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Energy, Sustainability and Society

REVIEW

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Sustainable energy recovery from thermal processes: a review

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Abstract

Background: With the increasing concerns on the energy shortage and carbon emission issues worldwide, sustainable energy recovery from thermal processes is consistently attracting extensive attention. Nowadays, a significant amount of usable thermal energy is wasted and not recovered worldwide every year. Meanwhile, discharging the wasted thermal energy often causes environmental hazards. Significant social and ecological impacts will be achieved if waste thermal energy can be effectively harnessed and reused. Hence, this study aims to provide a comprehensive review on the sustainable energy recovery from thermal processes, contributing to achieving energy security, environmental sustainability, and a low-carbon future.

Main text: To better understand the development of waste thermal energy utilization, this paper reviews the sustainable thermal energy sources and current waste energy recovery technologies, considering both waste heat and cold energy. The main waste heat sources are prime movers, renewable heat energy, and various industrial activities. Different waste heat recovery technologies to produce electricity, heating, and cooling are analyzed based on the types and temperatures of the waste heat sources. The typical purposes for waste heat energy utilization are power generation, spacing cooling, domestic heating, dehumidification, and heat storage. In addition, the performance of different waste heat recovery systems in multigeneration systems is introduced. The cold energy from the liquified natural gas (LNG) regasification process is one of the main waste cold sources. The popular LNG cold energy recovery strategies are power generation, combined cooling and power, air separation, cryogenic CO_2 capture, and cold warehouse. Furthermore, the existing challenges on the waste thermal energy utilization technologies are analyzed. Finally, potential prospects are discussed to provide greater insights for future works on waste thermal energy utilization.

Conclusions: Novel heat utilization materials and advanced heat recovery cycles are the key factors for the development of waste high-temperature energy utilization. Integrated systems with multiply products show significant application potential in waste thermal energy recovery. In addition, thermal energy storage and transportation are essential for the utilization of harnessed waste heat energy. In contrast, the low recovery rate, low utilization efficiency, and inadequate assessment are the main obstacles for the waste cold energy recovery systems.

Highlights

1. Industrial waste heat supply technologies and their exhaust features are reviewed.
2. Waste thermal heat recovery technologies are summarized and reviewed.
3. Thermal cold energy recovery technologies are summarized and reviewed.

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4. Challenges and prospects of sustainable energy recovery are analyzed.

Keywords: Sustainable energy, Waste heat recovery, Waste cold recovery, Multigeneration system, LNG

Background

With increasing concerns on fuel scarcity and environmental deterioration, more and more research attention has been drawn towards enhancing the waste heat recovery performance in industrial thermal processes, thereby improving fuel utilization efficiency [1]. It is reported that around 63% of consumed global primary energy is wasted during fuel combustion and heat transfer processes. Significantly, a major part of the wasted energy is identified as recoverable waste thermal energy [2]. Thus, research on waste thermal energy utilization is urgent and imperative.

The usable waste/renewable thermal heat sources are usually obtained from fuel-driven prime movers, renewable heat energy, data centers, and various industrial activities [3]. Clemens et al. [2] estimated that approximately 246 EJ potential waste heat energy was lost in 2012 worldwide. The distributions of waste heat with different temperatures are illustrated in Fig. 1. It is observed that a large amount of usable waste heat energy with high temperatures is wasted in various sectors. In the industrial sector, Miro et al. [4] illustrated that, in Fig. 2, the industrial waste heat potential and total energy consumption by countries worldwide. Unlike utilizing the waste heat from commercial or residential buildings, recovering the waste heat from industrial activities is more challenging. This is because the industries are usually located far from the consumers, which leads to thermal energy storage and transport issues. Papapetrou et al. [5] further give a provision of the industrial waste heat recovery status. The waste heat generated from various industrial activities, such as steel and chemical industries, is usually stored in thermal storage systems. Subsequently, the stored thermal energy can be utilized to generate electricity, cooling, or domestic heating by employing various waste heat recovery technologies. Sensible and latent heat storage technologies are the typical waste heat storage methods [6]. The working principals of sensible heat storage are to directly increase the storage material's temperature. For example, cold water can be used as a sensible heat storage material. The generated hot water can be employed as a heat source to produce useful heating or cooling. However, it is noteworthy that some heat will be dissipated to the ambient due to unavoidable entropy generation by employing sensible storage technologies. Comparatively, employing phase change materials is the main feature of the latent heat storage technology. It is inevitable that energy loss occurs during the phase-changing process. In

