can realize the switching of heating or cooling work conditions through four-way valve. Zeng et al. [102] proposed a CCHP-GSHP coupled system shown in Fig. 14, and optimized the system configuration and hourly operation strategies from the aspects of energy, economy and environment. The best comprehensive performance reaches 36.26%. Ren et al. [92] presented a multi-objective optimization model for natural gas driven CCHP and GSHP coupling system integrated with PV. The results showed that the application of GSHP can improve the system performance by adjusting the thermoelectric ratio. However, the integration mechanism of CCHP and GSHP in the above studies is somewhat simple without consideration to the deep coupling between different subsystems, or rather to say, GSHP is only employed as a supplementary system to provide heating or cooling. In order to further improve the total energy performance, the waste heat of CCHP can be utilized to preheat ground water. For example, Zhang et al. [103] presented a biomass based hybrid system integrated with GSHP and CAES, and evaluated the system performance through a case study. The results indicated that the round trip and exergy efficiencies can reach at about 90.06% and 31.52% under the simulation condition, respectively. Wang et al. [91] investigated a trigeneration system with three sub-units, including a power generation system, a GSHP and an absorption heat pump. The proposed coupling system can reduce primary energy consumption by about 40.6% in summer and 39.5% in winter, respectively. Li et al. [104] conducted a comparative study on simple (parallel) coupling and deep (series) coupling modes: GSHP only provides warm

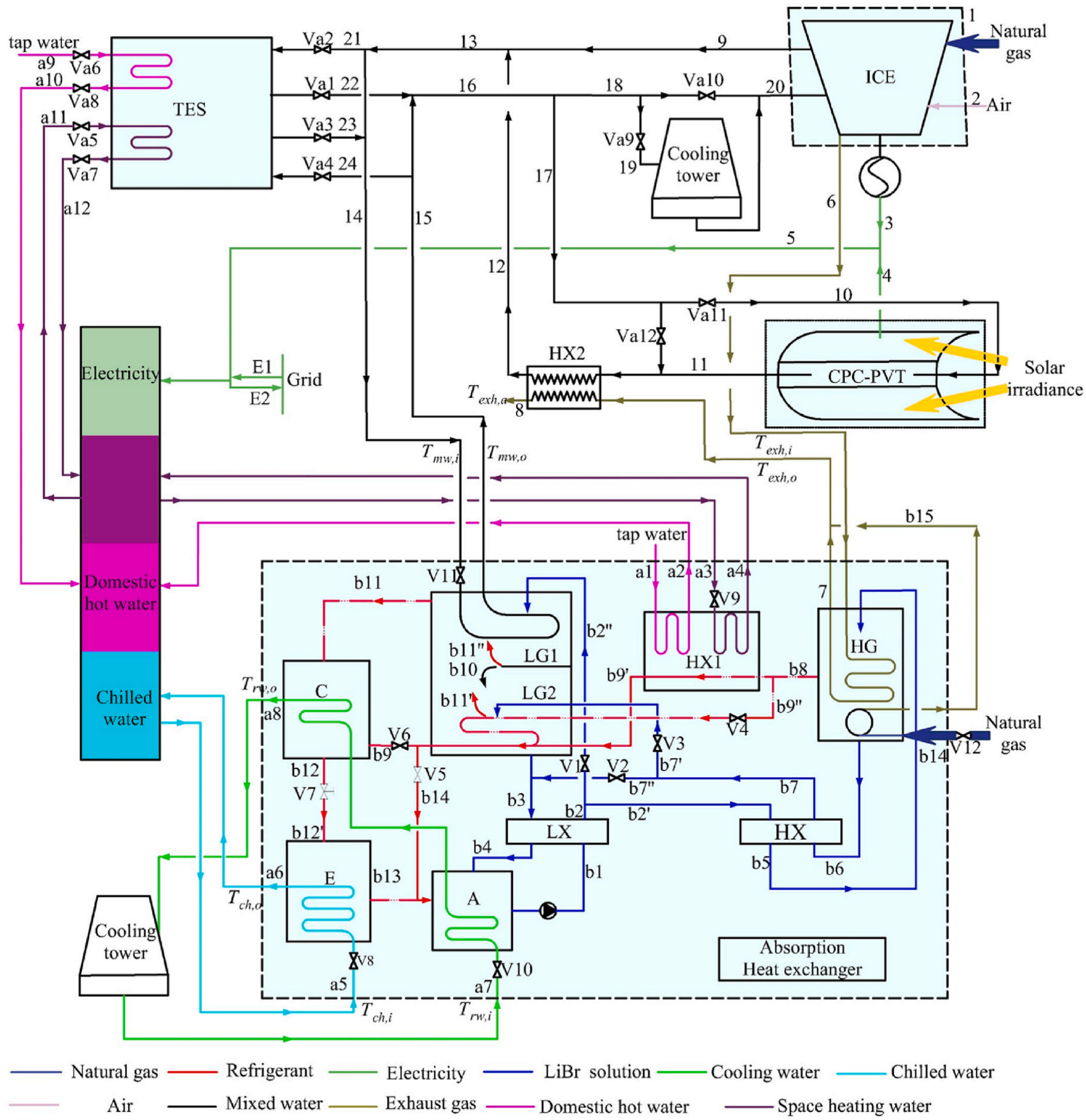

Fig. 10. Schematic diagram of hybrid CCHP system in Refs. [78–80].

water in series mode, while GSHP directly produces hot water in parallel mode. They found that the series mode has an advantage over the parallel mode, which can increase the energy efficiency by 4.4%. Chen et al. [105] designed a geothermal-assisted natural gas cogeneration system shown in Fig. 15. The hybrid system includes an ICE, an absorption heat pump, a geothermal heat pump and four heat exchangers. The allocation ratio of ground water after heating was optimized and the results showed that the optimum allocation ratio corresponding to the maximum efficiency is 90% of hot water to GSHP and 10% of hot water to absorption heat pump.

2.5. Wind energy systems

Wind energy caused by temperature difference is a clean and renewable energy source. Generally, wind energy is converted into electricity through wind turbine (WT), which first converts the kinetic energy of wind into the mechanical energy of the blades, and then relies on the blades to drive the generator to produce electricity [106]. According to the direction of the rotating axis of the blades, wind turbines can be grouped into two types: (1) horizontal axis wind turbines and (2) vertical axis wind turbines [107].

Similar to PV, the electricity yield from WT is directly employed to satisfy the electricity demand of buildings or devices. It does not have any impact on the thermal cycle of the integrated system. To make better use of wind power, great efforts have been made to find the optimal scheme. For instance, Li et al. [108] optimized the dispatch strategy of hybrid CCHP system combined with wind power to achieve the minimum daily operation cost. The annual operating cost and wind energy utilization rate of the studied case are $ 2,836,345.6 and 95.3%, respectively. Khalid et al. [109] studied a hybrid residential energy system driven by solar-wind-geothermal energy, as shown in Fig. 16, which comprises a WT, a concentrated solar collector, an ORC and a GSHP. It is found that the net present cost is $345,481 with the levelized cost of 0.181 $/kWh. In addition, to deal with the uncertain characteristics of wind, some probability density functions have been applied in the modeling stage. Zhang et al. [110] proposed a multi-criteria optimization framework based on Monte Carlo simulation to size the renewable energy system, in which the wind speed is described by

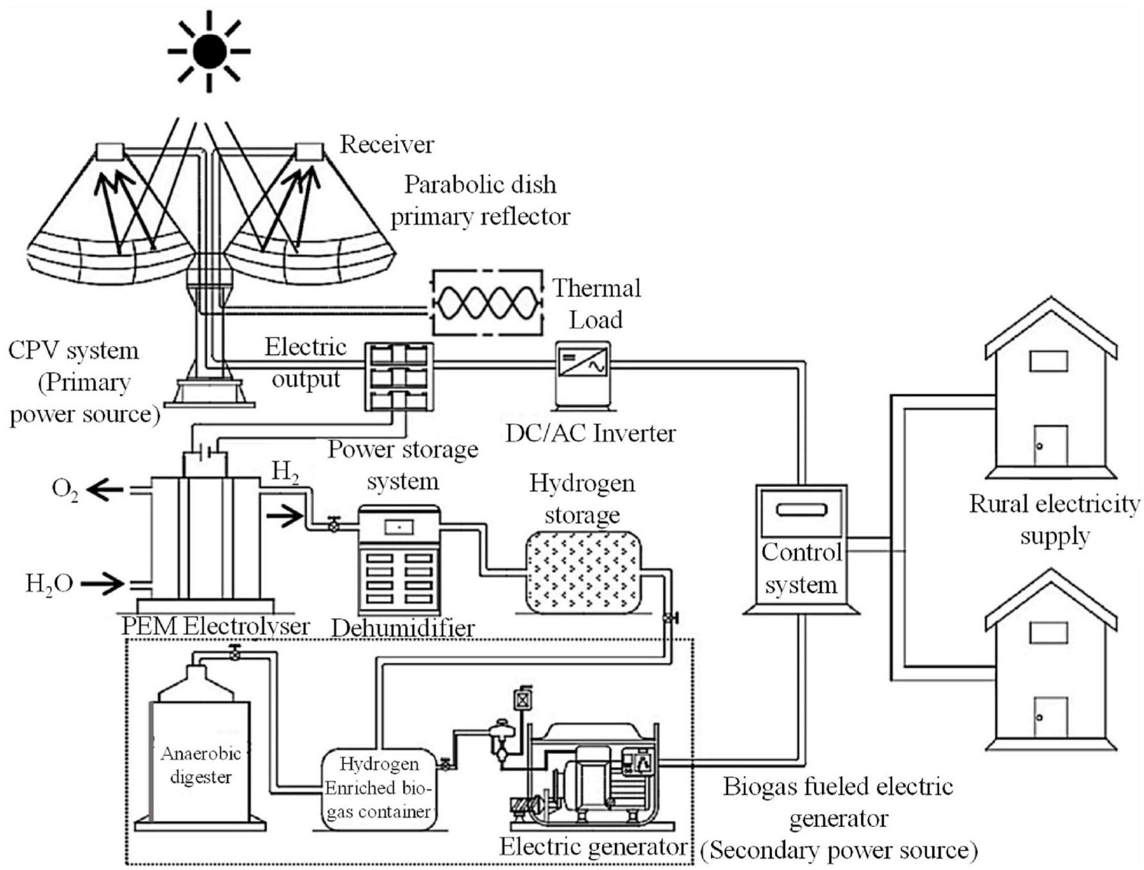

Fig. 11. Schematic diagram of hybrid CCHP system in Ref. [82].

Table 6
Cases of geothermal utilization.

Ref.	Type	Key findings
[87]	electricity type	.The optimal evaporating temperature of all candidate working media is almost the same .The working media with double bond or cyclic structure can provide higher efficiency
[88]	electricity type	.Exergy destruction is mainly caused by the temperature difference in the heat transfer process .As the inlet pressure of the turbine of the transcritical CO2 cycle increases, the system performance first increases and the decreases
[89]	electricity-cooling-heating type	.The internal heat exchanger can enhance system operating performance .With the turbine inlet pressure increasing, the exergy efficiency will increase, while the thermal efficiency will decrease
[90]	electricity-cooling-heating type	.When there is no power generated, the second law efficiency reaches its maximum value, which is 60% .The change of geothermal flow rate has little influence on the system performance
[91]	cooling-heating type	.When the output of geothermal equipment increases, the changing patterns of primary energy ratio and exergy efficiency are opposite .The primary energy saving ratio is 40.6% in summer and 39.5% in winter, respectively
[92]	cooling-heating type	.The following electric load is recommended as the operation strategy .Natural gas prices and electricity prices have opposite effects on annual cost saving rate

Rayleigh distribution. Compared with the worst-scenario design method, the overall performance is improved by 44%. Lu et al. [111] conducted a sensitivity analysis to search design parameters with high robustness and concluded that controllable energy generation units can enhance overall performance. Zidan et al. [112] established the models of wind velocity and solar irradiation with Weibull distribution and Beta distribution respectively, and integrated them into the optimal planning of cogeneration system.

Furthermore, the electrical storage units [113] and the water electrolysis systems [114,115] driven by surplus electricity from wind turbines are the alternative components to improve the operational flexibility and reliability and increase the utilization space of wind energy. Hossain et al. [113] presented an energy scheduling model for a hybrid wind-solar driven system that takes into account the degradation cost of battery. Through the optimization of the operation strategy from the perspective of overall operational cost, it is showed that the proposed method can reduce the cost by 40%. Sezer and Koç [114] proposed a hybrid solar-wind-osmotic power based multi-generation system to produce hydrogen, oxygen, freshwater, cooling and electricity. The proposed system combined solar field, wind turbine, pressure retarded osmosis thermal energy storage, fuel cell, electrolysis unit, desalination unit and compression refrigeration cycle. The energetic and exergetic efficiencies are found to be 73.3% and 30.6%, respectively. Ozlu and Dincer [115] designed and optimized an integrated system including parabolic solar collector, domestic water heater, thermal storage, wind turbine, Rankine cycle, absorption chiller and electrolyzer. The optimum condition has 43% energy efficiency and 65% exergy efficiency with CO_2 emissions reduction of 1614 tons.

