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Application of abandoned wells integrated with renewables

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Abbreviations

AOW	abandoned oil well
BIPVT	building integrated photovoltaic/thermal
CCHP	combined cooling, heat and power
CHP	combined heat and power
COP	coefficient of performance
DPT	discounted payback time
EMV	expected monetary value
LCA	life cycle assessment
LCOE	levelized cost of electricity
LCOH	levelized cost of heating
MINLP	mixed-integer and nonlinear programming
NPV	net present value
NSGA-II	nondominated sorting genetic algorithm-II
ORC	Organic Rankine Cycle

1 Introduction

Due to the high energy density, thermal performance stability, and large abundance in resources, geothermal energy utilization from abandoned wells is full of promising prospects to promote the carbon-neutrality transition of district energy systems. Depending on the energy forms, the geothermal energy can be used for direct thermal energy supply for district heating [1] or be converted into electricity through the Organic Rankine Cycle (ORC) [2]. Compared to other renewables, such as solar and wind energy, geothermal energy shows advantages such as higher thermal efficiency, higher performance stability, weather-proof and base-load abilities, less land requirement, and less ecological effect [3]. However, barriers limit the widespread application of geothermal energy including high initial investment, long payback time

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and construction time, difficulty in assessing resource, and difficulty in modularization. The combination of abandoned wells with various renewable energy sources can compensate the disadvantages and popularize the widespread applications. On the other hand, due to the intermittence and stochastic nature of solar or wind energy resources, geothermal energy can stabilize the energy supply in terms of fluctuations in renewable energy generation, through the seasonal energy storages. In the academia, typical systems for renewable integrations include solar-geothermal energy systems [4], building integrated photovoltaic/thermal (BIPVT) systems and earth-air heat exchanger systems [5], abandoned wells with waste heat recovery [6], and abandoned wells integrated with renewable systems [1].

Criteria for thermal energy systems include outlet fluid temperature, extracted thermal output, static payback time, and carbon emission. The multicriteria for geothermal-based power systems include electricity generation cost, simple payback time, and levelized cost of electricity. Strategies for performance enhancement of geothermal energy systems mainly include optimal design and smart operation. Approaches for optimal system design include Taguchi Statistical Method [7,8], advanced optimization algorithms such as genetic algorithm, mixed-integer and nonlinear programming (MINLP) optimization [9], mixed-integer linear optimization [10], and a three-stage heuristic approach. Advantages of the Taguchi Statistical Method include dimensionality reduction from redundant experiments, labor cost saving, and time saving.

In this chapter, a state-of-the-art review on abandoned wells for thermal and power generations is conducted. In order to overcome the disadvantages of geothermal energy systems, such as high initial investment, high labor cost, long payback time and construction time, and so on, the integrations of abandoned wells with various renewable energy sources with compensatory functions are reviewed, to popularize the widespread applications. Abandoned wells with renewable integrations are reviewed, in terms of different system configurations (such as solar-geothermal energy systems, BIPVT, and earth-air heat exchanger systems) and technologies (such as waste heat recovery). Advanced strategies for multicriteria performance enhancement have been reviewed from perspectives of optimal design and smart operation. Last but not the but not least, real applications and future prospects for geothermal energy from abandoned wells are listed, including techno-economic and environmental performance analysis, geothermal integrated energy systems with synergistic functions, and geothermal energy potential analysis. This chapter can provide preliminary knowledge and cutting-edge technologies on renewable integrations with abandoned wells, so as to demonstrate techno-economic-environmental potentials of abandoned wells and contributions toward the carbon-neutrality transition.

2 Systematic literature review of abandoned wells for thermal and power generations

2.1 Abandoned wells for thermal energy generation

Abandoned wells have been applied for thermal energy generation. Moya et al. [11] reviewed the cascade configurations for geothermal energy utilization to improve the thermal efficiency. Over the past several decades, researchers have mainly focused on experimental, numerical study, and parametrical analysis. Bu et al. [12] experimentally and numerically studied a geothermal well for space heating. Gharibi et al. [13] developed a three-dimensional numerical model to characterize the thermal performance of a U-tube heat exchanger. Parametrical analysis was conducted on geometrical and operating parameters. The results showed that the optimal outlet temperature at 324.73 K can be achieved, in the case with 288.16 K inlet temperature and 0.03 m/s inlet velocity. The system performance is stable after 5 years. Hu et al. [14] evaluated the geothermal energy potential of abandoned petroleum wells, through a coaxial borehole heat exchanger. Based on the model developed in COMSOL Multiphysics, the temperature and power are stable at ~29°C and 0.38 MW.