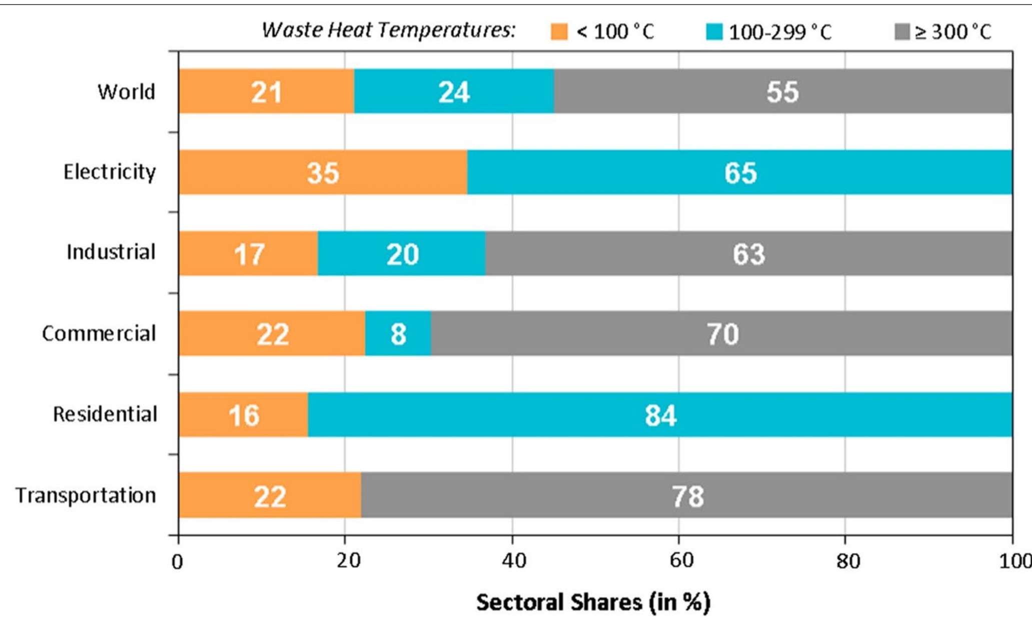

Fig. 1 Distributions of waste heat with different temperatures [2]

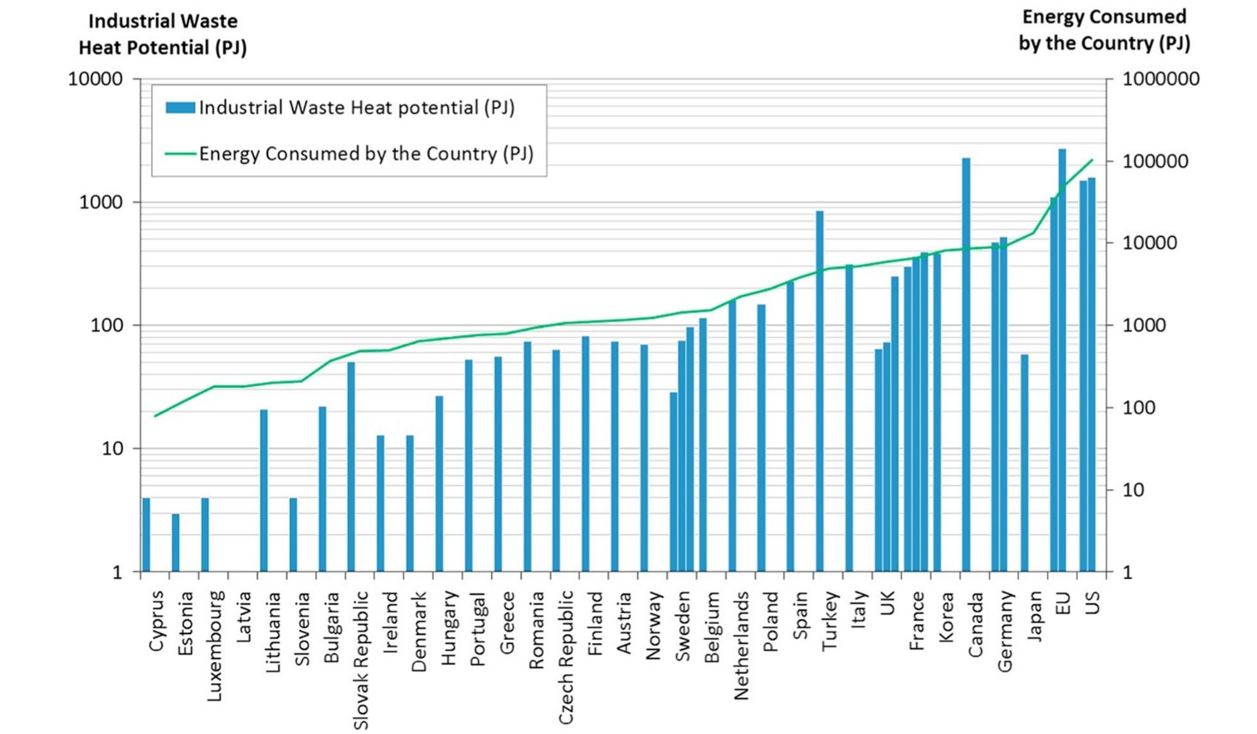

Fig. 2 Industrial waste heat potential worldwide [4]

addition, utilizing some phase change materials is corrosive and may damage the storage equipment [6]. Furthermore, the energy loss during the transportation of heat energy over a long distance is reported to be significant. This is because a major part of heat is dissipated into the ambient when the temperature and distance exceed 300 °C and 10 km, respectively [7]. Therefore, heat loss is unavoidable during the heat storage and transportation processes. The heat loss analysis by employing heat storage system need to be conducted based on the specific application conditions.

Muñoz et al. [8] reviewed multigeneration systems' solar thermal energy utilization statuses. Research shows that an advanced solar integrated combined cycle contributes to improving the system's efficiency. However, the high initial investment of equipment installation and long payback period impedes the development of renewable solar utilization. Furthermore, DeLovato et al. [3] discussed the applications and challenges of harnessing geothermal to improve power plants' efficiency. Their findings indicate that the efficient utilization of renewable geothermal energy is still infant, although it may be a promising technology in the future. There are many existing reviews on industrial activities and renewable thermal utilization. Comparatively, reviews considering both fuel-driven prime movers and their waste heat recovery subsystems in residential and commercial are few and inadequate. However, they are imperative for the development of waste thermal heat energy utilization.