2.6. Energy storage systems

In the context of high penetration rate of renewable energy, the intermittence and randomness of renewable energy should be considered in the design and planning stage. At the same time, the asynchronous characteristics of various demands will cause the discontinuous

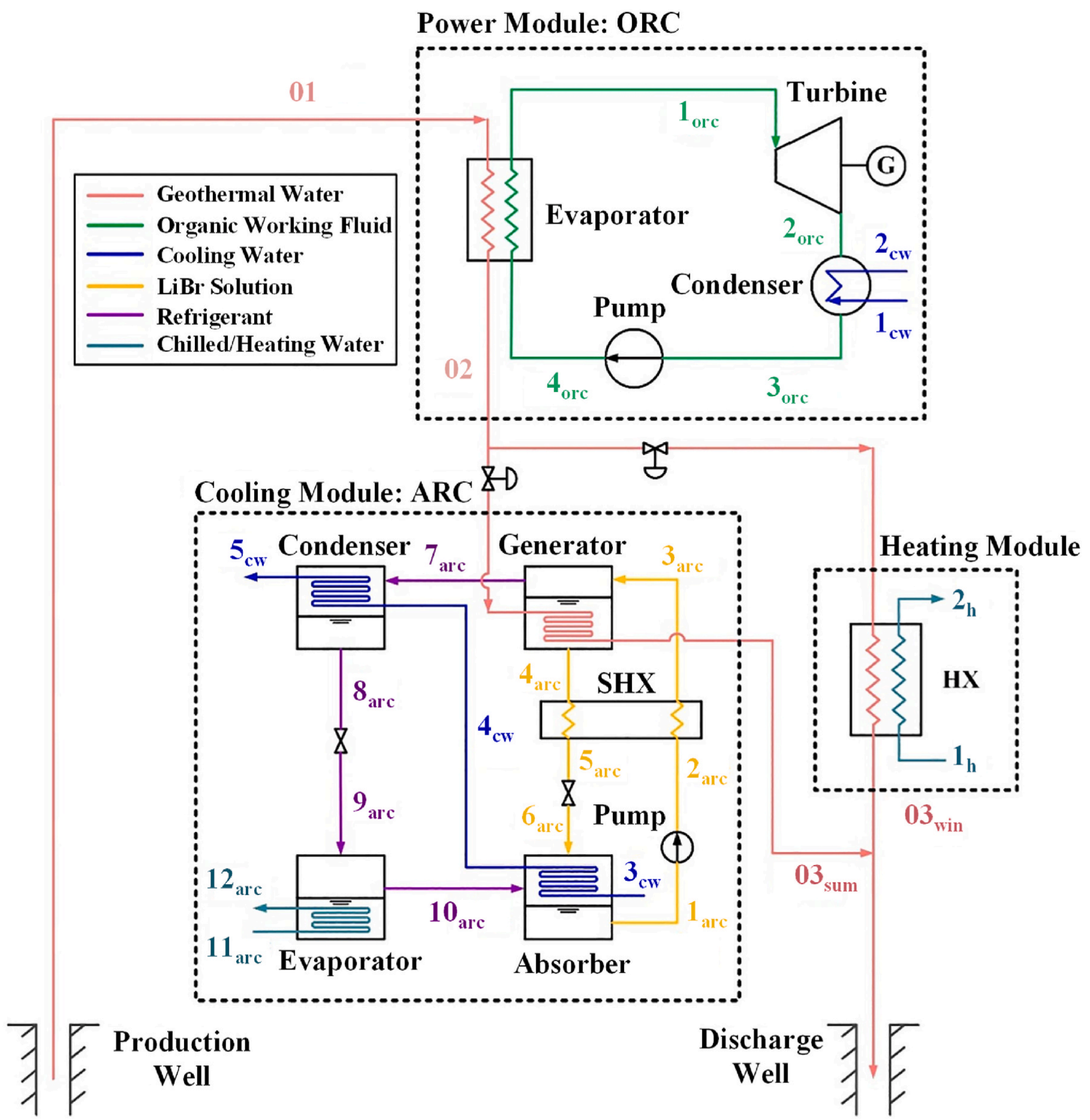

Fig. 12. Schematic diagram of hybrid CCHP system in Ref. [97].

operation of the energy systems, thus reducing energy efficiency. The introduction of energy storage systems can well solve the above-mentioned problems, including: (1) the mismatch between electric and thermal loads, (2) the mismatch between available renewable energy sources and building demands, thereby improving the flexibility and reliability of system operation and realizing more effective consumption of renewable energy. Table 7 shows the results of some cases conducted on energy storage technology.

With regard to electrical energy storage, batteries are a common choice due to their relatively mature technology [36]. Wang et al. [123] used the energy hub model to evaluate the effects of the uncertainty of solar irradiance and building loads on system design, and found that the small capacity battery is more suitable for all scenarios. Yan et al. [116] conducted a multi-criteria decision to optimize the hybrid CCHP system shown in Fig. 17, taking into account annual cost saving rate and energy supply independence. They found that as the battery capacity increases, the dependence on the municipal gird will reduce while the total cost will increase. The above analysis demonstrates that the high cost limits the widespread application of the battery. Nowadays, compressed air energy storage with lower cost and higher efficiency has been studied and developed as an alternative to battery [124]. Alirahmi et al. [117] proposed a green CAES system comprising a solar-driven Brayton cycle, a steam Rankine cycle, a CAES, a thermoelectric generator, an electrolyzer and a gas turbine, and analyzed the thermodynamic and economic performances. The results indicated that the energy and exergy efficiencies reach 58.7 and 60.4%, respectively, and its levelized cost of electricity is 0.171 $/kWh. Wang et al. [125] developed a small-scale CAES system combined with solar energy as shown in Fig. 18, in which the air compressor is driven by the surplus electricity of the gas turbine. The optimal exergy efficiency is 53.1% in maximum heating condition and 45.4% in maximum cooling condition, respectively. Li et al. [118] established the thermodynamic model of the CAES CCHP system and investigated the influence of the working media in the CAES system and the storage media in the thermal energy storage system. They found that the system with air and water as the medium has the highest exergy efficiency and energy density.

Concerning thermal energy storage, water tanks (WSTs) are the most favorable solution. This is because the specific heat of water is high and the water tank is cheap [28]. Wang et al. [126] introduced the operation concept of following the daily average electrical load into the following

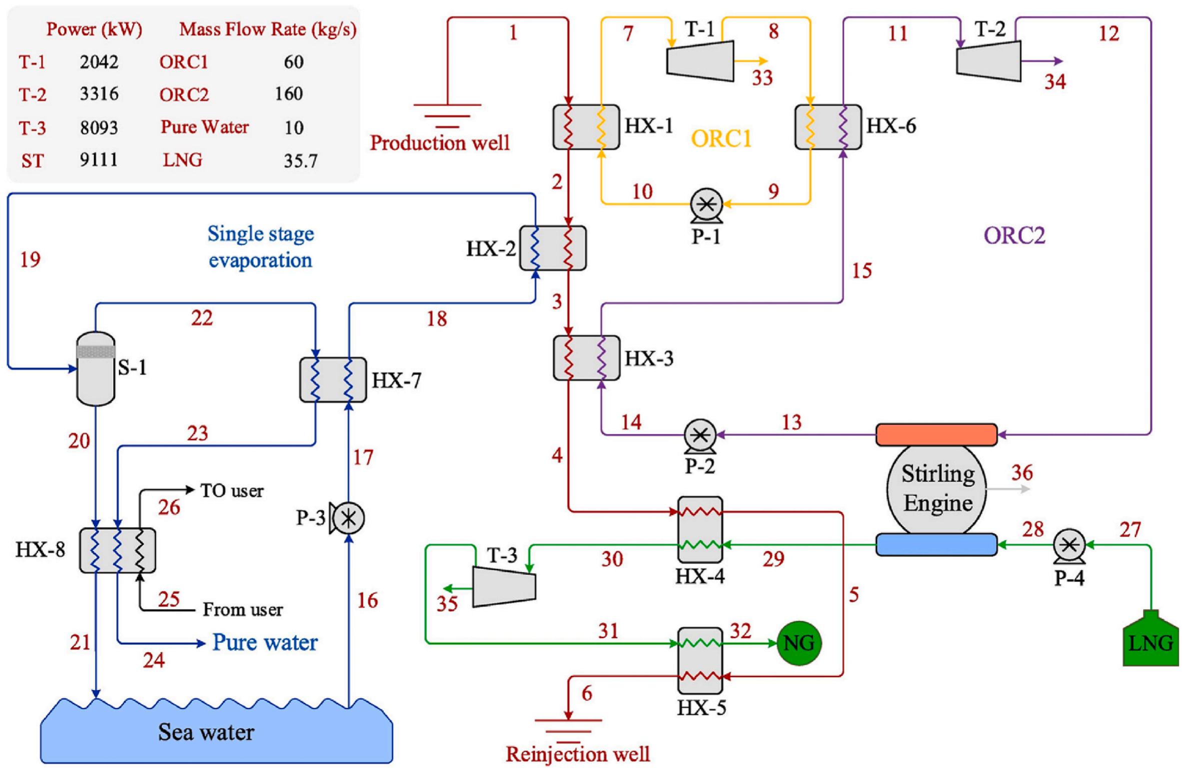

Fig. 13. Schematic diagram of hybrid CCHP system in Ref. [101].

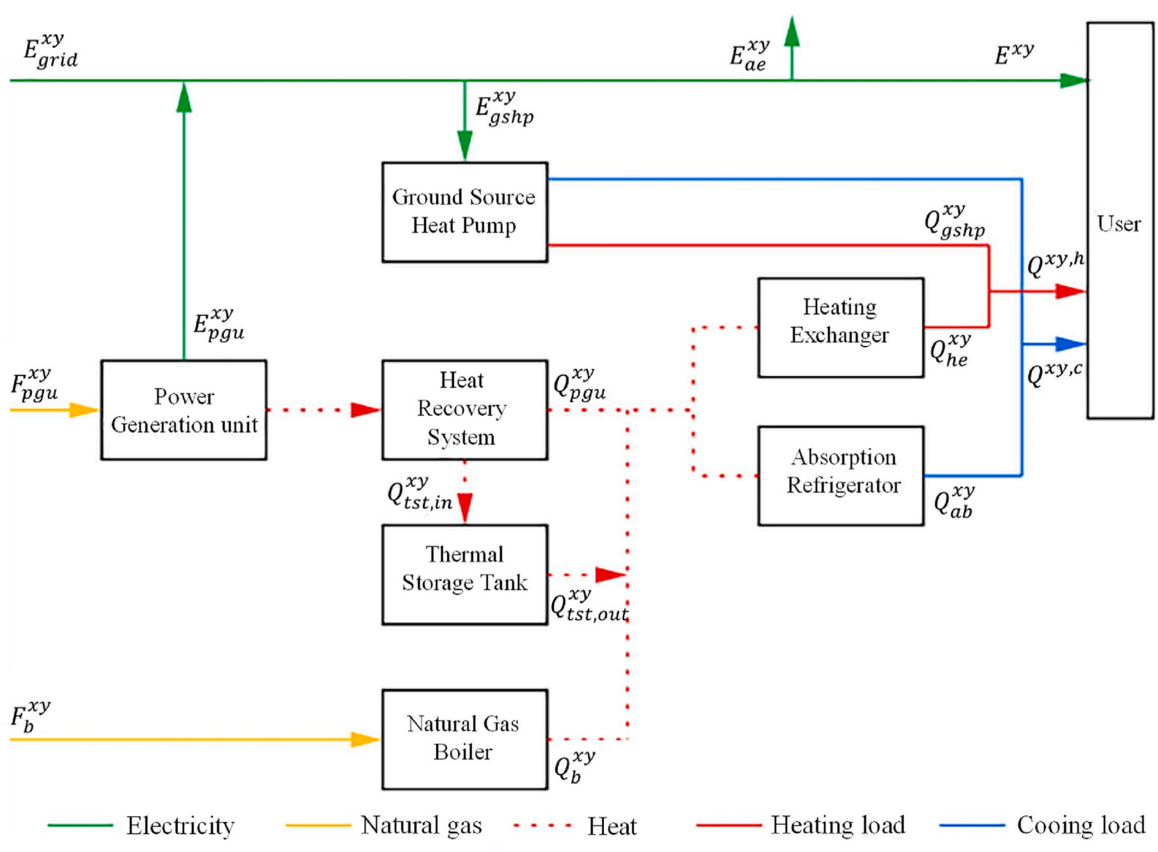

Fig. 14. Schematic diagram of hybrid CCHP system in Ref. [102].