Thermal and energy performances have also been studied. Nian and Cheng [15] applied an abandoned oil well (AOW) for space heating, as shown in Fig. 1. The parametrical analysis indicates that the AOW can maintain the indoor air temperature at 26°C with the water flow rate at 20 m^3/h. The annual energy performance indicates that the total geothermal energy was 5.5×10^{12} J, decreasing the carbon emission by 457 ton each year. Caulk and Tomac [16] applied abandoned oil and gas wells for district heating. The outlet fluid temperatures higher than 40°C can be obtained. Naicker and Rees [17] studied the dynamic performance of a large-scale geothermal system for heating and cooling, with part load ratio, and energy saving. Nian and Cheng [18] studied the geothermal energy performance of abandoned oil and gas wells, in terms of heat transfer models and working fluids. The results showed that the system can keep a 10,000-m^2 building at 26°C, with around half the cost of the conventional system.

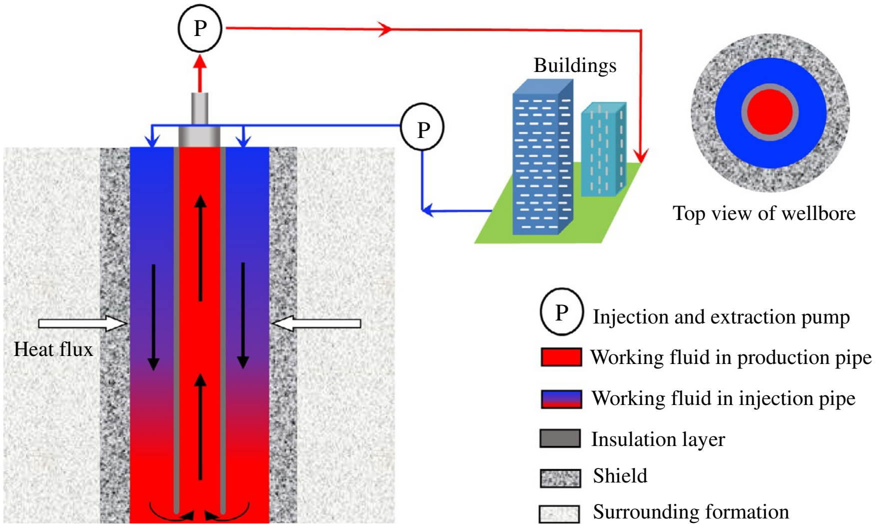

Fig. 1 Geothermal energy for space heating from abandoned oil well.
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2.2 Abandoned wells for power generation

In addition to thermal energy generation, abandoned wells for power generations have also been studied. Geothermal power potentials have been studied in different countries. Pambudi [19] comprehensively reviewed geothermal power generation in Indonesia. Based on the historical power generation data, the geothermal power generation is predicted to be 7000MW in 2025. Davis and Michaelides [20] studied the geothermal power potential from abandoned oil wells. A total of 2–3MW of electric power can be generated. Wang et al. [21] reviewed geothermal power generation over the past 60years in China. The review highlights the necessity for advanced power cycles and multiobjective optimization of geothermal ORC systems. Ahmadi et al. [22] systematically reviewed the applications of geothermal-ORC power systems, in terms of organic fluids' choice, ORC configurations, operating conditions, and key factors. The economic and environmental performances of the geothermal-ORC power systems validated the feasibility performance of the hybrid system.

Parametrical analysis of thermal and energy performance has been carried out. Cheng et al. [23] conducted the parametrical analysis on electricity production from abandoned oil wells, based on a transient formation heat transfer model,