Waste cold energy recovery is another aspect that has raised public interest in recent years. Natural gas is the only fossil fuel rising in the past 10 years and is expected to be the most consumed fossil fuel by 2035 [9], as shown in Fig. 3. It is worthy to note that primary energy comprises commercially traded fuels and excludes traditional biomass. Pipeline and liquified natural gas (LNG) are the two dominating methods to transport natural gas. LNG is first stored at a very low temperature (− 162 °C) which releases a large amount of cold energy (830 kJ/kg) when it is regasified to natural gas. High-quality LNG cold energy is often dumped into the ocean and becomes an environmental hazard if LNG is vapored by the conventional Open Rack Vaporizers (ORVs). The LNG trade has projected a more robust growth than the pipeline trade due to the market flexibility and energy independence issues, as presented in Fig. 4 [10]. In 2010, the total natural gas trade was about 737.7 billion cube meters, and only 41% (338.8 billion cube meters) of the natural gas was traded by the LNG. However, the share of LNG trade exceeded the pipeline trade and occupied about 52% in 2020. According to the current global LNG trade quantity, the available cold energy can potentially reach as high as

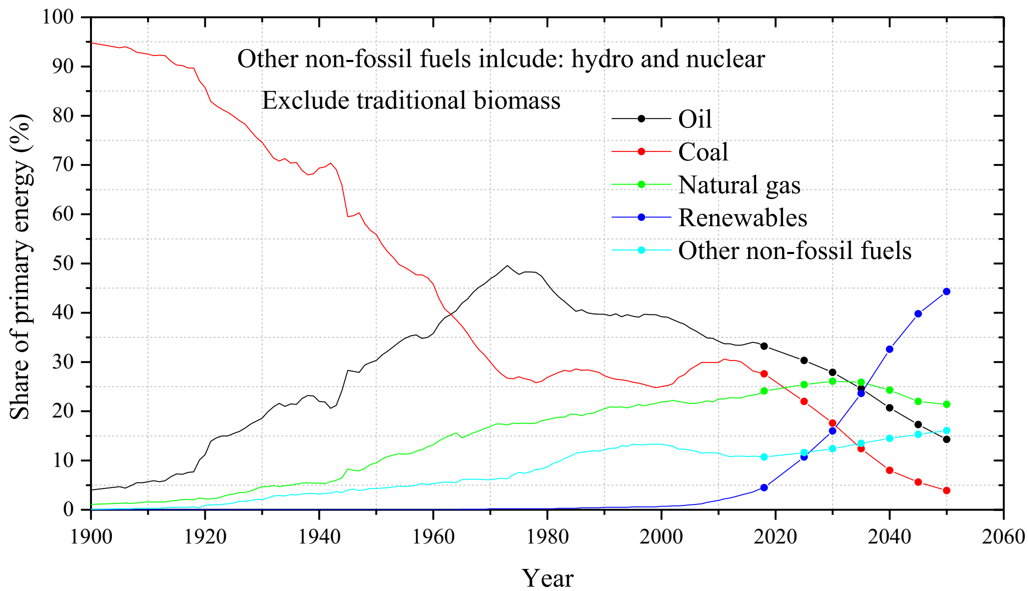

Fig. 3 Share of world primary energy consumption [9]

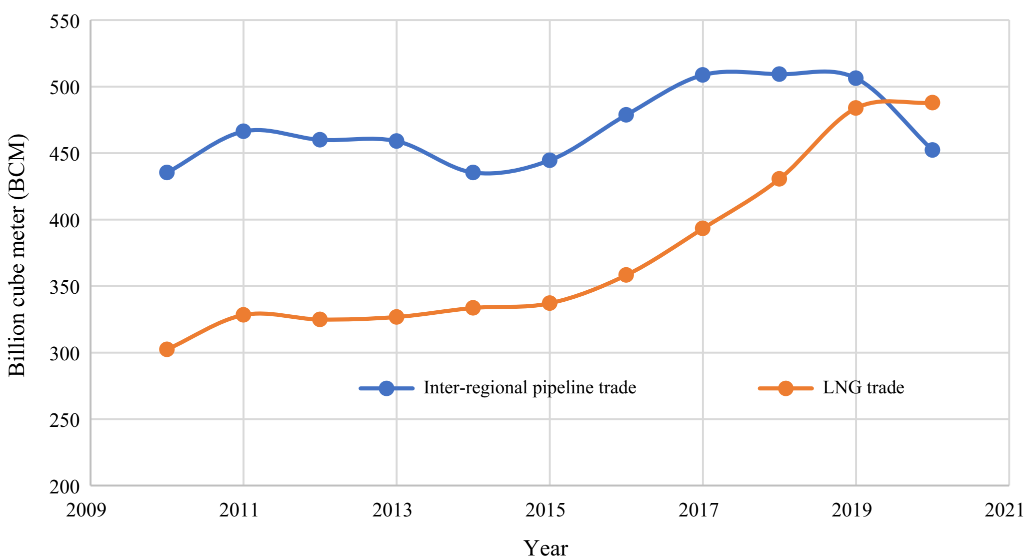

Fig. 4 Variation of LNG trade and pipeline trade in recent years [10]

9211 MW. Hence, recovery of the cold energy during the LNG regasification process is challenging research worthy of being pursued.

The recovery of waste heat and cold energy is equally important as they can contribute to primary energy savings and reduce the hazards being exhausted into the environment. Thus far, a comprehensive review of the current status of both waste heat and cold energy recovery systems is still lacking. Specifically, this paper provides a comprehensive perspective on understanding the existing waste thermal energy recovery technologies, summarizing their current application statutes, and discussing the deficiencies and potential developments. The waste thermal energy sources, including both heat and cold sides, are first briefly introduced. Key waste energy recovery technologies are then reviewed. Subsequently, the existing challenges of the current systems and potential developments are presented and discussed.