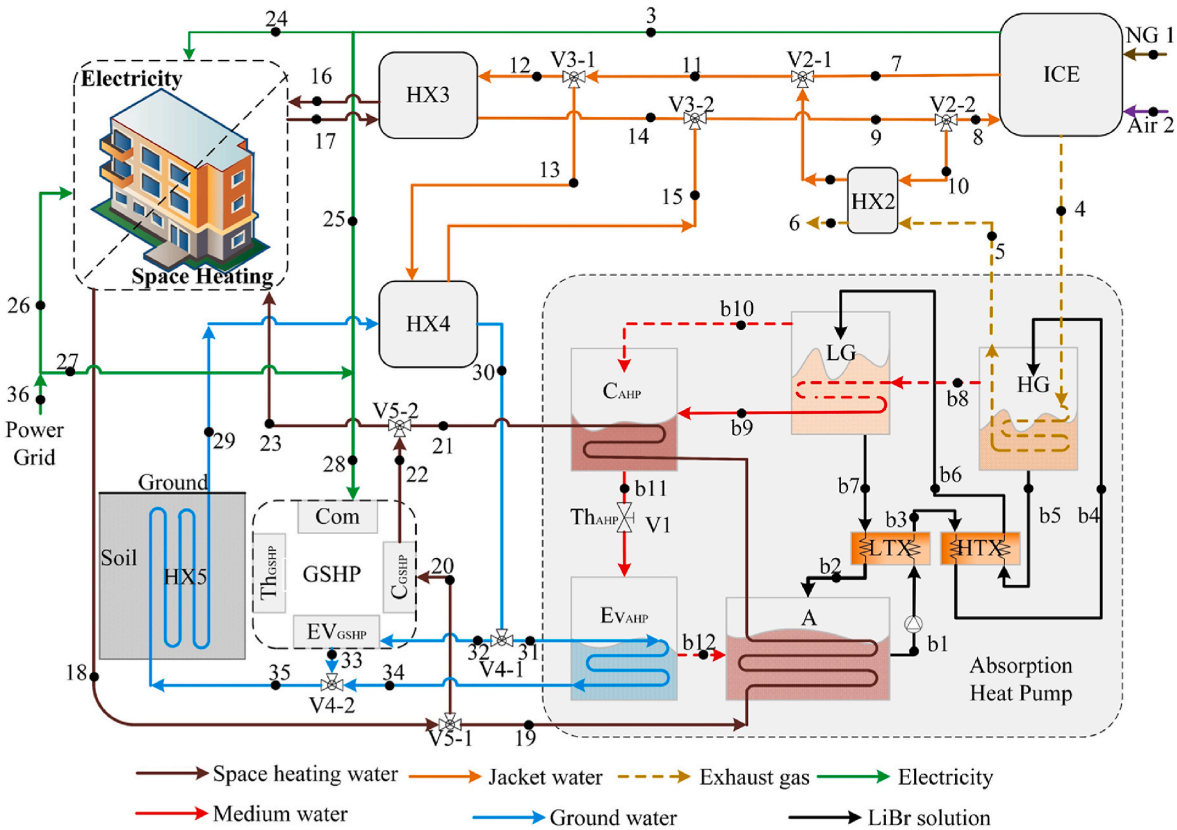

Fig. 15. Schematic diagram of hybrid CCHP system in Ref. [105].

electric load strategy to improve energy utilization efficiency and thus decrease primary energy consumption. They concluded that the proposed strategy is more suitable for buildings with dramatic fluctuations in electrical demand. Ren et al. [13] accomplished a multi-objective optimization to study the impact of solar technologies and building types on system performance. It is worth mentioning that there are differences in the utilization of the water storage tanks of the above two references. The former is coupled with the input end of the absorption unit, while the latter is coupled with the output end of the absorption unit. However, the water tank also has some obvious disadvantages such as low storage capacity per unit volume. Phase change materials with compact structure have been studied to assist the heat storage, which can store and release heat during the phase changing process of substance [127]. Zhao et al. [119] designed a novel CCHP system as shown in Fig. 19, which can realize independent control of refrigeration unit and dehumidification unit, and optimized the operating parameters from environment, economy, energy and exergy points of view. Zhang et al. [120] evaluated the energy-saving potential of two phase change material integration methods and found that when the load fluctuates greatly, the combination of phase change material and absorption chiller/heat pump is more conductive to improving system performance. Xiong et al. [128] analyzed the relationship between phase change temperature and energy consumption from the perspective of thermodynamics. In addition, chemical storage with high storage density and less heat loss can be used for energy storage in the future. The charging and discharging processes are completed in a reversible chemical reaction, which can be described as $A + \Delta H \leftrightarrow B + C$[129]. During the endothermic reaction, material A is separated into material B and material C; conversely, materials B and C are mixed to release energy. Ortiz et al. [121] integrated the high-temperature thermochemical energy storage unit into the solar combined cycle to make full use of solar energy. The simulations indicated that with the assistance of storage module, the annual solar share is up to 50%. Peng et al. [122] constructed nine storage strategies for the solar power system according to reactants, reaction beds, heat transfer mechanisms and gas storage modes. They concluded that the optimized strategy can reduce the levelized cost of electricity by 10%.

3. Researches on the planning of multi-scenario energy systems

After determining the available energy technologies, the appropriate capacity and operation strategy should be selected for the equipment under the guidance of certain objectives [130]. The previous studies on the optimal planning of distributed energy systems can be roughly classified as building-level, neighborhood-level, district-level and city-level according to the scale [131]. Among them, the optimization of building-level energy systems, such as system configuration, equipment capacity and scheduling strategy, has been extensively investigated in the past, aiming to improve economic, energetic and environmental performances [13,92]. Moreover, there are many reviews on these kinds of systems, such as literatures [24,132]. Therefore, the following sections will only discuss the details of the other three energy systems.

3.1. Neighborhood-level energy systems

The building-level energy systems usually provide energy for a specific building. However, the energy demand may not match the output of the system, which results in low operating hours and poor economic performance of the system. Hence, the neighborhood-level energy systems composed of at least two building-level energy systems have been developed, where multiple energy systems can interact by means of multiple energy networks, mainly including electric networks, heating networks and cooling networks [133]. The main purposes are to reduce the total energy cost of the whole energy network, increase the rated load operation time of the equipment and improve the utilization rate of local renewable energy. However, due to the existence of multiple sets of

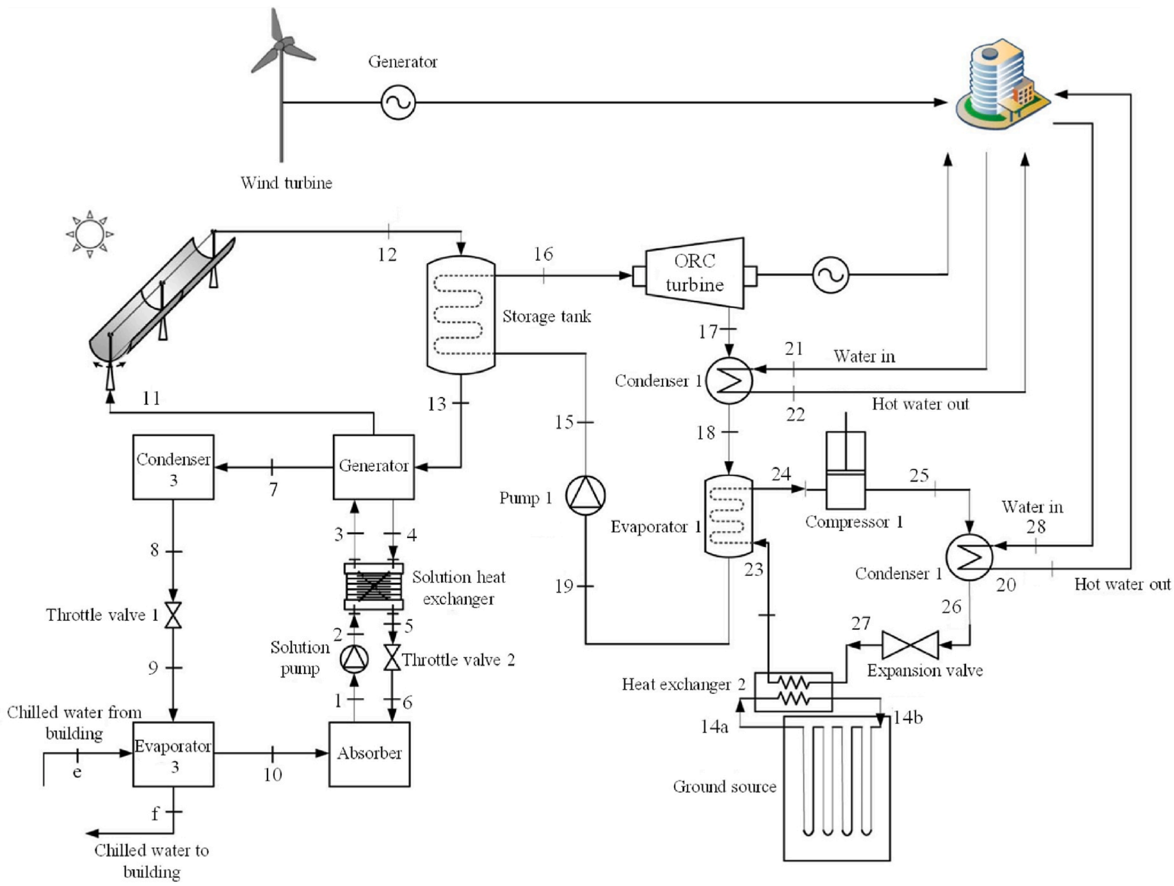

Fig. 16. Schematic diagram of hybrid CCHP system in Ref. [109].

energy systems and multiple energy exchanges, the modelling of this type of energy system is characterized by high computational complexity [134]. To tackle such a complicated task, numerous studies have been done on the equipment selection, network layout and operation scheduling of such systems. Besides, according to the classification of the energy networks, they are summarized as electricity networks integration, heating networks integration, cooling and heating networks integration, electricity and heating networks integration as well as the networks integration including electricity, cooling and heating.

Electricity networks: Wakui and Yokoyama [135] studied the performances of cogeneration systems with different capacities and optimized the operation strategy to maximize energy saving. They suggested that the system with a rated electric output of 1 kW has the greatest energy saving effect. Subsequently, Wakui et al. [136] examined the correlation between energy-saving effects and the scale of residential systems. It is reported that the saving rate is mainly affected by the temporal distribution of energy demand, especially hot water demand.

Heating networks: Wu et al. [137] developed a mathematical model to optimize the structure and schedule of a distributed energy network consisting of five types of buildings. The simulation results showed that the overall economic and environmental performances have been improved. Another important finding is that the function of the building has a considerable influence on the overall performance. Bracco et al. [138] addressed the problem of optimal design and operation with the aim of maximizing the economic and environmental benefits in comparison with the separate production mode. It was found that the savings in cost and emissions are more than 40%. Morvaj et al. [139] proposed an optimization model with the aid of ε-constraint method to design and operate a distributed cogeneration system, whose objective function is to minimize the annual cost. The best economic and environmental performance can be achieved when all available technologies are considered, meanwhile, carbon emission restriction has a great influence on the network layout. Bracco et al. [140] developed a distributed energy system optimal design (DESOD) tool based on mixed-integer linear programming model, which can optimize simultaneously equipment configuration and network layout with minimization of annual cost as the objective function. Mehleri et al. [141] used the similar method to address the synergy planning of integrated energy stations. Whereas, there was a special constraint to simplify the model: a station can only receive energy from one station. In order to reduce the calculation time and the complexity of the model, Falke et al. [142] decomposed the planning and dispatching problem of the distributed energy network into three sub-problems: (i) network planning; (ii) configuration selection; (iii) operation strategy simulation, and verified the viability of the proposed model through a case study.

Heating and cooling networks: Jing et al. [143] proposed a new concept “system value” to evaluate the contribution of energy supply technologies and energy-saving strategies towards improving the economic performance of the system. The results showed that the cogeneration unit has the highest impact on the total cost thanks to their capability to supply both electricity and heat. As for energy-saving strategies, the window upgrade is not recommended due to its high cost. After that, they further introduced the concept of “impact space” to explore the economic and environmental benefits that each technology can bring to the whole system by adjusting the threshold value of portfolio constraint [144]. They summarized that the cogeneration unit provides the most benefits, while the cooling storage brings the least benefits. In order to determine the possibility of integration of heating and cooling pipelines, Ameri and Besharati [145] economically selected the configuration and capacity of the equipment, and defined the network topology, which achieved the benefits of 40.8% of cost

Table 7
Cases of energy storage technology.

Ref.	Energy source	Type	Key findings
[116]	electrical energy	battery type	.The net interaction level with the national grid will decrease with the increase of battery capacity .The increase of renewable energy capacity can improve economic and environmental performance
[117]	electrical energy	compressed air type	.The energy and exergy efficiencies are 58.7% and 60.4%, respectively .The levelized cost of electricity is 0.171 $/kWh
[118]	electrical energy	compressed air type	.The pair composed of air and water has the highest energy density and exergy efficiency .The gas storage chamber is the most critical component when therminol 66 is adopted
[13]	thermal energy	water tank type	.The benefits achieved by PV + ST are higher than PVT .The system configuration is closely related to building load
[119]	thermal energy	phase change type	.The system performance and emissions reduction are positively correlated with inlet pressure .The optimized operating parameters improve the energy efficiency by 5.5% but increase the annual cost by 10%
[120]	thermal energy	phase change type	.The optimal integration location is influenced by the load characteristics .The number of transfer units has a great impact on energy consumption
[121]	thermal energy	chemical type	.The annual share of solar energy is expected to be 50% .As the turbine inlet temperature increases, the overall efficiency is improved
[122]	thermal energy	chemical type	.For systems equipped with fixed-bed reactors, the cost is higher because of their lower heat transfer coefficient .The equilibrium temperature is the most critical reaction property

reduction and 38.7% of energy saving with respect to a separate system.

Electricity and heating networks: Karmellos and Mavrotas [146] presented two optimization models to determine the optimal configuration and operation strategy considering both economy and environment. The difference is that the first model can realize the optimization of the equipment capacity based on the given range, while the equipment capacity in the second model can only be selected from the limited predefined capacity. They stated that the first model can offer better solutions due to the high degree of freedom. Zhang et al. [44] constructed a collaborative optimization framework to determine the optimal planning of multiple energy stations to improve energy utilization efficiency. Compared with independent operation, the fuel saving rate, annual cost saving rate and emission reduction rate have been increased by 5.3%, 5.1% and 1.1%, respectively. Wakui et al. [147] built an energy consumption minimization model to deal with the optimal hourly operation of residential systems, whereas the equipment capacity is directly given. The results indicated that the energy saving rate is increased by 3.24% relative to the case that only considers electricity exchange. Wu et al. [148] proposed a collaborative optimization method that combines orthogonal experimental design to narrow the search space of decision variables and genetic algorithm to obtain system configuration and operation information. It is concluded that utilizing the proposed framework can reduce annual total cost by 0.67% and improve energy efficiency by 6.42%. Considering the long service life of the actual projects, Mavromatidis and Petkov [149] developed a dynamic multiple stage planning model to optimally design and operate the decentralized multi-energy systems, which allows the flexible investment strategies through taking into account the variations in energy demands, energy prices, technical improvements and equipment degradation. In order to reduce the operating cost and greenhouse gas emissions, Maroufmashat et al. [150] simulated an energy supply network with two or three energy hubs. The performance analysis showed that the network with diverse energy users and more energy stations achieves significant benefits. Sameti and Haghighat [151] investigated the integration of electrical and thermal energy storage technologies into a net-zero energy zone to minimize annualized cost and CO_2 emissions. It is demonstrated that the system with energy storage has higher overall efficiency in comparison to the reference system without considering energy storage.