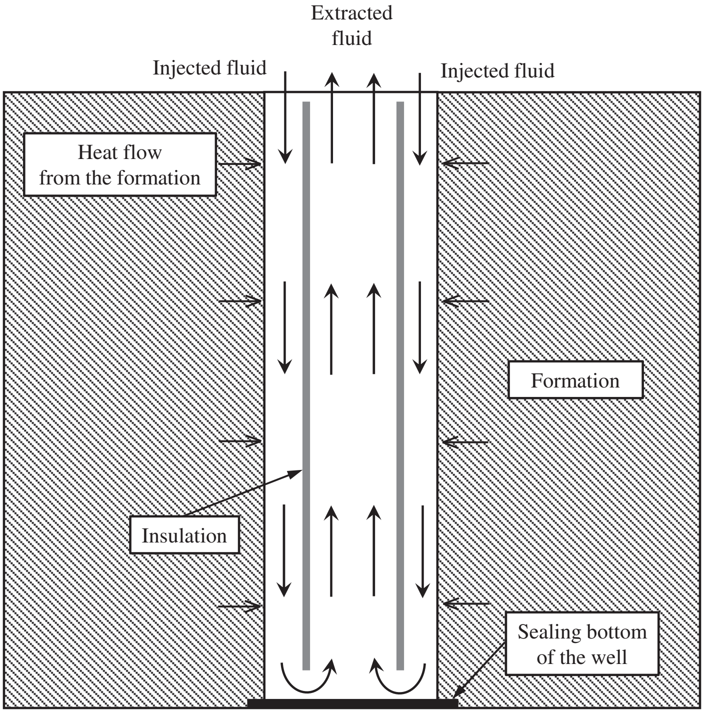

Fig. 2 Double-pipe heat exchanger.
Reprinted from W.L. Cheng, T.T. Li, Y.L. Nian, C.L. Wang, Studies on geothermal power generation using abandoned oil wells, Energy 59 (2013) 248–254. Copyright with permission from Elsevier.

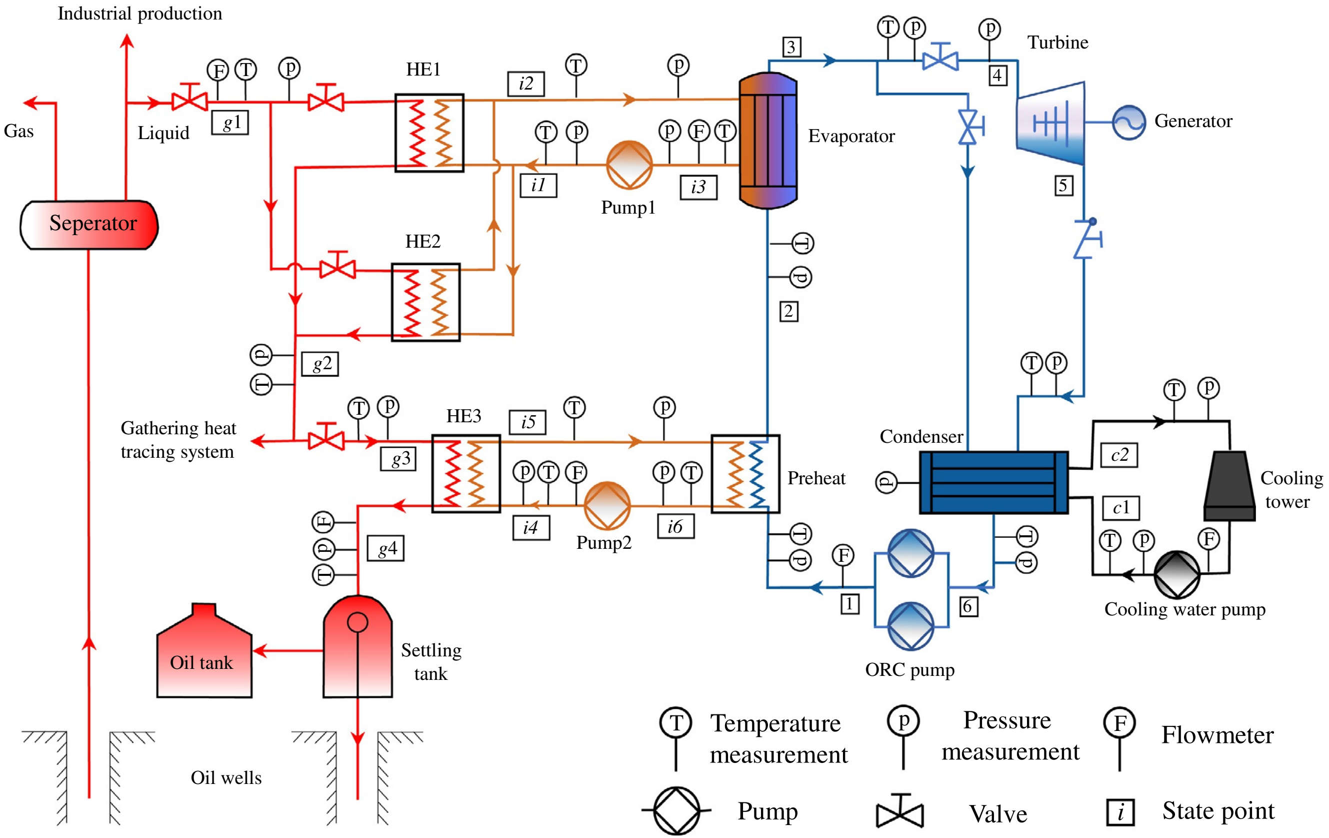

Fig. 3 Schematic diagram of the geothermal ORC system.