Current status on waste thermal energy recovery

Heat energy recovery

In the early 1970s, the severe Middle-East oil crisis had led to a sharp increase in fuel prices in the industry. Thus, the efficient utilization of fuel has overwhelmingly attracted researchers' attention [11]. In addition, with more significant concerns placed on environmental sustainability, recovery energy from dissipated waste heat by fuel-burning processes became a pressing issue. Consequently, significant research efforts have been devoted to the high-efficient utilization of the fuel by recovering the exhausted waste heat energy. At this moment, the utilization of renewable thermal energy at a large scale is still considered at its infancy stage. Comparatively, the prime movers deployed in residential and commercial areas have constantly produced a significant amount of thermal heat energy. The schematic flow chart for various energy recovery technologies is illustrated in Fig. 5.

Prime movers

Prime movers generate electricity or mechanical power while simultaneously producing waste heat. A good understanding of the prime movers contributes to improving waste heat utilization. This is because waste heat recovery processes are primarily aimed to enhance the prime movers' efficiencies. In addition, the temperatures and types of dissipated heat have significant impacts on heat recovery performance. The structures, working principles, and generated heat features of gas turbines, internal combustion engines, Stirling engines, steam turbines, and fuel cells are discussed and presented in this section.

Gas turbine Gas turbines (GT) are deemed one of the cleanest technologies to produce heating and electricity, since their emissions of NO_x and CO_2 are much lower than other commercial combustion-type prime movers. The gas turbine is known to operate based on the Brayton cycle. In the Brayton cycle, atmospheric air is compressed, heated, and mixed with fuel in the combustor. The mixed air and fuel are then burned. The expanded gas is then employed to operate the turbine to generate electricity. Accordingly, the fuel energy is converted to mechanical energy, with electricity generated. The dissipated superheated exhaust can be further exploited to produce heating or cooling. Figure 6 shows the schematic diagram of a gas turbine cum CNG supply system [12]. Firstly, the air is compressed into the combustor and mixed with fuel. The mixed gas is combusted to drive the turbine to generate electricity. Then, the burned gas is used to increase

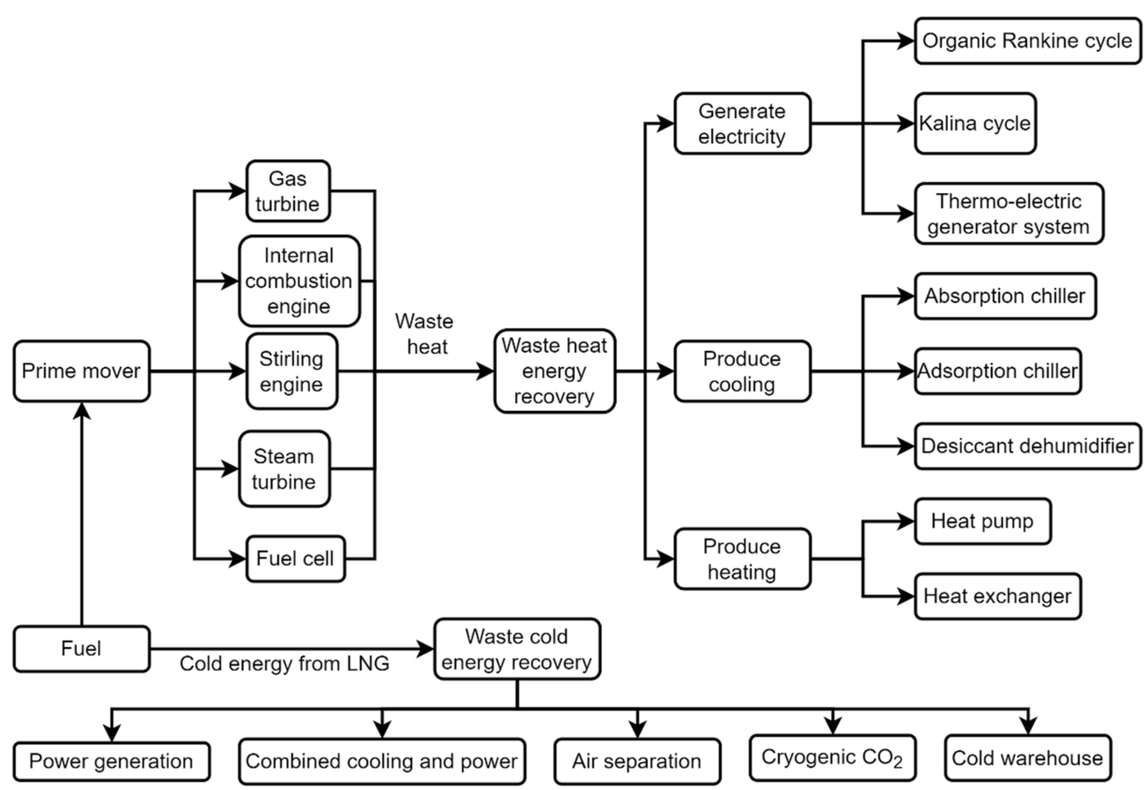

Fig. 5 Flow chart for various energy recovery technologies

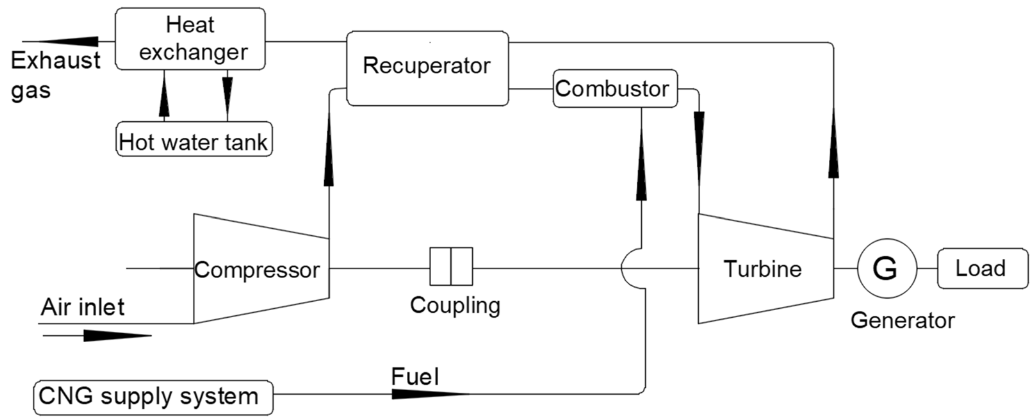

Fig. 6 Schematic of a gas turbine system with CNG supply and heat recovery system

the temperature of compressed air and produce hot water. The exhaust fuel gas is then dissipated into the ambient.