Electricity, heating and cooling networks: Comodi et al. [152] conducted a study to assess the impact of different primary energy saving rates on the economic performance and configuration of the system. They found that, compared with the case of only considering cost, the cost almost did not increase in the case of 10% reduction of energy consumption, while the cost doubled in the case of 20% reduction of energy consumption due to the large cost of PV. Ghorab [153] evaluated and compared the potential economic and environmental benefits of different energy supply systems that combine various distributed energy devices for a smart community located in Canada. They concluded that the energy system with PV and electrical energy storage can save 43% of emissions. Yang et al. [134] conducted a comparative study to quantify the effect of distributed generation technologies, energy distribution networks and energy storage on annual total costs. The urban area including a residence, a hotel, a hospital and a mall was examined. They summarized that the annual cost is reduced by 20%–25% and the payback period can be shortened to three years. Li et al. [154] proposed a deterministic optimization model for the collaborative design and management of distributed energy networks including residential and office buildings. Their conclusion is that with the increase of the weight of emission reduction rate in the objective function, the economic benefit shows a downward trend, whereas the emission benefit exhibits an upward trend. Liu et al. [155] investigated the optimal operation strategy of interconnected energy systems considering the total energy saving ratio, and found that the fuel saving ratio increased by 4.6% points.

As shown in the reviewed literatures, the collaborative optimization method does improve the overall performance of the entire energy system including multiple energy stations because of the load shifting between different buildings. It can be seen that due to the existence of the electricity grid, some studies only focus on heating or/and cooling exchange to reduce the amount of waste heat discharged into the environment. The surplus electricity can be fed back into the grid. Recently, in order to further expand the benefits, more and more attention has been paid to the systems that integrate electricity and heating networks or the systems that integrate electricity, heating and cooling networks. Table 8 summarizes the main insights of some of the most important studies.

In addition, it is worth noting that the above studies are all carried out for the design and performance analysis of the energy networks belonging to a stakeholder, which only needs to consider the energy flows between various distributed energy systems to obtain the maximum overall performance. However, there may be another situation where each system belongs to a specific stakeholder. Thus, it is necessary to consider the cost flows other than the energy flows, because the benefits of the whole network do not necessarily lead to satisfying benefits for each system. Table 9 lists the cases focusing on the allocation of benefits and summarizes the main insights. Game theory, as an effective tool to deal with the conflicting interests, has been extensively used for studying coordination problems, which includes cooperative game theory and noncooperative game theory.

Cooperative game theory: The main steps of this method consist of: (1) coalition formation to improve overall performance: the principle is that the profit of the coalition composed of all or some individuals are

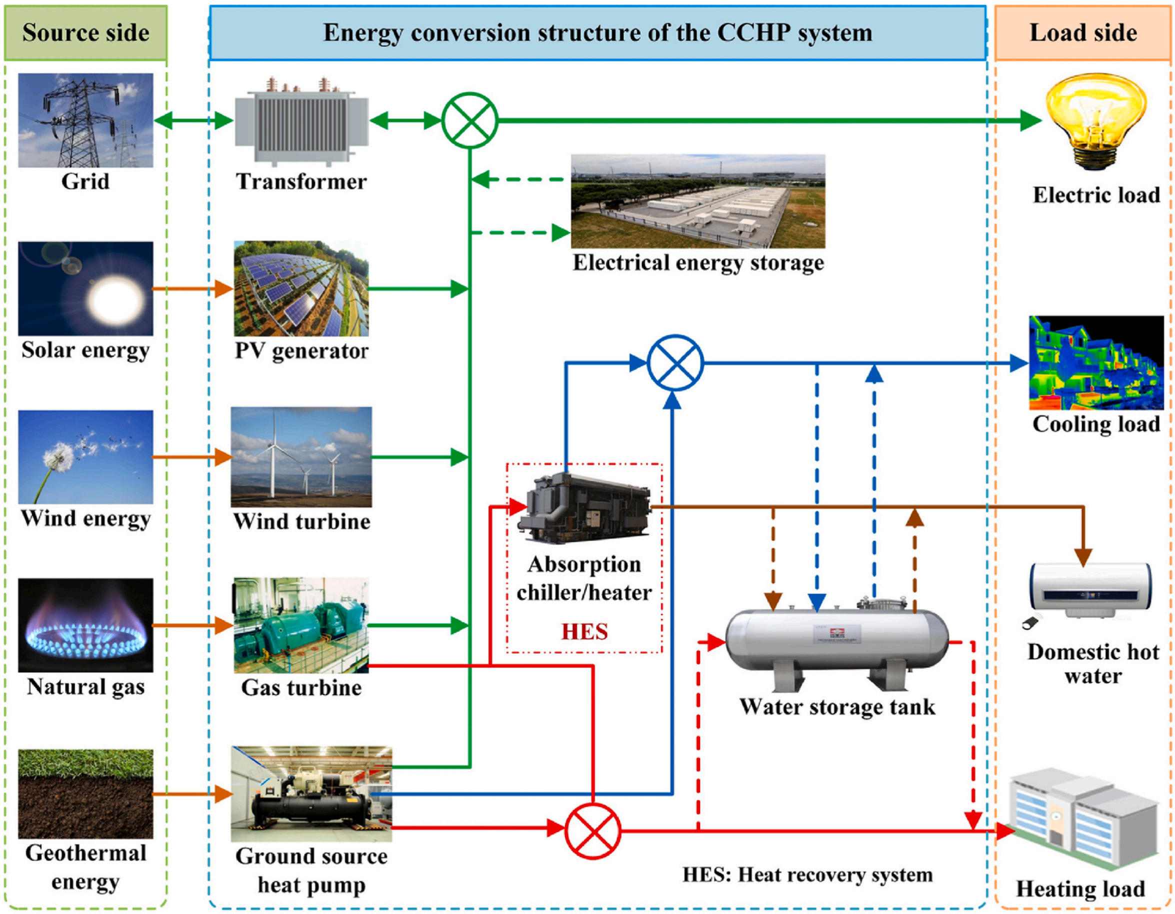

Fig. 17. Schematic diagram of hybrid CCHP system in Ref. [116].

greater than the sum of the individual profit when acting alone; (2) benefit assignment to maintain cooperation: the principle is that each individual in the coalition should earn a higher profit than operating alone. Some attempts have been made to explore how to establish coalitions and how to allocate the benefits of the coalition. Ren et al. [156] developed a collaborative optimization model to select the system configuration and hourly operation strategies of a distributed energy network integrated with heating and electric networks, and a profit allocation model based on Core method and Shapely Value method. The profit allocation coefficients of commerce, office and residence are 25%, 42% and 33%, respectively. Luo et al. [157] proposed an economic benefit allocation scheme based on Shapely Value method for a distributed energy network, where the electric and cooling networks were considered. Jing et al. [133] introduced the benefit allocation constraints into the multi-objective optimization model of the urban energy network, and discussed the influence of economic benefit allocation and emission benefit allocation on the Pareto frontier, respectively. They concluded that the Pareto frontier is more sensitive to the former. Wu et al. [158] established a mathematical model to determine the optimal technology combination and energy trading activities taking the unit prices of heating and electrical energies into consideration, and applied it to a local energy network including an office, a hospital and an apartment. The annual costs of office, hospital and apartment have been reduced by 20%, 13.9% and 4.1%, respectively. To handle the profit allocation issue, Wu et al. [159] further combined the Shapley-Shubik Power Index and the Propensity to Disrupt value to quantify the fairness and stability of different allocation methods including DP equivalent, Nucleolus, Nash-Harsanyi and Shapely value. It is deduced that the most favorable allocation method is Shapely value method.

Noncooperative game theory: The main feature of this method is that each individual tries to maximize his own profit, and all individuals will eventually reach an equilibrium, where no individual can benefit from changing strategy alone. Generally, Nash equilibrium is the most common solution. Jing et al. [160] constructed an economic performance evaluation model to optimize the electrical and thermal energy trading prices and linearized the model with McCormick relaxation method. The prices of electricity and heating are respectively 0.090 \$/kWh and 0.015 \$/kWh, while the annual cost is reduced by 4.9%. Zhang et al. [161] proposed a separable programming method based on logarithmic differentiation and approximations to linearize the planning problem of the microgrid involving five participants. The electricity trading price, system configuration and operation strategies were determined to achieve the best economic performance.

In addition to the game theory, there are also some interesting studies focusing on energy trading prices and strategies. Liu et al. [162] proposed a novel energy price determination method based on exergoeconomic analysis and optimized the operation strategy of the interconnected energy systems according to the determined energy price. The optimization process increased energy utilization ratio of 4.9% and energy saving ratio of 5.9%, and decreased operation cost of 2.7%. Bui et al. [163] proposed a multi-stage energy trading model to promote energy sharing between multiple supply energy systems and minimize energy exchange with external energy system. The internal trading strategy includes barter trading, surplus energy trading and increasing energy trading. It is deduced that the operation cost is reduced by 7.43%.

3.2. District-level energy systems

Generally, the number of buildings included in the district-level

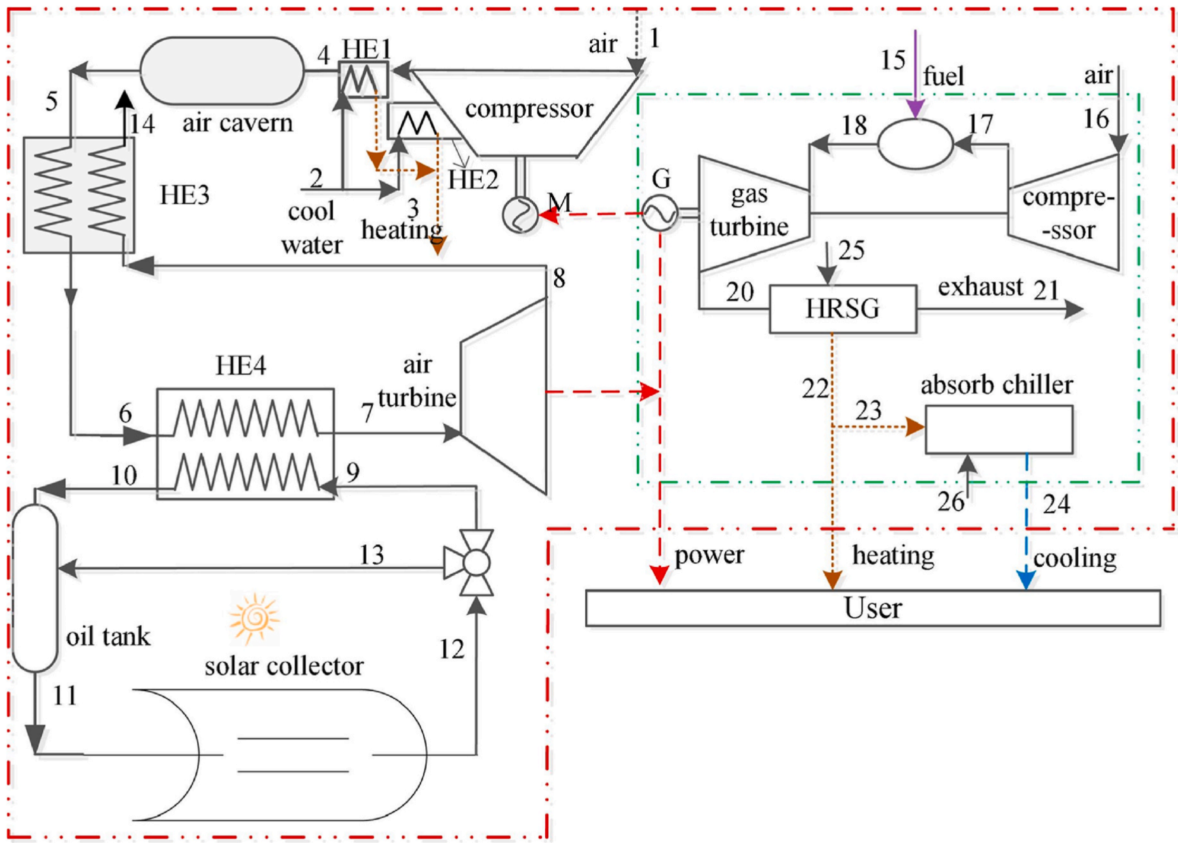

Fig. 18. Schematic diagram of hybrid CCHP system in Ref. [125].