Reprinted from Y. Yang, Y. Huo, W. Xia, X. Wang, P. Zhao, Y. Dai, Construction and preliminary test of a geothermal ORC system using geothermal resource from abandoned oil wells in the Huabei oilfield of China, Energy 140 (2017) 633–645. Copyright with permission from Elsevier.

as shown in Fig. 2. The results showed that an optimal inlet velocity can be obtained to maximize the net power generation, with the trade-off between total obtained heat and the fluid outlet temperature. Kharseh et al. [24] indicated that, maximum electricity generation at 11 kW can be realized. A low-temperature geothermal ORC system, as shown in Fig. 3 [25], consists of oil wells and ORC, with the turbine efficiency at 78.52% and the ORC efficiency at 5.33%. Altun and Kilic [26] studied the thermodynamics of a geothermal ORC power plant. Due to the change of meteorological parameters, the transition from winter to summer will reduce the net power output by 36%.

2.3 System assessment criteria

In the academia, criteria for thermal energy systems include outlet fluid temperature, extracted thermal output, static payback time, and carbon emission. Table 1 shows a holistic overview of multicriteria performances of geothermal-based thermal and power systems. Researchers are mainly focused on thermal and power generation of geothermal energy systems. In terms of heating applications, with the abandoned oil well (AOW) for space heating, Nian and Cheng [15] indicate that carbon emission can be reduced by 457 ton each year. Bu et al. [27] concluded that the static payback period was 7.17 and 5.16 years for continuous and intermittent heating, with the extracted thermal output at 448.49 and around 619.12 kW, respectively. With respect to the power generation, Yildirim et al. [28] designed downhole heat exchangers for electricity generation, and concluded that power generation cost was 46 $/MWh and the simple payback time was 2.25 years. Kharseh et al. [29] studied oil wells for power generation. They concluded that the levelized cost of electricity was between 5.6 and 5.2 ¢/kW, and the payback time was between 5.8 and 4.8 years. Systems for thermal energy generation include a U-tube heat exchanger [13] and a coaxial borehole heat exchanger [14]. Variables for parametrical analysis include geometrical and operating variables. With respect to geothermal-based power systems, multicriteria performances include electricity generation cost, simple payback time, and levelized cost of electricity. Systems for thermal energy generation include downhole heat exchangers [28], integrated absorption refrigeration and solar energy [4]. Variables for parametrical analysis include fluid mass flow rate, inner pipe diameter, depth of downhole heat exchanger, and so on.

3 Renewable integrations with abandoned wells for district heating

Barriers limiting the widespread application of geothermal energy include high initial investment, long payback time, and construction time, difficulty in assessing resource and difficulty in modularization. The combination of abandoned wells with various renewable energy sources can compensate the disadvantages and popularize the wide applications. In the academia, typical systems for renewable integrations include

Table 1 A holistic overview on multicriteria performances of geothermal-based thermal and power systems.

	Studies	Systems	Variables	Criteria	Results
Thermal energy generation	Nian and Cheng [15]	Abandoned oil well (AOW) for space heating	Water flow rate	Indoor air temperature, total geothermal energy and carbon emission	The carbon emission can be reduced by 457 ton each year.
	Gharibi et al. [13]	A U-tube heat exchanger	Geometrical and operating variables	Outlet fluid temperature	The inlet velocity and the outlet temperature are 0.03 m/s and 324.73 K, respectively.
	Caulk and Tomac [16]	Abandoned oil and gas wells for district heating	Depth of wells	Outlet fluid temperature	The outlet fluid temperatures higher than 40°C can be obtained.
	Hu et al. [14]	A borehole heat exchanger for geothermal energy utilization	Working fluid and thermodynamic property	Fluid temperature and generated power	The production temperature and power stabilize at around 29°C and 0.38 MW
	Bu et al. [27]	Intermittent heating	Injection temperature and velocity	Extracted thermal output and static payback time	The static payback period is 7.17 and 5.16 years for continuous and intermittent heating, with the extracted thermal output at 448.49 and around 619.12 kW, respectively.

Continued

Table 1 Continued

	Studies	Systems	Variables	Criteria	Results
Power generation	Yildirim et al. [28]	Downhole heat exchangers for electricity generation	Fluid mass flow rate, inner pipe diameter and depth of downhole heat exchanger	Electricity generation cost and simple payback time	Power generation cost is 46 $/MWh and the simple payback time is 2.25 years.
	Kharseh et al. [29]	Oil wells for power generation	Optimal working fluid and design	Levelized cost of electricity (LCOE) and payback period	The LCOE is between 5.6 and 5.2 ¢/kW, and the payback time is between 5.8 and 4.8 years.
	Bayer et al. [30]	Geothermal power generation system	Life cycle emissions	Life cycle assessment (LCA) on geothermal electricity production	Emissions and resource are provided for worldwide geothermal power generation
	Khosravi and Syri [4]	Absorption refrigeration and solar integrated systems	Meteorological and operating parameters	Payback time	The payback time is around 8 years.

solar-geothermal energy systems, BIPVT and earth-air heat exchanger systems, abandoned wells with waste heat recovery, and abandoned wells integrated with renewable systems.