Internal combustion engine

Internal combustion engines (ICE) [13] are the most common form of heat engines. Spark ignition (SI) and compression ignition (CI) are the typical reciprocating engines. Compression ignition engines employ heavy oil and diesel oil as fuel, posing severe emission issues. In contrast, spark ignition uses natural gas as fuel. In the ICE's combustion chamber, the superheat gases expand with high pressure to provide the mechanical energy to generate electricity. At the same time, a heat exchanger is employed to recover the waste heat from the exhaust gas. Figure 7 presents a schematic diagram of an internal combustion engine. The waste heat recovery processes are accomplished by cooling down the oil, water, and exhaust gas. In general, the fuel is burned to produce electricity. The thermal energy from the exhausted gas is harnessed by a heat exchanger to produce hot water. Lube oil heat exchanger and jacket water heat exchanger are employed to recover the waste heat from lube oil and water. Accordingly, the engine is cooled.

Stirling engine A Stirling engine (SE) [14] can cyclically compress and expand the working fluid at different temperatures. Consequently, a net conversion of heat energy to mechanical energy is realized. The working fluid is continuously circulated inside the engines in the closed regenerative Stirling cycle. In other words, the combus-

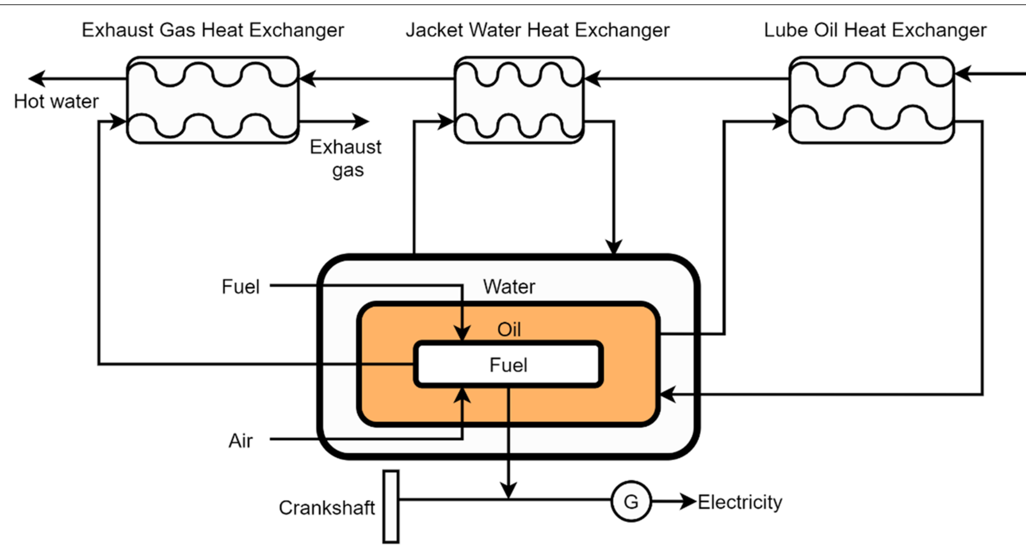

Fig. 7 Schematic of an internal combustion engine

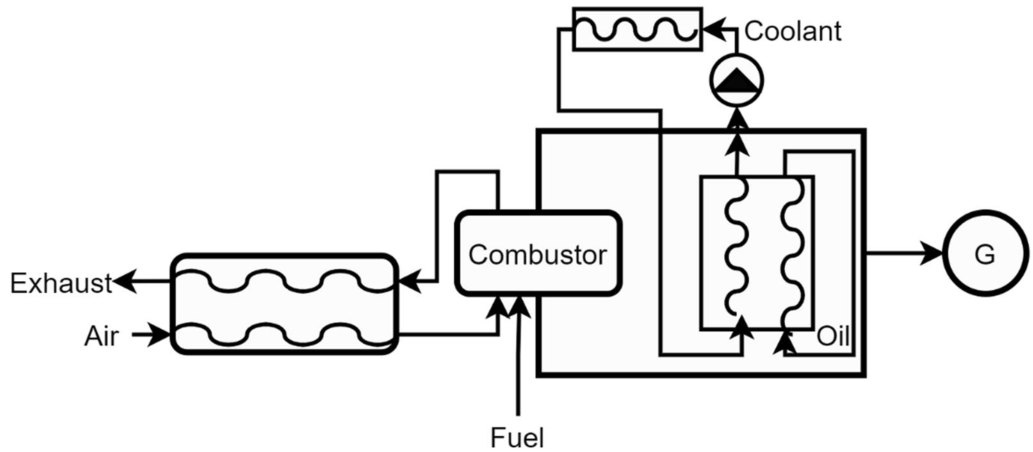

Fig. 8 Schematic of a Stirling engine

tion products do not contact the working fluid or any internal parts. A Stirling engine is able to utilize toxic fuels (landfill gas) as its primary energy source. Figure 8 provides a schematic diagram of a Stirling engine. Accordingly, it consists of a combustor, a generator, and two heat exchangers. One exchanger utilizes the water heat from the exhausted gas. The other one is employing coolant to cool down the Stirling engine.