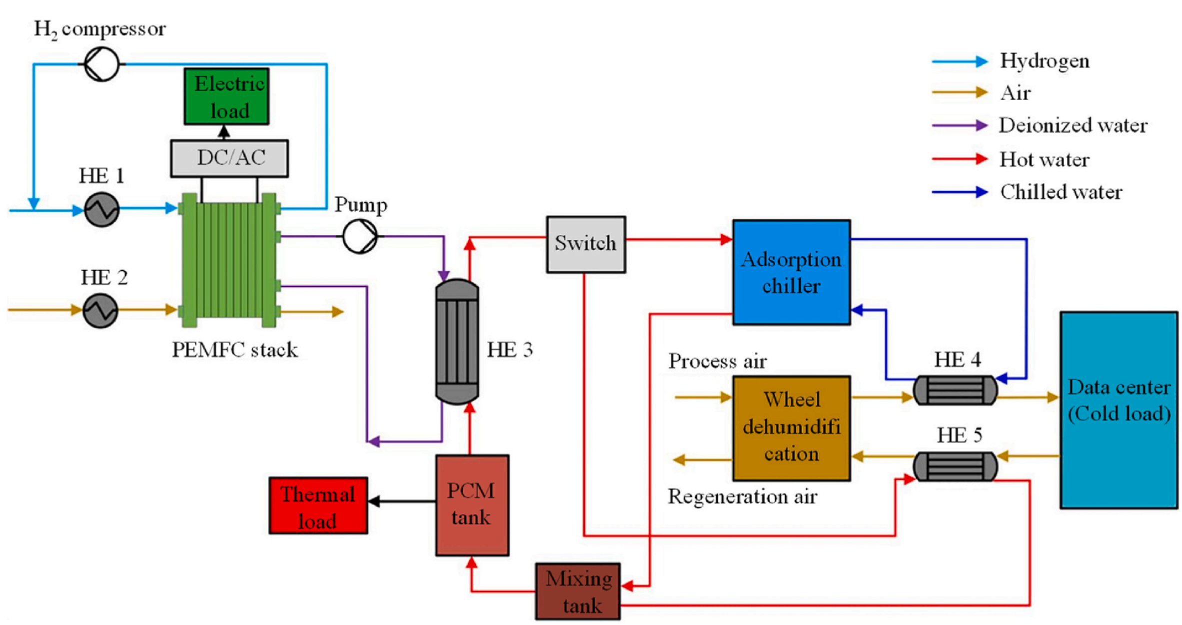

Fig. 19. Schematic diagram of hybrid CCHP system in Ref. [119].

energy systems is dozens or even hundreds. On the one hand, if each building can freely establish its own energy system and connect to each other through energy networks like the buildings in the neighborhood-level energy systems, the optimal design may be time-consuming or even impossible to solve. On the other hand, if each building with its own energy system operates independently, the optimal design problem can be easily solved; obviously, the corresponding result is not the best option for the whole district. Therefore, how to make a trade-off between the complexity of the model and the performance of the designed system is a research hotspot in recent years. The clustering techniques are applied to decompose the large district into several small zones, in which the distributed energy systems are installed; these techniques include K-means and OPTICS (Ordering Points To Identify the Clustering Structure) as shown in Table 10.

Table 8
Cases of neighborhood-level energy systems with one stakeholder.

Ref.	Energy networks	Energy sources	Technologies	Key findings
[136]	electricity	natural gas, electricity	ICE, GB, WST	.The introduction of network can improve the operation time of cogeneration system .The energy saving rate is mainly affected by the distribution of hot water demand .The number of households has little impact on the energy saving rate
[137]	heating	natural gas, electricity, solar	ICE, GB, WST, STC, EC	.User preferences have a major influence on system performance .The changes in energy prices have a significant impact on annual costs .The function of the selected building is of vital importance
[138]	heating	natural gas, electricity	GT, ICE, GB	.The reductions in cost, emission and energy are both more than 40% .The energy efficiency of the whole system reaches 84%
[139]	heating	natural gas, electricity, solar	ICE, WST, PV, STC, GB,	.The emission reduction up to 23% .With the increase of emission restriction, more and more buildings are connected .Limitations on network routes have a strong impact on optimal planning
[144]	heating, cooling	natural gas, electricity, solar	ICE, ABS, PV, EB, WST	.ICE brings the greatest benefits, while WST has the least benefits .More than 50% of the investment should be spent on ICE, while the investment in EB and WST should less than 10%
[145]	heating, cooling	natural gas, electricity, solar	GT, ABS, GB, HRSG, EC, PV	.The optimal system can save 38.7% energy and 40.8% energy cost .The payback period of the system without PV is the shortest, only 57 months
[146]	electricity, heating	natural gas, electricity, solar, wind	ICE, GB, ABS, HP, PV, STC, WT, EB, WST	.The solutions provided by the method with flexible combination are better than that provided by the method with predefined combination .The system involving all available devices has the best performance
[44]	electricity, heating	natural gas, electricity, geothermal heat, solar, wind	GT, WT, STC, PV, ORC, WST, GSHP, AC, EB	.The energy saving, cost saving and emission reduction increased by 5.3%, 5.1% and 1.1%, respectively .The impact of natural gas price change on annual cost is greater than grid electricity price change .The full load running time of GT is increased, thereby improving the efficiency
[151]	electricity, heating	natural gas, electricity, solar	ICE, GB, PV, WST, EB	.The energy storage system can reduce emissions by 4% and provide a more flexible network structure
[152]	electricity, heating, cooling	natural gas, electricity, solar	ICE, PV, GB, EC, ABS, EB, WST	.With the improvement of energy-saving level, zero-energy PVs and high-efficiency ICEs have been installed .The cost of 10% energy saving only increased by 1%, while the cost of 20% energy saving has doubled
[154]	electricity, heating, cooling	natural gas, electricity, solar	ICE, GB, ABS, EC, PV, WST, HE, HRSG	.ICEs are more suitable than PVs when only considering the cost .As the weight of emission reduction increases, the annual cost gradually increases

K-means is a distance-based clustering technique, in which the distance between each point and each cluster centroid is calculated first, and then each point is allocated to the nearest cluster center. Notedly, the number of clusters needs to be defined before the clustering process. Jing et al. [131] designed a hierarchical method to tackle the optimal planning problem of regional energy system, which mainly includes k-means clustering method based spatial clustering, Delaunay triangulation based grid generation, Kruskal minimum Spanning tree based pipework mapping. They also compared the effect of distributed and centralized energy model on cost-saving and found that the distributed model is about 3.9% higher than the centralized model. Unternährer et al. [164] proposed an integrated planning approach based on K-means to economically optimize the system configuration and energy network layout of geothermal energy assisted urban energy system, in which three graph theory methods were considered. Max Bittel et al. [168] discussed the relationship between the investment cost and the number

Table 9
Cases of neighborhood-level energy systems with multiple stakeholders.

Ref.	Energy networks	Energy sources	Technologies	Key findings
[156]	electricity, heating	natural gas, electricity, solar	ICE, GT, EC, SOFC, GB, PV	.The reduction in total cost, emissions and fuel consumption are respectively 33.9%, 53.7% and 56.8% .The allocation of total cost saving is 25% for commerce, 42% for office and 33% for residence, respectively .The unit prices of electricity and heat are 0.056 $/kWh and 0.141 $/kWh, respectively
[133]	electricity, cooling	natural gas, electricity, solar	SOFC, PV, EC, ASHP, HRSG, GB, ABS,	.The constraint of emission profit allocation has little effect on Pareto frontier, while the constraint of cost profit allocation has more impact on Pareto frontier .The economy and environment of distributed model are better than centralized model
[159]	heating	natural gas, electricity	ICE, GB, EC	.When considering fairness, the Nash-Harsanyi solution and Shapely value are relatively better .The DP equivalent and Shapely value are relatively better when considering stability .The Shapely value is the most suitable choice from the perspective of fairness and stability
[160]	electricity, heating, cooling	natural gas, electricity, solar	ICE, ABS, PV, EB, WST, HP, GB, EC,	.The fair trade model may result in a slight sacrifice in total cost saving .The trading price of electricity is 0.090 $/kWh and that of heating is 0.015 $/kWh .Battery is not recommended because excess energy can be sold to prosumers or to the grid
[163]	electricity, heating, cooling	natural gas, electricity, solar, wind	ICE, EB, ABS, HP, HE, PV, WT	.The electricity from/ to the grid decreased by 4.24% and 24.8%, and the heating from/to heating pipeline system decreased by 28.67% and 97.45% .The total operating cost is reduced by 7.43%

Table 10
Cases of district-level energy systems.

Ref.	Basic type	Number of buildings	Key findings
[131]	K-means	60	.The optimal number of clusters is 10 or 12 .Load complementarity and pipeline length have significant impacts on cost
[164]	K-means	6224	.The relative error of the estimated pipe length is 3.7% .Resource status and heating demand have great influences on system design
[165]	K-means	60	.The optimized solution can reduce the cost of 6.74% and 3.21% compared to energy hub mode and distributed energy mode, respectively .The tradeoff between economic performance and computational time can be realized
[166]	K-means	20	.The hybrid method achieves the benefits of cost saving of 23.65% and emissions reduction of 75.32%
[167]	OPTICS	221	.The calculation time is reduced by 10–100 times .The reduction rates of cost and emission are 14.4% and 3.7%, respectively

of clusters. By gradually increasing the number of clusters, they found that the cost of heating network decreased, while the cost of heat generation system increased. With the consideration of the total cost, the best number of clusters for the studied case is 14.

Different from K-means, OPTICS is a density-based clustering technique and does not need to define the number of clusters in advance, whose input parameters are the minimum number of points contained in a cluster and the maximum reachability-distance. In addition, this method allows several points to remain independent after the clustering process. Marquant et al. [167] proposed a holarchic optimization approach that combines OPTICS and rolling hub method to address the planning problem of the large-scale energy systems. The results showed that the computational cost can be significantly reduced, while the system performance obtained is acceptable.

The above studies only focus on the spatial distribution of buildings, that is, the relative position of buildings. However, the demand complementary effect between buildings also has a great impact on the overall efficiency. Hence, both of these need to be carefully considered. Wang et al. [165] first constructed a novel clustering method based on the typical density clustering approach, in which the density constraint providing the possibility of integrating outlier buildings into each clusters and the coefficient of variation evaluating the demand complementary effect were introduced. They further optimized the configuration and operation of an energy-water nexus system. The results indicated that the developed method can provide 45 clustering options and achieve up to 6.74% cost savings compared with the typical clustering approach. Yan et al. [166] proposed a novel optimization method for district-scale energy system by combining k-means clustering method, genetic algorithm (GA) and mixed-integer linear programming (MILP). Firstly, considering the maximum and minimum energy demands, the number of feasible clusters is determined. Secondly, the k-means clustering method is used to carry out the initial clustering based on the minimum energy demand difference. And then, the clustering results are used as the inputs of hybrid MILP and GA methods to get the promising clustering and system planning. The hybrid optimization method can reduce the annual total cost by 23.65% and carbon emissions by 75.32%. Marquant et al. [169] introduced a novel combined clustering method, which takes into account the spatial and temporal characteristics of buildings including density, homogeneity index and load magnitude to quantify the potential of adopting district heating networks.

3.3. City-level energy systems

Recently, a number of studies have been carried out on city-level energy systems, which attempt to provide some suggestions for local governments on when, where and how to invest in energy infrastructure, so as to realize the transformation of energy consumption structure. Some representative researches are as follows.

Jing et al. [170] proposed a long-term programming framework for optimizing the energy structure considering technology update, and used diversity index, that is, the proportion of energy provided by each equipment to total energy, to evaluate the system resilience. The results showed that, compared with the most cost-effective scenario, the cost of achieving the diversity-optimal scenario increased by 3.9%, whereas the cost of achieving the least-emissions scenario increased by 26.8%. Yu et al. [171] developed an interval possibilistic-stochastic planning model to optimize the electricity generation components with the consideration of multiple uncertainties. They found that when there is a subsidy policy, the contribution rate of purchased electricity can be reduced by 2.0%–4.5%, and the contribution rate of renewable energy can be increased by 2.4%–3.2%. Jin et al. [172] established a hybrid optimization model that combined interval type2 fuzzy sets boundary programming and stochastic linear programming to facilitate energy system planning. They concluded that in the next 15 years, coal-fired electricity generation equipment with lower operating cost will still occupy a large proportion of the electricity market, followed by natural gas with relatively high economic and environmental performance. Dong et al. [173] conducted a comparative study from the perspective of air pollution control, and provided the optimal solution including energy resources allocation and energy technologies combination.

4. Challenges and future prospects

Based on the above analysis, great efforts have been made in the integration and optimization of distributed energy systems. To promote the development of distributed energy systems, further research is necessary which can be categorized into four classes: (1) research on energy demand forecasting models; (2) research on energy conversion technologies; (3) research on network models; (4) research on planning frameworks. Each of these research areas is significant and is discussed in detail below.

- **Formulating advanced energy demand forecasting methods.** Accurate load prediction is the prerequisite for optimal dispatch of integrated energy systems. Currently, there are two mainstream methods, namely building simulation software and data-driven techniques. The former requires a very specific description of the geometric structure, physical properties and operation mechanism of the building, resulting in high modeling complexity. Moreover, the heat and humidity process of the building is simplified, which leads to low accuracy of simulation results [174]. The latter relies on historical data to predict energy consumption and has been widely used in various load forecasts [175]. However, most of the research only focuses on single load forecasting, such as, electrical load [176,177], heating load [178,179], cooling load [180,181], without considering the coupling relationship between various loads. The multiple load prediction to improve simulation accuracy is suggested to be conducted. The core of multi-load forecasting is to model the coupling characteristics of different loads. Tan et al. [182] utilized the multiple tasks learning model to process the coupling relationship. Wang et al. [183] developed a novel method that combines long short-term memory and encoder-decoder to determine the coupling characteristics. Therefore, more attention should be put on algorithm research. In addition, multi-time scale optimization should be considered in the planning process, including long-term load predication to optimize system configuration and short-term load predication to determine hourly scheduling.
- **Developing cost-effective energy conversion technologies.** Although various types of energy technologies have been proposed and theoretically proved the possibility of integration into distributed energy systems, there are few commercial applications. Some problems such as high investment cost and high-quality fuel demand limit its wide application. The economic feasibility and thermodynamic improvements will still be one of the research topics in the near future. The former necessarily require the study of novel cost-effective materials and manufacturing processes, while the latter focuses on how to strength the variable condition operation characteristics of the equipment.
- **Constructing detailed network models to evaluate dynamic characteristics.** On the one hand, the proportion coefficient method is used for calculating the loss of energy transfer, such as, heating pipeline with 15%/km [146], cooling pipeline with 5%/km [154]. On the other hand, based on the energy flow calculation, the steady-state models of the energy networks have been established. However, the time scale and dynamic characteristics of heating and electricity networks are quite different. If the transient process of energy flow transmission is ignored, the real-time operating state cannot be accurately described. The description of the dynamic characteristics of the heating network includes two dimensions: time and space. The finite difference method is the most commonly used algorithm for solving space-time partial differential equations [184]. However, the quality of the solution is affected by the number of grids. Therefore, more accurate dynamic models and more efficient solution algorithms are suggested to be further studied. In addition, geographic information is also suggested to be fully considered when determining the layout of the energy networks.
- **Proposing appropriate frameworks to conduct the long-term planning.** Most of the current studies are static plan, that is, no additional investment is considered in the service life. However, there are many dynamic parameters in real applications, including energy demand, fuel price, energy technology price and efficiency, energy policy and so on. These parameters will affect the investment decisions during the project lifetime. Therefore, the multi-stage investment scheme, namely dynamic plan, is necessary. Accurate description of the variation trend of the above parameters is important for optimization. Thus, the combination of data mining for predicting and evolutionary algorithms for solving is essential. In addition, there are multiple energy flows with different properties. As a result, some novel indicators are suggested to be further proposed to guide the optimization.