3.1 Solar-geothermal energy system integration

Due to the low or moderate temperature (around 150°C) of geothermal systems, Li et al. [31] integrated solar energy to escalate the working temperature and improve geothermal power generation. The state-of-the-art review can promote the synergistic function of solar and geothermal energy for efficiency improvement in power generation. An absorption refrigeration and solar integrated geothermal power system is shown in Fig. 4. The operational principle is that the geothermal fluid absorbs heat from the production well, and the superheated vapor is reheated by a solar collector. Afterwards, the vapor goes to the turbine for power generation, and then moves to the condenser for absorption refrigeration. Due to the intermittence of geothermal energy, the hydrogen system is designed for stable electrical power generation. The techno-economic performance analysis indicates that the payback time is around 8 years when the interest rate is 3%.

In addition, the energy and exergy performances were studied on an integrated BIPVT and earth-air heat exchanger [5], with the annual thermal energy, annual electrical energy, and annual thermal exergy at 3499.59, 5908.19, and 55.59 kWh. Chen et al. [32] studied the combined geothermal and solar systems for district heating, as shown in Fig. 5. The sensitivity analysis results indicate that the annual cost saving ratio can be improved, for a higher solar beam irradiance. Yao et al. [33] studied a combined borehole heat exchanger and solar-assisted PV/T heat pump for space heating of a residential building. The COP of the hybrid system is 7.4, when the solar fraction is 67.5%.

3.2 Abandoned wells with waste heat recovery

Waste heat recovery, as an effective strategy for decarbonization, has also been integrated with abandoned wells for thermal and power energy generation. DeLovato et al. [34] comprehensively reviewed advanced heat recovery techniques for energy performance improvement of solar and geothermal power plants. The waste heat recovery can effectively improve the system efficiency. In addition, Loni et al. [6] systematically reviewed the industrial waste heat recovery techniques with ORC. The results showed that the waste heat recovery can increase the system efficiency of up to 70%.

Numerical models for heating energy assessment have been studied. Sharma et al. [35] developed an analytical model to study the heat recovery of geothermal energy. The results showed that critical parameters are identified. The heat recovery will improve the power output of the geothermal ORC power plant by 15% [26]. In terms of the application through system integration, Manente et al. [36] studied the hydraulic performance of a district heating system with geothermal and waste energy. Electric power for pumping can be reduced by 30%, and the enhanced