Steam turbine A steam turbine (ST) [15] utilizes the thermal energy from high-pressure steam to produce mechanical energy. The steam is generated in the boiler and then expanded into the turbine. It provides thermal heat, while electricity is the byproduct of the steam turbine during the steam generation process. Therefore, the steam turbine is also adopted as a recovery subsystem to utilize the waste steam energy to produce electricity. Figure 9 presents the schematic diagrams of two typical steam turbines.

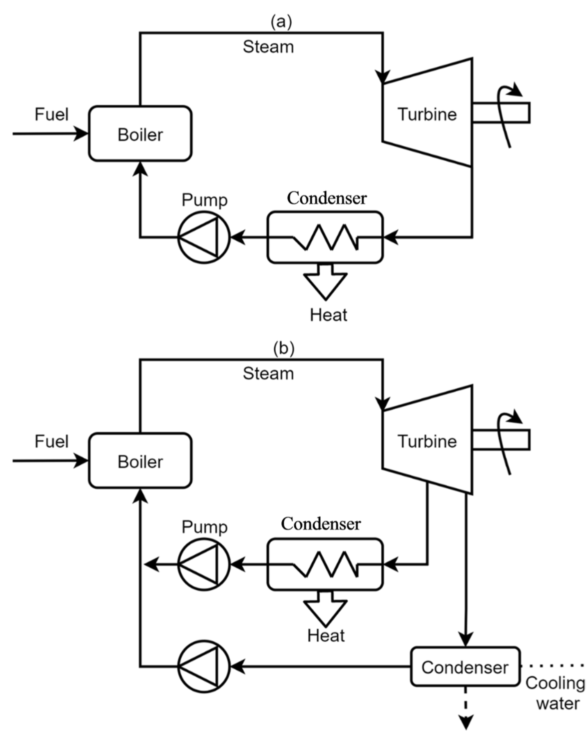

Fig. 9 Schematic diagram of **a** back-pressure steam turbine; **b** extraction-condensing steam turbine

Fuel cell Unlike the traditional combustion method in prime movers, a fuel cell (FC) converts chemical energy into electricity in a different way, along with waste heat generated. William Grove firstly invented a fuel cell in the 1830s [16]. However, the interest in this technology has been relatively subdued for more than one hundred years. It is only recently that the desire for a power system that yields high efficiency while producing low emissions places the FC technologies at the forefront of research. Unlike batteries that provide energy with limited stored energy, the FC system is capable of generating electricity and heat simultaneously. Figure 10 shows the schematic diagram of a fuel cell. Briefly, the fuel and air are fed to the anode and the cathode, respectively. Then, a catalyst at the anode side separates hydrogen molecules into protons and electrons. After that, the electrons move through an external circuit. Consequently, electricity is generated. It is noteworthy that fuel cells usually incorporate the ORC cycle as the bottoming cycle to further improve the electricity generation efficiency [17].

Prime movers are widely deployed for commercial and residential applications. It is observed from the exhaust of most prime movers that the recoverable waste is