5. Conclusions

Distributed energy systems, as a technological alternative to centralized power plants, have been extensively investigated due to their high energy efficiency, cost-effectiveness and environmental friendliness. To enhance the operational flexibility, multi-energy input systems have been proposed. Integration and optimization are two research hotspots. In this context, this paper mainly reviewed the progression of distributed energy systems from the perspective of available energy technologies and possible application scenarios.

As for available energy technologies, the main equipment applied in distributed energy systems includes fuel-based units, waste heat-based units, renewable energy-based units and energy storage units. The following conclusions can be drawn on the basis of cited literature.

- The ICEs are still the dominator of the market because of their relatively excellent performances such as good reliability, lower investment cost and higher partial load efficiency. Other types of prime movers have also shown the possibility of integration. For example, GTs with less floor area and high exhaust temperature, MTs with easy connection and low noise, SEs with easy to control and low noise, FCs with quiet operation and high electrical efficiency. But the relatively higher investment cost hinders their wide application.

- The waste heat-based units can produce various products for consumers, which are the key components to improve the comprehensive efficiency. Moreover, their practical applications are closely related to the temperature and form of heat source. Generally, thermodynamic Rankine cycles are utilized to adjust the electricity-to-heat ratio and provide more electricity. Sorption chillers driven by medium/low temperature thermal energy is used for cooling or heating. Therefore, the series connection of Rankine cycles and sorption chillers can ensure the effective utilization of high-grade heat energy and reduce the exergy destruction.
- The integration forms of solar technologies mainly include PVs, STCs and PVTs. Firstly, PVs can be easily integrated to provide electricity for users or components. This integration has no impact on thermodynamic performance, but will lead to changes in system operation mode Secondly, because the temperatures of solar heat vary greatly (25 °C–2000 °C), the integrated forms of STCs are more complex and diverse, which have strong influences on the thermodynamic cycle. Their applications include providing domestic hot water, producing high-temperature and high-pressure steam, preheating air, heating cycle working medium and facilitating fuel conversion. These processes will produce various products with different energy levels; thus, exergy destruction should be considered when designing the system energy flow. Thirdly, the utilization modes of PVTs are similar to PVs and STCs, which can output electricity and heat simultaneously.
- The integration forms of geothermal energy are less than that of solar heat. Meanwhile, its availability also depends on the temperature of the heat source. In general, the medium and high-grade geothermal source can be used for electricity generation, and the remaining heat at the outlet of power plant or low-grade geothermal source can be used to drive heat pump for heating and cooling.
- Similar to PVs, the WTs are directly integrated with distributed energy systems to supplement electricity. The dispatching strategy needs to be designed according to the comprehensive benefits such as energy, economy and environment. In addition, both of them can be connected to the electrolyzer to make full use of the surplus electricity, which can provide hydrogen to the prime mover.

As for possible application scenarios, four typical situations have been studied, including building-level, neighborhood-level, district-level and city-level. This paper mainly focuses on the latter three situations and the following points can be obtained.

- The neighborhood-level research can be divided into two categories according to the number of stakeholders, namely one stakeholder or multiple stakeholders. For the former, a variety of optimization algorithms have been adopted to determine the optimal equipment capacity, network layout and hourly operating strategies to improve the overall performances of the neighborhood-level energy system. The benefits of energy exchange between multiple energy stations have been proven. For the latter, in addition to energy flows, cost flow must also be considered. The cooperative game theory and noncooperative game theory are two effective tools to design energy transaction prices and realize benefit allocation.
- The planning of district-level energy systems is more complicated than that of the neighborhood-level energy systems due to the large number of buildings. To reduce the computational cost and maintain the accurate solution, clustering techniques such as K-means and OPTICS have been applied to decompose the district-level optimization problem to multiple neighborhood-level optimization problems. Similarly, multiple neighborhood-level energy systems can exchange energy through pipelines. One or more energy stations can be installed in each neighborhood-level energy system.
- Generally speaking, the design of city-level energy systems is a macro issue, whose purpose is to provide valuable insight and guidance for the transformation of city energy structure. The energy policy is one of the most important input parameters. In addition, descriptions of changing trends in energy demands, technology and energy prices are also included.

Finally, to promote the development of distributed energy systems, the challenges in the future research are classified into four categories: (1) accurate load forecasting methods; (2) cost-effective energy conversion technologies; (3) accurate networks models; (4) long-term planning frameworks. The above research areas cover some significant aspects.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] Bagherian MA, Mehranzamir K. A comprehensive review on renewable energy integration for combined heat and power production. Energy Convers Manag 2020;224:113454.
[2] Wen Q, Liu G, Rao Z, Liao S. Applications, evaluations and supportive strategies of distributed energy systems: a review. Energy Build 2020;225:110314.
[3] Breeze P. Chapter 6 - combined heat and power. In: Breeze P, editor. Power generation technologies. third ed. Newnes; 2019. p. 121–43.
[4] Marvuglia A, Havinga L, Heidrich O, Fonseca J, Gaitani N, Reckien D. Advances and challenges in assessing urban sustainability: an advanced bibliometric review. Renew Sustain Energy Rev 2020;124.
[5] Yang G, Zhai XQ. Optimal design and performance analysis of solar hybrid CCHP system considering influence of building type and climate condition. Energy 2019;174:647–63.
[6] Yousefi H, Ghodusinejad MH, Kasaeian A. Multi-objective optimal component sizing of a hybrid ICE+PV/T driven CCHP microgrid. Appl Therm Eng 2017;122:126–38.
[7] Yang G, Zhai X. Optimization and performance analysis of solar hybrid CCHP systems under different operation strategies. Appl Therm Eng 2018;133:327–40.
[8] Prieto A, Knaack U, Auer T, Klein T. COOLFACADE: state-of-the-art review and evaluation of solar cooling technologies on their potential for façade integration. Renew Sustain Energy Rev 2019;101:395–414.
[9] Liu T, Liu Q, Lei J, Sui J, Jin H. Solar-clean fuel distributed energy system with solar thermochemistry and chemical recuperation. Appl Energy 2018;225:380–91.
[10] Zhang N, Wang Z, Lior N, Han W. Advancement of distributed energy methods by a novel high efficiency solar-assisted combined cooling, heating and power system. Appl Energy 2018;219:179–86.
[11] Su B, Han W, Jin H. Proposal and assessment of a novel integrated CCHP system with biogas steam reforming using solar energy. Appl Energy 2017;206:1–11.
[12] Wang J, Liu Y, Ren F, Lu S. Multi-objective optimization and selection of hybrid combined cooling, heating and power systems considering operational flexibility. Energy 2020;197:117313.
[13] Ren F, Wei Z, Zhai X. Multi-objective optimization and evaluation of hybrid CCHP systems for different building types. Energy 2021;215:119096.
[14] Gazda W, Stanek W. Energy and environmental assessment of integrated biogas trigeneration and photovoltaic plant as more sustainable industrial system. Appl Energy 2016;169:138–49.
[15] Gao L, Hwang Y, Cao T. An overview of optimization technologies applied in combined cooling, heating and power systems. Renew Sustain Energy Rev 2019;114.
[16] Azaza M, Wallin F. Multi objective particle swarm optimization of hybrid micro-grid system: a case study in Sweden. Energy 2017;123:108–18.
[17] Wang H, Zhang R, Peng J, Wang G, Liu Y, Jiang H, et al. GPNBI-inspired MOSFA for Pareto operation optimization of integrated energy system. Energy Convers Manag 2017;151:524–37.
[18] Muhsen DH, Ghazali AB, Khatib T, Abed IA, Natsheh EM. Sizing of a standalone photovoltaic water pumping system using a multi-objective evolutionary algorithm. Energy 2016;109:961–73.
[19] Mebarek-Oudina F, Fares R, Aissa A, Lewis RW, Abu-Hamdeh N H. Entropy and convection effect on magnetized hybrid nano-liquid flow inside a trapezoidal cavity with zigzagged wall. Int Commun Heat Mass Tran 2021;125:105279.