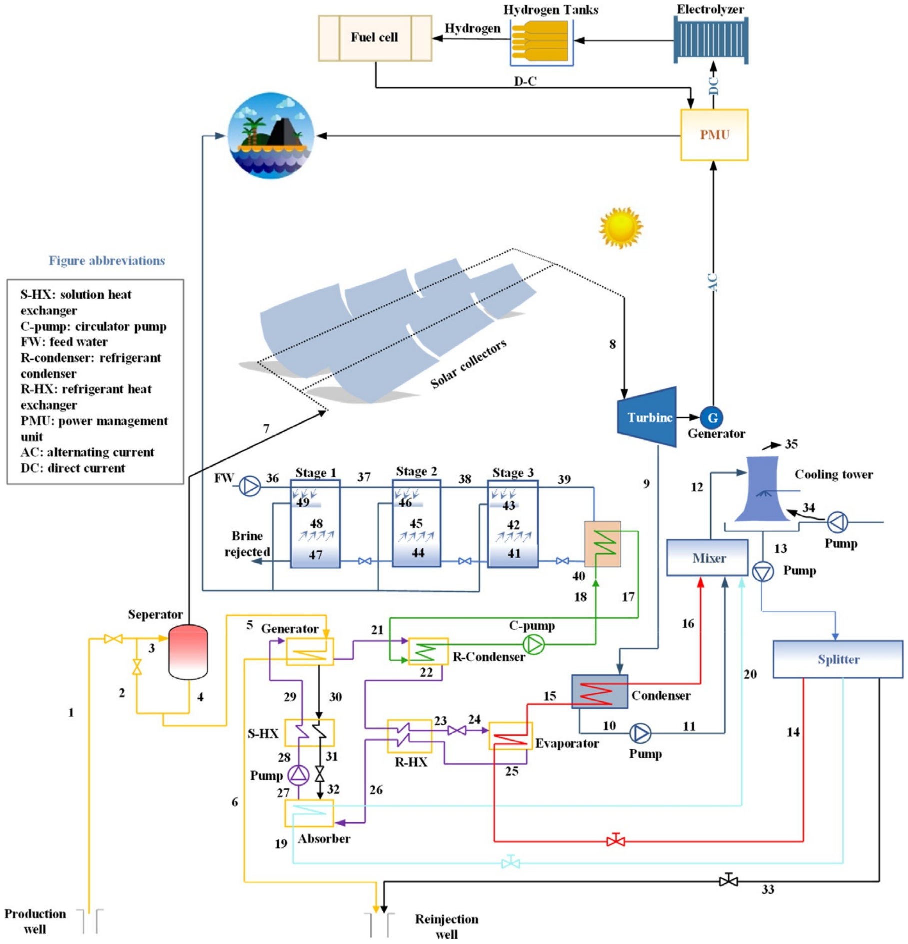

Fig. 4 A schematic diagram on an absorption refrigeration and solar-integrated geothermal power system with hydrogen storage.
Reprinted from A. Khosravi, S. Syri, Modeling of geothermal power system equipped with absorption refrigeration and solar energy using multilayer perceptron neural network optimized with imperialist competitive algorithm, J. Clean. Prod. 276 (2020) 124216. Copyright with permission from Elsevier.

storage system can save 7000 MWh/year energy, equivalent to 11% to the annual heat demand. Hall et al. [37] studied the heat recovery from underground mines for space heating. The energy source provided by the warm mine water can improve the energy resilience and offset the greenhouse gas emissions. Willems and Nick [38] studied the impact of geothermal heat recovery on demand coverage. The results showed that the heat recovery efficiency can be 30%, and the geothermal heat can cover around 4% of the total demand.

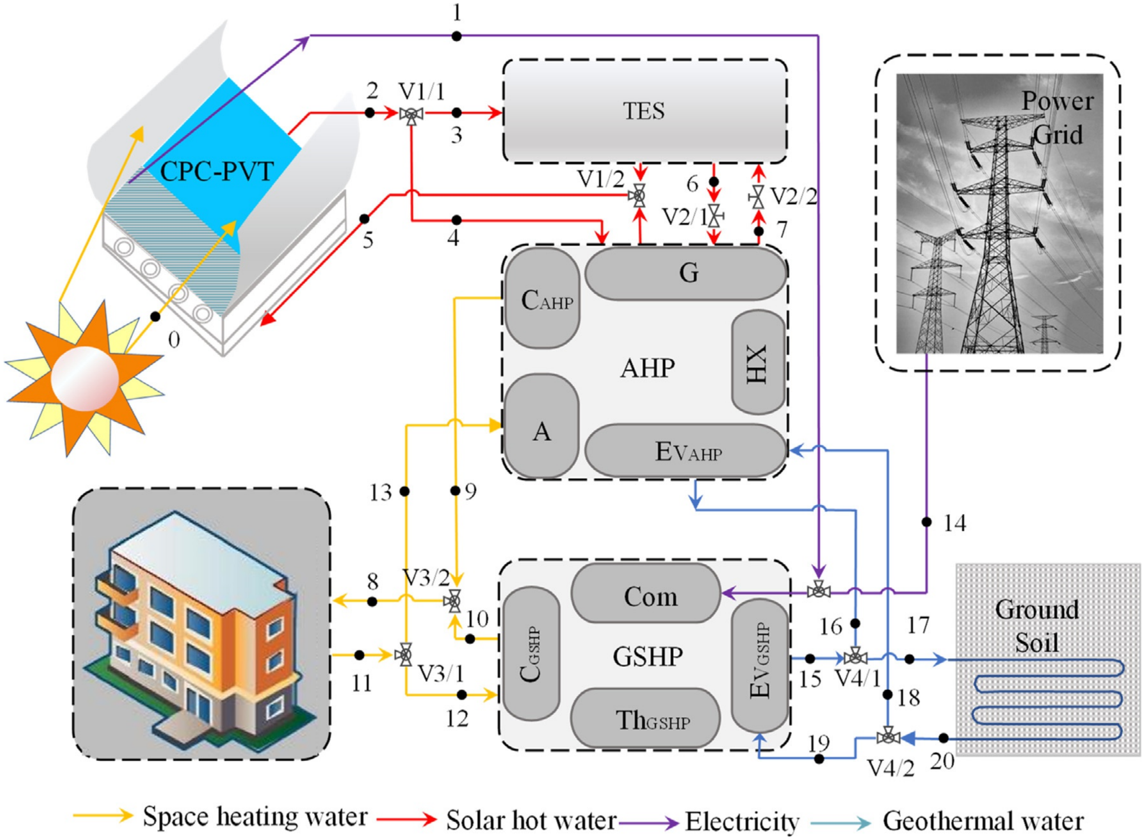

Fig. 5 A district heating system integrated with geothermal and solar resources.