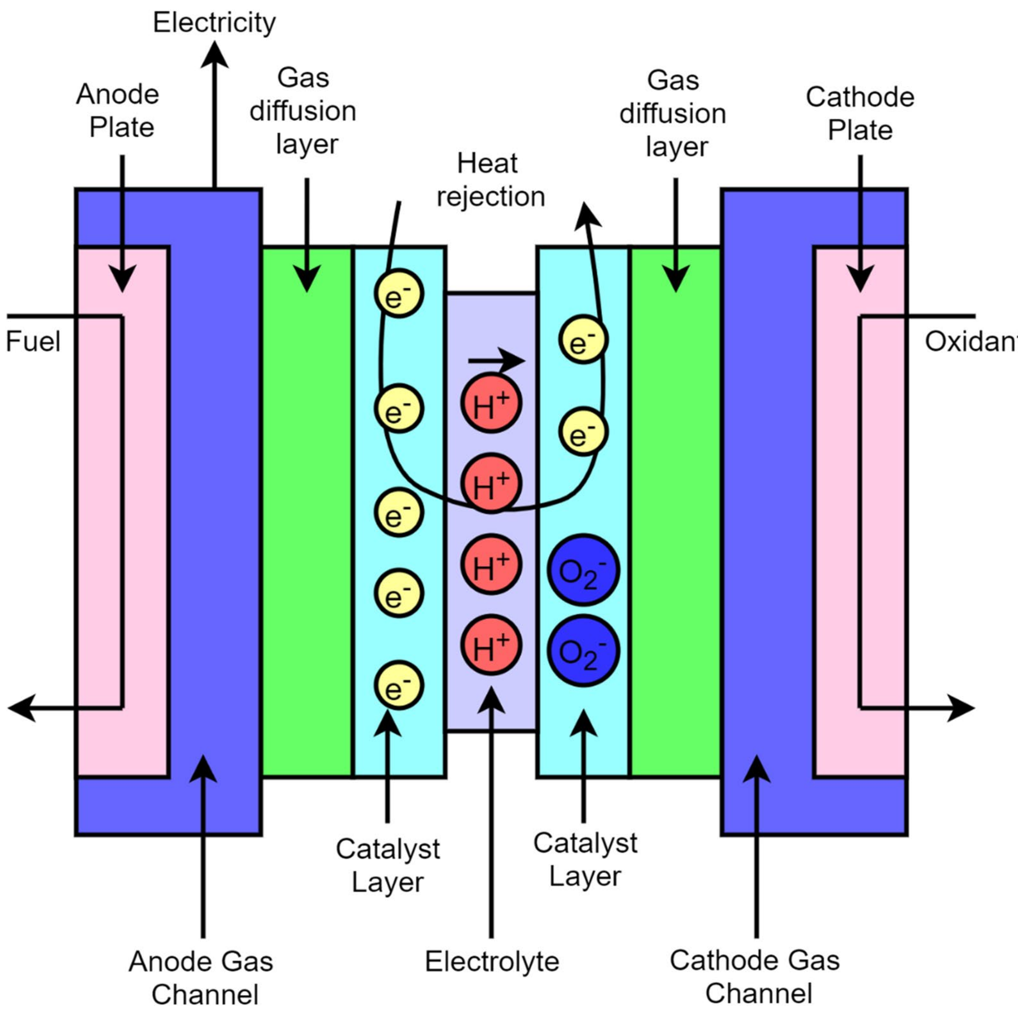

Fig. 10 Schematic diagram of a fuel cell

Table 1 Typical types of different prime movers

	ICE [21]	SE [22]	GT [23]	ST [24]	FC [25]
Capacity (kW)	10–18,000	1–55	500–300,000	100–250,000	5–1400
Electric efficiency (%)	27–41	20–35	22–36	6.27–7.31	35–42.5
Fuel type	NG, biogas, propane	ALL	NG, biogas, propane, oil	All	Hydrogen, NG, propane, methanol
Thermal product	Hot water, low-pressure steam	–	Hot water, low-pressure steam, high-pressure steam	Low-pressure steam, high-pressure steam	Hot water, low-pressure steam, high-pressure steam
Temperature of dissipated heat (°C)	350–648	–	380–550	147–192	371
Exhaust flow (kg/h)	0.5–55	–	67–474	9094–224,285	–
Advantages	Fast start-up	Low noise, maintenance, and vibration	High-quality thermal output	Lifetime is very long (more than 50 years)	Low emission

usually in the form of superheated steam/gas, hot water, or harnessed from solid carriers. An appropriate heat recovery system can be designed and engineered to produce cooling, heating, or electricity based on the quality of waste heat types and temperatures. It is noteworthy that recovering waste heat from supercritical Brayton cycles using CO_2 has gained significant research attention in recent years [18–20]. The typical types of prime movers and their features are listed in Table 1.

Recovering waste heat

The grade of the waste heat must be judiciously considered during the employment of heat recovery technologies. That is because different technologies achieve optimal heat recovery performance at different temperature ranges. Conventionally, the waste heat energy is categorized into (1) low-temperature range (< 100 °C), (2) medium-temperature range (100–300 °C), and (3) high-temperature range (> 300 °C) [2]. In addition, the capacities of the heat recovery system are highly dependent on the quantity of the waste heat and the consumers' demands. Thermal energy storage systems such as heat exchangers or thermal materials are classified as passive heat recovery technologies. In contrast, heat recovery technologies that transfer heat to other forms of energy are labelled as active technologies [26]. Typically, waste heat is recovered to produce cooling and domestic heating simultaneously. However, some heat recovery systems are designed to utilize waste heat to generate electricity.

Recovering waste heat to generate electricity (A) Organic Rankine cycle

An organic working fluid with a low boiling point is employed in the Organic Rankine cycle (ORC) to generate electricity by feeding on the thermal energy from a low-grade waste heat source [27]. Figure 11 shows the schematic and T-s diagram of an ORC. Firstly, the organic working fluid with a low boiling point is pumped into the evaporator. Then, the evaporated working fluid flow through an expander. After that, the working material pass through a condenser and then is condensed. Different working fluids have been employed in ORC, including HCFC123, PF5050, HFC-245fa, HFC245ca, isobutene, and aromatic hydrocarbons [28]. Research has shown that ORCs are able to better recover thermal energy from lower temperature heat sources than the conventional steam Rankine cycle. ORCs are usually installed to harness waste heat from gas turbines, compressor stations, and metal industries. The key impediment of wide-scale ORCs deployment is the long payback period [29].

(b) Kalina cycle

A Kalina cycle (KC) employs ammonia/water as its working fluid pair and utilizes thermal energy to generate electricity. Alexander Kalina invented the Kalina cycle in the 1980s. Figure 12 presents a schematic diagram of the Kalina cycle. The Kalina cycle is basically an improved Rankine cycle. The components of a Kalina cycle include a boiler, a turbine, a distiller, a reheater, an absorber, a condenser, a feed water heater, and a separator. In addition, the Kalina cycle is able to utilize mixed water and ammonia as working fluids. Greater details on the working principle of the Kalina cycle are documented in the literature [31]. Both ORC and Kalina cycles are derived from the basic Rankine cycle. Research results have shown that the Kalina cycle is able to achieve 15–50% more power than the ORC. However, it is worthy to note that the ORC technology is considered a mature technology and has been commercially deployed worldwide. The Kalina cycle is still not commercially deployed [32].

(c) Thermo-electric generator system

A thermoelectric generator (TEG) generates electricity based on the temperature differences between two materials [33]. Figure 13 shows the schematic diagram of a TEG. The main working principle of the thermoelectric generator is converting the heat directly to voltage.