[20] Al-Turki YA, Mebarek-Oudina F, Ahmadian A, Baleanu D. Flat sheet direct contact membrane distillation desalination system using temperature-dependent correlations: thermal efficiency via a multi-parameter sensitivity analysis based on Monte Carlo method. J Therm Anal Calorim 2021;144:2641–52.
[21] Abusorrah AM, Mebarek-Oudina F, Ahmadian A, Baleanu D. Modeling of a MED-TVC desalination system by considering the effects of nanoparticles: energetic and exergetic analysis. J Therm Anal Calorim 2021;144:2675–87.
[22] Chen Y, Wang J, Ma C, Shi G. Multicriteria performance investigations of a hybrid ground source heat pump system integrated with concentrated photovoltaic thermal solar collectors. Energy Convers Manag 2019;197:111862.
[23] Chen Y, Wang J, Lund PD. Sustainability evaluation and sensitivity analysis of district heating systems coupled to geothermal and solar resources. Energy Convers Manag 2020;220:113084.
[24] Al Moussawi H, Fardoun F, Louahlia-Gualous H. Review of tri-generation technologies: design evaluation, optimization, decision-making, and selection approach. Energy Convers Manag 2016;120:157–96.
[25] Mohammadi K, Khanmohammadi S, Khorasanizadeh H, Powell K. A comprehensive review of solar only and hybrid solar driven multigeneration systems: classifications, benefits, design and prospective. Appl Energy 2020:268.
[26] Kasaeian A, Bellos E, Shamaeizadeh A, Tzivanidis C. Solar-driven polygeneration systems: recent progress and outlook. Appl Energy 2020:264.
[27] Wen Q, Liu G, Rao Z, Liao S. Applications, evaluations and supportive strategies of distributed energy systems: a review. Energy Build 2020:225.
[28] Wegener M, Malmquist A, Isalgué A, Martin A. Biomass-fired combined cooling, heating and power for small scale applications – a review. Renew Sustain Energy Rev 2018;96:392–410.
[29] Lucia U. Overview on fuel cells. Renew Sustain Energy Rev 2014;30:164–9.
[30] Wang J-J, Jing Y-Y, Zhang C-F, Zhao J-H. Review on multi-criteria decision analysis aid in sustainable energy decision-making. Renew Sustain Energy Rev 2009;13:2263–78.
[31] Liu M, Shi Y, Fang F. Combined cooling, heating and power systems: a survey. Renew Sustain Energy Rev 2014;35:1–22.
[32] Wu DW, Wang RZ. Combined cooling, heating and power: a review. Prog Energy Combust Sci 2006;32:459–95.
[33] Group C. Introducing combined heat and power. Carbon trust; 2010.
[34] Isa NM, Tan CW, Yatim AHM. A comprehensive review of cogeneration system in a microgrid: a perspective from architecture and operating system. Renew Sustain Energy Rev 2018;81:2236–63.
[35] Gao L, Hwang Y, Cao T. An overview of optimization technologies applied in combined cooling, heating and power systems. Renew Sustain Energy Rev 2019;114:109344.
[36] Gu W, Wu Z, Bo R, Liu W, Zhou G, Chen W, et al. Modeling, planning and optimal energy management of combined cooling, heating and power microgrid: a review. Int J Electr Power Energy Syst 2014;54:26–37.
[37] Hou Q, Zhao H, Yang X. Economic performance study of the integrated MR-SOFC-CCHP system. Energy 2019;166:236–45.
[38] Roman KK, Alvey JB. Selection of prime mover for combined cooling, heating, and power systems based on energy savings, life cycle analysis and environmental consideration. Energy Build 2016;110:170–81.
[39] Ebrahimi M, Keshavarz A. Prime mover selection for a residential micro-CCHP by using two multi-criteria decision-making methods. Energy Build 2012;55:322–31.
[40] Wang J, Han Z, Guan Z. Hybrid solar-assisted combined cooling, heating, and power systems: a review. Renew Sustain Energy Rev 2020;133:110256.
[41] Al Moussawi H, Fardoun F, Louahlia H. Selection based on differences between cogeneration and trigeneration in various prime mover technologies. Renew Sustain Energy Rev 2017;74:491–511.
[42] Jradi M, Riffat S. Tri-generation systems: energy policies, prime movers, cooling technologies, configurations and operation strategies. Renew Sustain Energy Rev 2014;32:396–415.
[43] Ma W, Liu T, Min R, Li M. Effects of physical and chemical properties of working fluids on thermodynamic performances of medium-low temperature organic Rankine cycles (ORCs). Energy Convers Manag 2018;171:742–9.
[44] Zhang G, Wang J, Ren F, Liu Y, Dong F. Collaborative optimization for multiple energy stations in distributed energy network based on electricity and heat interchanges. Energy 2021;222:119987.
[45] Deng J, Wang RZ, Han GY. A review of thermally activated cooling technologies for combined cooling, heating and power systems. Prog Energy Combust Sci 2011;37:172–203.
[46] Evangelisti L, De Lieto Vollaro R, Asdrubali F. Latest advances on solar thermal collectors: a comprehensive review. Renew Sustain Energy Rev 2019;114:109318.
[47] Di Somma M, Yan B, Bianco N, Graditi G, Luh PB, Mongibello L, et al. Operation optimization of a distributed energy system considering energy costs and exergy efficiency. Energy Convers Manag 2015;103:739–51.
[48] Luo Z, Yang S, Xie N, Xie W, Liu J, Souley Agbodjan Y, et al. Multi-objective capacity optimization of a distributed energy system considering economy, environment and energy. Energy Convers Manag 2019;200:112081.
[49] Wang J, Li S, Zhang G, Yang Y. Performance investigation of a solar-assisted hybrid combined cooling, heating and power system based on energy, exergy, exergo-economic and exergo-environmental analyses. Energy Convers Manag 2019;196:227–41.
[50] Baghernejad A, Yaghoubi M, Jafarpur K. Exergoeconomic optimization and environmental analysis of a novel solar-trigeneration system for heating, cooling and power production purpose. Sol Energy 2016;134:165–79.
[51] Saini P, Singh J, Sarkar J. Thermodynamic, economic and environmental analyses of a novel solar energy driven small-scale combined cooling, heating and power system. Energy Convers Manag 2020;226:113542.
[52] Li Y, Yang Y. Thermodynamic analysis of a novel integrated solar combined cycle. Appl Energy 2014;122:133–42.
[53] Wang J, Lu Z, Li M, Lior N, Li W. Energy, exergy, exergoeconomic and environmental (4E) analysis of a distributed generation solar-assisted CCHP (combined cooling, heating and power) gas turbine system. Energy 2019;175:1246–58.
[54] Behar O. A novel hybrid solar preheating gas turbine. Energy Convers Manag 2018;158:120–32.
[55] Colakoglu M, Durmayaz A. Energy, exergy and environmental-based design and multiobjective optimization of a novel solar-driven multi-generation system. Energy Convers Manag 2021;227:113603.
[56] Yang C, Wang X, Huang M, Ding S, Ma X. Design and simulation of gas turbine-based CCHP combined with solar and compressed air energy storage in a hotel building. Energy Build 2017;153:412–20.
[57] Wang X, Yang C, Huang M, Ma X. Off-design performances of gas turbine-based CCHP combined with solar and compressed air energy storage with organic Rankine cycle. Energy Convers Manag 2018;156:626–38.
[58] Wang S, Fu Z. Thermodynamic and economic analysis of solar assisted CCHP-ORC system with DME as fuel. Energy Convers Manag 2019;186:535–45.
[59] Eisavi B, Khalilarya S, Chitsaz A, Rosen MA. Thermodynamic analysis of a novel combined cooling, heating and power system driven by solar energy. Appl Therm Eng 2018;129:1219–29.
[60] Khaliq A, Mokheimer EMA, Yaqub M. Thermodynamic investigations on a novel solar powered trigeneration energy system. Energy Convers Manag 2019;188:398–413.
[61] Said SAM, Waseeuddin M, Simakov DSA. A review on solar reforming systems. Renew Sustain Energy Rev 2016;59:149–59.
[62] Su B, Han W, Chen Y, Wang Z, Qu W, Jin H. Performance optimization of a solar assisted CCHP based on biogas reforming. Energy Convers Manag 2018;171:604–17.
[63] Xu D, Liu Q, Lei J, Jin H. Performance of a combined cooling heating and power system with mid-and-low temperature solar thermal energy and methanol decomposition integration. Energy Convers Manag 2015;102:17–25.
[64] Liu R, Liu M, Zhao Y, Ma Y, Yan J. Thermodynamic study of a novel lignite poly-generation system driven by solar energy. Energy 2021;214:119075.
[65] Bai Z, Liu Q, Lei J, Hong H, Jin H. New solar-biomass power generation system integrated a two-stage gasifier. Appl Energy 2017;194:310–9.
[66] Wu H, Liu Q, Bai Z, Xie G, Zheng J, Su B. Thermodynamics analysis of a novel steam/air biomass gasification combined cooling, heating and power system with solar energy. Appl Therm Eng 2020;164:114494.
[67] Liu Q, Bai Z, Wang X, Lei J, Jin H. Investigation of thermodynamic performances for two solar-biomass hybrid combined cycle power generation systems. Energy Convers Manag 2016;122:252–62.
[68] Asadi J, Amani P, Amani M, Kasaeian A, Bahiraei M. Thermo-economic analysis and multi-objective optimization of absorption cooling system driven by various solar collectors. Energy Convers Manag 2018;173:715–27.
[69] Guo L, Liu W, Cai J, Hong B, Wang C. A two-stage optimal planning and design method for combined cooling, heat and power microgrid system. Energy Convers Manag 2013;74:433–45.
[70] Ahmad L, Khordehgah N, Malinauskaite J, Jouhara H. Recent advances and applications of solar photovoltaics and thermal technologies. Energy 2020;207:118254.
[71] Zervas PL, Sarimveis H, Palyvos JA, Markatos NCG. Model-based optimal control of a hybrid power generation system consisting of photovoltaic arrays and fuel cells. J Power Sources 2008;181:327–38.
[72] Lototskyy M, Nyallang Nyamsi S, Pasupathi S, Wærnhus I, Vik A, Ilea C, et al. A concept of combined cooling, heating and power system utilising solar power and based on reversible solid oxide fuel cell and metal hydrides. Int J Hydrogen Energy 2018;43:18650–63.
[73] Joshi SS, Dhoble AS. Photovoltaic -Thermal systems (PVT): technology review and future trends. Renew Sustain Energy Rev 2018;92:848–82.
[74] Yazdanifard F, Ameri M. Exergetic advancement of photovoltaic/thermal systems (PV/T): a review. Renew Sustain Energy Rev 2018;97:529–53.
[75] Jia Y, Alva G, Fang G. Development and applications of photovoltaic–thermal systems: a review. Renew Sustain Energy Rev 2019;102:249–65.
[76] Wang R, Hong H, Sun J, Jin H. A solar hybrid system integrating concentrating photovoltaic direct steam generation by chemical heat pump. Energy Convers Manag 2019;196:856–65.
[77] Li Z, Chen H, Xu Y, Tiow Ooi K. Comprehensive evaluation of low-grade solar trigeneration system by photovoltaic-thermal collectors. Energy Convers Manag 2020;215:112895.
[78] Wang J, Chen Y, Lior N, Li W. Energy, exergy and environmental analysis of a hybrid combined cooling heating and power system integrated with compound parabolic concentrated-photovoltaic thermal solar collectors. Energy 2019;185:463–76.
[79] Wang J, Chen Y, Lior N. Exergo-economic analysis method and optimization of a novel photovoltaic/thermal solar-assisted hybrid combined cooling, heating and power system. Energy Convers Manag 2019;199:111945.
[80] Chen Y, Wang J, Ma C, Gao Y. Thermo-ecological cost assessment and optimization for a hybrid combined cooling, heating and power system coupled with compound parabolic concentrated-photovoltaic thermal solar collectors. Energy 2019;176:479–92.

[81] Bicer Y, Dincer I. Development of a new solar and geothermal based combined system for hydrogen production. Sol Energy 2016;127:269–84.
[82] Reddy KS, Aravindhan S, Mallick TK. Investigation of performance and emission characteristics of a biogas fuelled electric generator integrated with solar concentrated photovoltaic system. Renew Energy 2016;92:233–43.
[83] Raja AA, Huang Y. Novel parabolic trough solar collector and solar photovoltaic/thermal hybrid system for multi-generational systems. Energy Convers Manag 2020;211:112750.
[84] Aste N, Del Pero C, Leonforte F. Water PVT collectors performance comparison. Energy Proc 2017;105:961–6.
[85] Su B, Han W, Qu W, Liu C, Jin H. A new hybrid photovoltaic/thermal and liquid desiccant system for trigeneration application. Appl Energy 2018;226:808–18.
[86] Mahmoud M, Ramadan M, Naher S, Pullen K, Ali Abdelkareem M, Olabi A-G. A review of geothermal energy-driven hydrogen production systems. Therm Sci Eng Prog 2021:100854.
[87] Zhai H, Shi L, An Q. Influence of working fluid properties on system performance and screen evaluation indicators for geothermal ORC (organic Rankine cycle) system. Energy 2014;74:2–11.
[88] Yu Z, Su R, Feng C. Thermodynamic analysis and multi-objective optimization of a novel power generation system driven by geothermal energy. Energy 2020;199:117381.
[89] Zare V, Rostamnejad Takleh H. Novel geothermal driven CCHP systems integrating ejector transcritical CO2 and Rankine cycles: thermodynamic modeling and parametric study. Energy Convers Manag 2020;205:112396.
[90] Nami H, Anvari-Moghaddam A. Geothermal driven micro-CCHP for domestic application – exergy, economic and sustainability analysis. Energy 2020;207:118195.
[91] Wang J, Chen Y, Dou C, Gao Y, Zhao Z. Adjustable performance analysis of combined cooling heating and power system integrated with ground source heat pump. Energy 2018;163:475–89.
[92] Ren F, Wang J, Zhu S, Chen Y. Multi-objective optimization of combined cooling, heating and power system integrated with solar and geothermal energies. Energy Convers Manag 2019;197:111866.
[93] Nasruddin Idrus Alhamid M, Daud Y, Surachman A, Sugiyono A, Aditya HB, et al. Potential of geothermal energy for electricity generation in Indonesia: a review. Renew Sustain Energy Rev 2016;53:733–40.
[94] Guzović Z, Lončar D, Ferdelji N. Possibilities of electricity generation in the Republic of Croatia by means of geothermal energy. Energy 2010;35:3429–40.
[95] Ambriz-Díaz VM, Rubio-Maya C, Ruiz-Casanova E, Martínez-Patiño J, Pastor-Martínez E. Advanced exergy and exergoeconomic analysis for a polygeneration plant operating in geothermal cascade. Energy Convers Manag 2020;203:112227.
[96] Zare V. A comparative thermodynamic analysis of two tri-generation systems utilizing low-grade geothermal energy. Energy Convers Manag 2016;118:264–74.
[97] Cao L, Wang J, Yang Y, Wang Y, Li H, Lou J, et al. Dynamic analysis and operation simulation for a combined cooling heating and power system driven by geothermal energy. Energy Convers Manag 2021;228:113656.
[98] Musharavati F, Khanmohammadi S, Pakseresht A. A novel multi-generation energy system based on geothermal energy source: thermo-economic evaluation and optimization. Energy Convers Manag 2021;230:113829.
[99] Rostamzadeh H, Gargari SG, Namin AS, Ghaebi H. A novel multigeneration system driven by a hybrid biogas-geothermal heat source, Part I: thermodynamic modeling. Energy Convers Manag 2018;177:535–62.
[100] Rostamzadeh H, Gargari SG, Namin AS, Ghaebi H. A novel multigeneration system driven by a hybrid biogas-geothermal heat source, Part II: multi-criteria optimization. Energy Convers Manag 2019;180:859–88.
[101] Ansarinasab H, Hajabdollahi H. Multi-objective optimization of a geothermal-based multigeneration system for heating, power and purified water production purpose using evolutionary algorithm. Energy Convers Manag 2020;223:113476.
[102] Zeng R, Zhang X, Deng Y, Li H, Zhang G. An off-design model to optimize CCHP-GSHP system considering carbon tax. Energy Convers Manag 2019;189:105–17.
[103] Zhang X, Zeng R, Deng Q, Gu X, Liu H, He Y, et al. Energy, exergy and economic analysis of biomass and geothermal energy based CCHP system integrated with compressed air energy storage (CAES). Energy Convers Manag 2019;199:111953.
[104] Li H, Kang S, Yu Z, Cai B, Zhang G. A feasible system integrating combined heating and power system with ground-source heat pump. Energy 2014;74:240–7.
[105] Chen Y, Wang J, Lund PD. Thermodynamic performance analysis and multi-criteria optimization of a hybrid combined heat and power system coupled with geothermal energy. Energy Convers Manag 2020;210:112741.
[106] Hand B, Kelly G, Cashman A. Aerodynamic design and performance parameters of a lift-type vertical axis wind turbine: a comprehensive review. Renew Sustain Energy Rev 2021;139:110699.
[107] Zuo H, Bi K, Hao H. A state-of-the-art review on the vibration mitigation of wind turbines. Renew Sustain Energy Rev 2020;121:109710.
[108] Li G, Zhang R, Jiang T, Chen H, Bai L, Cui H, et al. Optimal dispatch strategy for integrated energy systems with CCHP and wind power. Appl Energy 2017;192:408–19.
[109] Khalid F, Dincer I, Rosen MA. Techno-economic assessment of a renewable energy based integrated multigeneration system for green buildings. Appl Therm Eng 2016;99:1286–94.
[110] Zhang S, Huang P, Sun Y. A multi-criterion renewable energy system design optimization for net zero energy buildings under uncertainties. Energy 2016;94:654–65.
[111] Lu Y, Wang S, Yan C, Shan K. Impacts of renewable energy system design inputs on the performance robustness of net zero energy buildings. Energy 2015;93:1595–606.
[112] Zidan A, Gabbar HA, Eldessouky A. Optimal planning of combined heat and power systems within microgrids. Energy 2015;93:235–44.
[113] Hossain MA, Pota HR, Squartini S, Zaman F, Guerrero JM. Energy scheduling of community microgrid with battery cost using particle swarm optimisation. Appl Energy 2019;254:113723.
[114] Sezer N, Koç M. Development and performance assessment of a new integrated solar, wind, and osmotic power system for multigeneration, based on thermodynamic principles. Energy Convers Manag 2019;188:94–111.
[115] Ozlu S, Dincer I. Development and analysis of a solar and wind energy based multigeneration system. Sol Energy 2015;122:1279–95.
[116] Yan R, Lu Z, Wang J, Chen H, Wang J, Yang Y, et al. Stochastic multi-scenario optimization for a hybrid combined cooling, heating and power system considering multi-criteria. Energy Convers Manag 2021;233:113911.
[117] Alirahmi SM, Razmi AR, Arabkoohsar A. Comprehensive assessment and multi-objective optimization of a green concept based on a combination of hydrogen and compressed air energy storage (CAES) systems. Renew Sustain Energy Rev 2021;142:110850.
[118] Li P, Hu Q, Han Z, Wang C, Wang R, Han X, et al. Thermodynamic analysis and multi-objective optimization of a trigenerative system based on compressed air energy storage under different working media and heating storage media. Energy 2022;239:122252.
[119] Zhao J, Cai S, Huang X, Luo X, Tu Z. 4E analysis and multiobjective optimization of a PEMFC-based CCHP system with dehumidification. Energy Convers Manag 2021;248:114789.
[120] Zhang Y, Wang X, Zhang Y, Zhuo S. A simplified model to study the location impact of latent thermal energy storage in building cooling heating and power system. Energy 2016;114:885–94.
[121] Ortiz C, Tejada C, Chacartegui R, Bravo R, Carro A, Valverde JM, et al. Solar combined cycle with high-temperature thermochemical energy storage. Energy Convers Manag 2021;241:114274.
[122] Peng X, Bajaj I, Yao M, Maravelias CT. Solid-gas thermochemical energy storage strategies for concentrating solar power: optimization and system analysis. Energy Convers Manag 2021;245:114636.
[123] Wang J, Qi X, Ren F, Zhang G, Wang J. Optimal design of hybrid combined cooling, heating and power systems considering the uncertainties of load demands and renewable energy sources. J Clean Prod 2021;281:125357.
[124] Venkataramani G, Parankusam P, Ramalingam V, Wang J. A review on compressed air energy storage – a pathway for smart grid and polygeneration. Renew Sustain Energy Rev 2016;62:895–907.
[125] Wang X, Yang C, Huang M, Ma X. Multi-objective optimization of a gas turbine-based CCHP combined with solar and compressed air energy storage system. Energy Convers Manag 2018;164:93–101.
[126] Wang J, Sui J, Jin H. An improved operation strategy of combined cooling heating and power system following electrical load. Energy 2015;85:654–66.
[127] Wu D, Chen J, Roskilly AP. Phase change material thermal storage for biofuel preheating in micro trigeneration application: a numerical study. Appl Energy 2015;137:832–44.
[128] Xiong F, Zhang Y, Wang X, Zhang Y. Optimal phase change temperature for energy storage based on fluctuating loads in building cooling heating and power system. Energy Proc 2015;75:1360–5.
[129] Zhang Z, Ding T, Zhou Q, Sun Y, Qu M, Zeng Z, et al. A review of technologies and applications on versatile energy storage systems. Renew Sustain Energy Rev 2021;148:111263.
[130] Han J, Ouyang L, Xu Y, Zeng R, Kang S, Zhang G. Current status of distributed energy system in China. Renew Sustain Energy Rev 2016;55:288–97.
[131] Jing R, Wang M, Zhang Z, Wang X, Li N, Shah N, et al. Distributed or centralized? Designing district-level urban energy systems by a hierarchical approach considering demand uncertainties. Appl Energy 2019;252:113424.
[132] Cho H, Smith AD, Mago P. Combined cooling, heating and power: a review of performance improvement and optimization. Appl Energy 2014;136:168–85.
[133] Jing R, Wang M, Liang H, Wang X, Li N, Shah N, et al. Multi-objective optimization of a neighborhood-level urban energy network: considering Game-theory inspired multi-benefit allocation constraints. Appl Energy 2018;231:534–48.
[134] Yang Y, Zhang S, Xiao Y. Optimal design of distributed energy resource systems coupled with energy distribution networks. Energy 2015;85:433–48.
[135] Wakui T, Yokoyama R. Optimal sizing of residential gas engine cogeneration system for power interchange operation from energy-saving viewpoint. Energy 2011;36:3816–24.
[136] Wakui T, Yokoyama R, Tamura I, Kegasa A. Effect of power interchange operation of multiple household gas engine cogeneration systems on energy-saving. Energy 2009;34:2092–100.
[137] Wu Q, Ren H, Gao W, Ren J. Multi-objective optimization of a distributed energy network integrated with heating interchange. Energy 2016;109:353–64.
[138] Bracco S, Dentici G, Siri S. Economic and environmental optimization model for the design and the operation of a combined heat and power distributed generation system in an urban area. Energy 2013;55:1014–24.
[139] Morvaj B, Evins R, Carmeliet J. Optimising urban energy systems: simultaneous system sizing, operation and district heating network layout. Energy 2016;116:619–36.
[140] Bracco S, Dentici G, Siri S. DESOD: a mathematical programming tool to optimally design a distributed energy system. Energy 2016;100:298–309.
[141] Mehleri ED, Sarimveis H, Markatos NC, Papageorgiou LG. A mathematical programming approach for optimal design of distributed energy systems at the neighbourhood level. Energy 2012;44:96–104.