Reprinted from Y. Chen, J. Wang, P.D. Lund, Sustainability evaluation and sensitivity analysis of district heating systems coupled to geothermal and solar resources, Energy Convers. Manag. 220 (2020) 113084. Copyright with permission from Elsevier.

3.3 Abandoned wells and renewable systems for district heating

Abandoned wells and renewable systems for district heating have also been studied. Ghasemi et al. [39] analyzed power generation of a solar-geothermal system, to improve the system efficiency. Østergaard and Lund [1] studied the replacement of fossil fuel sources with renewable systems for district heating in Frederikshavn. Østergaard et al. [40] designed a heating system in Aalborg, with geothermal heat, wind power, and biomass. The study indicated that the dependence on neighboring areas is necessary to dynamically balance the energy in the 100% renewable scenario. The system with an absorption heat pump is powerful for carbon reduction, with replacement of natural gas. Hepbasli [41] provided a holistic overview on the performances of geothermal-based heating systems. The review can provide technical guidance on system design and operation. Fabre et al. [42] designed a triple-pipe system to lower the primary return temperature, so as to improve the efficiency of district heating network. The underlying mechanism is the temperature-cascaded district heating, so as to cover heating loads with different temperatures, such as domestic heating and space heating. Ozgener et al. [43] systematically reviewed techniques to improve performance of geothermal heating systems. The results showed that the geothermal heating system in Gonen shows the highest exergy efficiency, whereas the system in Salihli shows the highest energy efficiency.

Techno-economic-environmental performances have also been evaluated. Keçebaş [44] studied thermo-economic performance of a geothermal heating system in Afyon, Turkey. The results showed that energy and exergy efficiencies are 37.59% and 47.54%, together with energy and exergy loss rate at 5.36 kW/$ and 0.2 kW/$, respectively. Carotenuto et al. [45] studied the energy-economic performance of a novel solar-geothermal system for district heating. The results showed that with the public funding policy, the simple payback time can be reduced from 20.9 to around 10.5 years. Galantino et al. [46] analyzed thermodynamic performance of a geothermal district heating system, from perspectives of levelized cost of heating (LCOH) and carbon abatement. Compared to the conventional system with the LCOH at \$15.53/MWh$_{th}$, the system is more economically competitive with the LCOH at \$4.55/MMBTU.

4 Strategies for performance enhancement

Strategies for performance improvement of abandoned wells with renewables can be proposed, from perspectives of optimal design and smart operation. In this section, approaches for optimal system design and smart operation have been reviewed, together with improvement in system performance.

4.1 Optimal system design

In the academia, approaches for optimal system design include Taguchi Statistical Method [7,8], advanced optimization algorithms, such as genetic algorithm, mixed-integer and nonlinear programming (MINLP) optimization [9], mixed-integer linear optimization [10], and a three-stage heuristic. The advantages of the Taguchi Statistical

Method include dimensionality reduction from redundant experiments, the cost saving and time saving. Cheng et al. [7] adopted the Taguchi Statistical Method to improve the geothermal energy extraction. The results showed that the well bottom curvature design can improve the thermal output by 30%. Liu et al. [8] adopted the Taguchi Method for sensitivity analysis of thermophysical and geometrical parameters of PCMs.

Furthermore, optimization on geothermal energy with geometrical and operating parameters has been studied. Erdeweghe et al. [47] optimized the temperature and flow rate to maximize the power generation. The results showed that the exergetic efficiency of the hybrid system is higher than that of the pure power plant by 22.8%. Erdeweghe et al. [48] indicated that a geothermal CHP plant shows a net present value (NPV) at 3.46 MEUR. Weinand et al. [10] developed a combinatorial optimization approach to minimize the operating cost. The proposed heuristic approach is more accurate and faster than the traditional optimization approach, with the avoidance on economic performance overestimation.

In addition to single objective optimization, multiobjective optimization was conducted to reach the "best of the best" solution along the Pareto front. Gerber and Maréchal [49] conducted the multiobjective optimization of an enhanced geothermal system. Ren et al. [50] conducted the multiobjective optimization of a combined cooling, heat and power (CCHP) system, using NSGA-II. The results showed that the optimal strategy following electric load strategy is much better than others. Song et al. [51] conducted the multiobjective optimization on a multilateral-well geothermal system for performance improvement, in respect to heat power and flow impedance. With the objective for maximum geothermal production, the optimal parameters are injection flow rate at 62.21 kg/s, injection temperature at 49.98°C, and production pressure at 27.44 MPa.