[142] Falke T, Krengel S, Meinerzhagen A-K, Schnettler A. Multi-objective optimization and simulation model for the design of distributed energy systems. Appl Energy 2016;184:1508–16.
[143] Jing R, Kuriyan K, Lin J, Shah N, Zhao Y. Quantifying the contribution of individual technologies in integrated urban energy systems – a system value approach. Appl Energy 2020;266:114859.
[144] Jing R, Kuriyan K, Kong Q, Zhang Z, Shah N, Li N, et al. Exploring the impact space of different technologies using a portfolio constraint based approach for multi-objective optimization of integrated urban energy systems. Renew Sustain Energy Rev 2019;113:109249.
[145] Ameri M, Besharati Z. Optimal design and operation of district heating and cooling networks with CCHP systems in a residential complex. Energy Build 2016;110:135–48.
[146] Karmellos M, Mavrotas G. Multi-objective optimization and comparison framework for the design of Distributed Energy Systems. Energy Convers Manag 2019;180:473–95.
[147] Wakui T, Sawada K, Kawayoshi H, Yokoyama R, Iitaka H, Aki H. Optimal operations management of residential energy supply networks with power and heat interchanges. Energy Build 2017;151:167–86.
[148] Wu D, Han Z, Liu Z, Li P, Ma F, Zhang H, et al. Comparative study of optimization method and optimal operation strategy for multi-scenario integrated energy system. Energy 2020:119311.
[149] Mavromatidis G, Petkov I. MANGO: a novel optimization model for the long-term, multi-stage planning of decentralized multi-energy systems. Appl Energy 2021;288:116585.
[150] Maroufmashat A, Elkamel A, Fowler M, Sattari S, Roshandel R, Hajimiragha A, et al. Modeling and optimization of a network of energy hubs to improve economic and emission considerations. Energy 2015;93:2546–58.
[151] Sameti M, Haghighat F. Integration of distributed energy storage into net-zero energy district systems: optimum design and operation. Energy 2018;153:575–91.
[152] Comodi G, Bartolini A, Carducci F, Nagaranjan B, Romagnoli A. Achieving low carbon local energy communities in hot climates by exploiting networks synergies in multi energy systems. Appl Energy 2019;256:113901.
[153] Ghorab M. Energy hubs optimization for smart energy network system to minimize economic and environmental impact at Canadian community. Appl Therm Eng 2019;151:214–30.
[154] Li L, Mu H, Li N, Li M. Economic and environmental optimization for distributed energy resource systems coupled with district energy networks. Energy 2016;109:947–60.
[155] Liu H, Xu C, Sui J, Han W. Energy-saving optimization of interconnected distributed cooling, heating and power systems. Kexue Tongbao/Chin Sci Bull 2017;62:3703–10.
[156] Ren H, Wu Q, Li Q, Yang Y. Optimal design and management of distributed energy network considering both efficiency and fairness. Energy 2020;213:118813.
[157] Luo X, Liu Y, Liu J, Liu X. Optimal design and cost allocation of a distributed energy resource (DER) system with district energy networks: a case study of an isolated island in the South China Sea. Sustainable Cities and Society; 2019. p. 51.
[158] Wu Q, Ren H, Gao W, Ren J, Lao C. Profit allocation analysis among the distributed energy network participants based on Game-theory. Energy 2017;118:783–94.
[159] Wu Q, Ren H, Gao W, Ren J. Benefit allocation for distributed energy network participants applying game theory based solutions. Energy 2017;119:384–91.
[160] Jing R, Xie MN, Wang FX, Chen LX. Fair P2P energy trading between residential and commercial multi-energy systems enabling integrated demand-side management. Appl Energy 2020;262:114551.
[161] Zhang D, Samsatli NJ, Hawkes AD, Brett DJL, Shah N, Papageorgiou LG. Fair electricity transfer price and unit capacity selection for microgrids. Energy Econ 2013;36:581–93.
[162] Liu H, Sui J, Han W, Wang Z, Zhang N. Operation strategy of interconnected combined cooling, heating, and power systems based on exergoeconomic analysis. J Clean Prod 2020;245:118822.
[163] Bui V-H, Hussain A, Im Y-H, Kim H-M. An internal trading strategy for optimal energy management of combined cooling, heat and power in building microgrids. Appl Energy 2019;239:536–48.
[164] Unternährer J, Moret S, Joost S, Maréchal F. Spatial clustering for district heating integration in urban energy systems: application to geothermal energy. Appl Energy 2017;190:749–63.
[165] Wang W, Jing R, Zhao Y, Zhang C, Wang X. A load-complementarity combined flexible clustering approach for large-scale urban energy-water nexus optimization. Appl Energy 2020;270:115163.
[166] Yan Y, Yan J, Song M, Zhou X, Zhang H, Liang Y. Design and optimal siting of regional heat-gas-renewable energy system based on building clusters. Energy Convers Manag 2020;217:112963.
[167] Marquant JF, Evins R, Bollinger LA, Carmeliet J. A holarchic approach for multi-scale distributed energy system optimisation. Appl Energy 2017;208:935–53.
[168] Max Bittel H, Perera ATD, Mauree D, Scartezzini J-L. Locating multi energy systems for A neighborhood in geneva using K-means clustering. Energy Proc 2017;122:169–74.
[169] Marquant JF, Bollinger LA, Evins R, Carmeliet J. A new combined clustering method to Analyse the potential of district heating networks at large-scale. Energy 2018;156:73–83.
[170] Jing R, Lin Y, Khanna N, Chen X, Wang M, Liu J, et al. Balancing the Energy Trilemma in energy system planning of coastal cities. Appl Energy 2020:116222.
[171] Yu L, Li YP, Huang GH. Planning municipal-scale mixed energy system for stimulating renewable energy under multiple uncertainties - the City of Qingdao in Shandong Province, China. Energy 2019;166:1120–33.
[172] Jin L, Huang GH, Fan YR, Wang L, Wu T. A pseudo-optimal inexact stochastic interval T2 fuzzy sets approach for energy and environmental systems planning under uncertainty: a case study for Xiamen City of China. Appl Energy 2015;138:71–90.
[173] Dong C, Huang GH, Cai YP, Liu Y. An inexact optimization modeling approach for supporting energy systems planning and air pollution mitigation in Beijing city. Energy 2012;37:673–88.
[174] Crawley DB, Hand JW, Kummert M, Griffith BT. Contrasting the capabilities of building energy performance simulation programs. Build Environ 2008;43:661–73.
[175] Bourdeau M, Zhai Xq, Nefzaoui E, Guo X, Chatellier P. Modeling and forecasting building energy consumption: a review of data-driven techniques. Sustain Cities Soc 2019;48:101533.
[176] Granell R, Axon CJ, Kolokotroni M, Wallom DCH. Predicting electricity demand profiles of new supermarkets using machine learning. Energy Build 2021;234:110635.
[177] Gao F, Chi H, Shao X. Forecasting residential electricity consumption using a hybrid machine learning model with online search data. Appl Energy 2021;300:117393.
[178] Wei Z, Zhang T, Yue B, Ding Y, Xiao R, Wang R, et al. Prediction of residential district heating load based on machine learning: a case study. Energy 2021;231:120950.
[179] Zhou Y, Liu Y, Wang D, Liu X. Comparison of machine-learning models for predicting short-term building heating load using operational parameters. Energy Build 2021;253:111505.
[180] Sha H, Moujahed M, Qi D. Machine learning-based cooling load prediction and optimal control for mechanical ventilative cooling in high-rise buildings. Energy Build 2021;242:110980.
[181] Gao Z, Yu J, Zhao A, Hu Q, Yang S. A hybrid method of cooling load forecasting for large commercial building based on extreme learning machine. Energy 2022;238:122073.
[182] Tan Z, De G, Li M, Lin H, Yang S, Huang L, et al. Combined electricity-heat-cooling-gas load forecasting model for integrated energy system based on multi-task learning and least square support vector machine. J Clean Prod 2020;248:119252.
[183] Wang S, Wang S, Chen H, Gu Q. Multi-energy load forecasting for regional integrated energy systems considering temporal dynamic and coupling characteristics. Energy 2020;195:116964.
[184] Li Z, Wu W, Shahidehpour M, Wang J, Zhang B. Combined heat and power dispatch considering pipeline energy storage of district heating network. IEEE Trans Sustain Energy 2016;7:12–22.