4.2 Smart system operation

In addition to optimal system design, smart operations on geothermal or geothermal integrated systems were investigated. Kharseh et al. [24] studied the optimization on operating parameters, and concluded the maximum electricity generation at 11 kW. Atam et al. [52] developed Hammerstein-Wiener models, and compared it with detailed finite-element borefield thermal model. The Hammerstein-Wiener models are validated to be effective in advanced model-based control. Bode et al. [53] developed a mode-based control strategy on heat pumps, with integrations of a geothermal field. The results showed that the mode-based control strategy is effective in integrating renewable energies in the built environment. Fallah et al. [54] studied the pressure control of deep closed-loop well systems, and concluded that over 40 MW initial thermal power can be generated.

5 Applications, challenges, and future prospects

5.1 Techno-economic and environmental performance analysis

Techno-economic feasibility analysis of geothermal systems is critical for the widespread acceptance and social popularity of geothermal energy systems. Guo et al. [55] assessed the sustainability of geothermal resources in an abandoned coal mine.

Templeton et al. [56] studied the abandoned petroleum wells for geothermal energy supply, with a finite element model. The results showed that the constant power model can extract energy with sustainable manner. Fan et al. [57] studied a regulated geothermal heating system, in terms of annual water consumption and power generation. Compared to an unregulated system, the regulated system can generate 25% more electricity with 50% less water.

From the lifetime perspective, lifetime performance analysis is essential, with the consideration on performance degradation, operational stability, and so on. Daniilidis et al. [58] conducted the uncertainty analysis on a deep geothermal heat system, in terms of NPV, LCOH, and expected monetary value (EMV). The results showed that flow rate is the most critical factor for economic performance. Westphal and Weijermars [59] indicated that by extracting geothermal energy from depleted hydrocarbon wells, a NPV of $1.2 billion can be obtained in the United States.

5.2 Geothermal integrated energy systems

Although the geothermal energy is characterized with thermal performance stability and large abundance in resources, the disadvantages of geothermal energy need to be noticed, such as initial capital cost and annual thermal imbalance. Future studies can be focused on:

(1) *geothermal-based hydrogen energy systems for low-carbon energy districts*

Ghazvini et al. [60] indicated that the geothermal-assisted hydrogen production cost is much lower than other renewable sources, such as wind, solar PV, grid power, and so on. Fig. 6 shows the roadmap diagram of geothermal-based hydrogen production. The hydrogen can be produced from either thermochemical cycles or electrolyzer, depending on the utilized energy forms from geotherm energy. The geothermal-assisted hydrogen production can compensate the high initial capital cost of geothermal systems, so as to popularize its practical application feasibility.

(2) *synergistic operation of geothermal sources and other renewable system for stable power supply*

Due to the spatiotemporally uneven distribution of solar and wind energy sources, the integration of geothermal source can improve the energy supply stability and

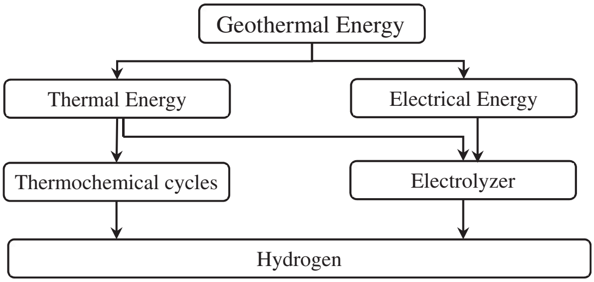

Fig. 6 Roadmap diagram of geothermal based hydrogen production.

reliability. From the long-term perspective, the geothermal storage can act as a seasonal storage, to balance the energy demands and renewable energy generation. Future studies can focus on dynamic and seasonal performance analysis of geothermal integrated hybrid renewable systems.

5.3 Potential assessment of abandoned wells for carbon-neutrality transition

Along with the target for the carbon-peak era in 2030, and the carbon-neutrality era in 2060 in China, the roles of abandoned wells in the carbon-neutrality transition need to be studied. Xia and Zhang [61] reviewed the national development of geothermal power systems. They concluded that the development prospects in China under the current condition are not attractive. Tian and You [62] indicated that the transition from natural gas to geothermal energy for electric power supply can decrease the CO_2 emission by 24.5%. Phillips [63] studied the trade-off balance between the negative environmental impact and positive socioeconomic impact. Santamarta et al. [64] studied the clean energy transition toward shallow geothermal energy. The case study indicates that the transition toward shallow geothermal energy can lead to 66% energy saving, and emissions savings at 256 tCO_2. Tarighaleslami et al. [65] studied sustainable energy transition toward geothermal energy. The comparative analysis indicates that the geothermal-based system shows the lowest carbon emission.

Future studies need to focus on

(1) potential assessment of geothermal energy provided by abandoned wells with machine learning models;
(2) quantifiable roles of abandoned wells in carbon-neutrality transition.

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