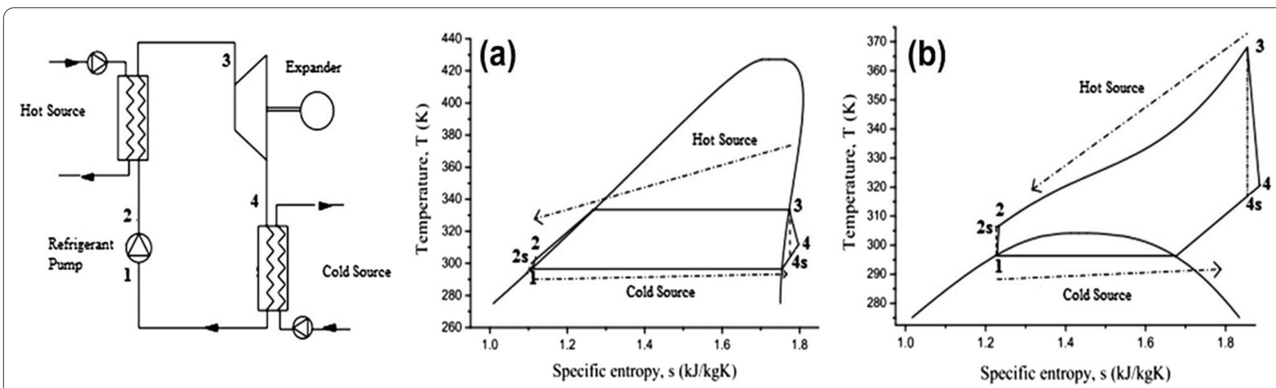

Fig. 11 Schematic diagram of ORC and T-s diagrams **a** subcritical; **b** transcritical [27, 30]

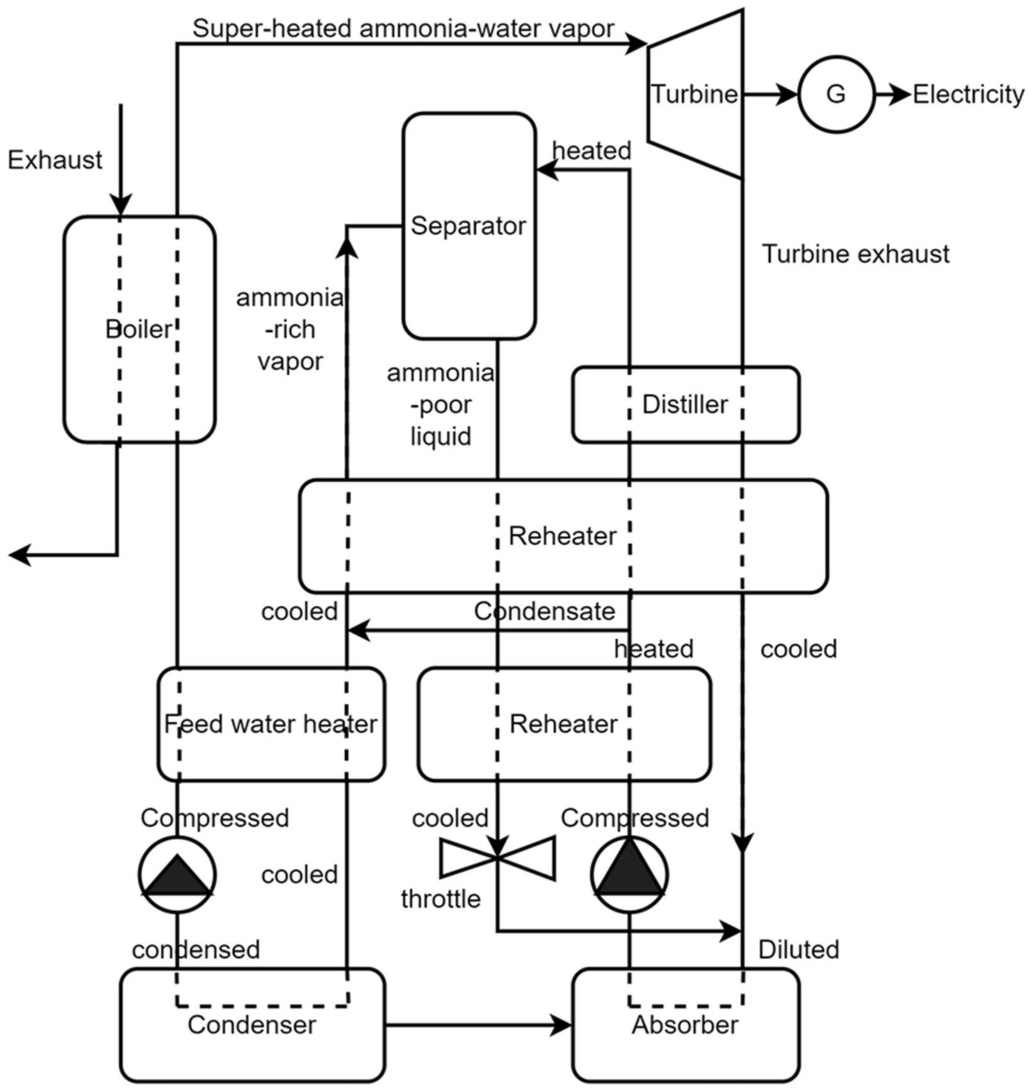

Fig. 12 Schematic diagram of a Kalina cycle

It mainly consists of a heat source, a cool side, and thermoelectric materials. When providing a heat source, the holes and electrons move in a specific direction. Then, the electricity is generated. It is an environmentally friendly technology that does not involve any working fluids or chemical products. In addition, TEGs operate without noise, since they do not have moving parts. It is highly resilient and has a long operating lifetime. In general, the application potential of TEG is significant. For example, it can be used in zero-gravity conditions, deep-sea applications, wearable devices, or other industries.

Recovering waste heat to produce cooling Absorption and adsorption chillers are well-known technologies that are employed to recover waste heat to produce cooling. Solid and liquid desiccant dehumidifiers can utilize waste heat to remove latent load, thereby improving the energy performance in the air-conditioning processes.

(a) Absorption chiller

Absorption chillers are mature commercial heat-driven cooling technology. A schematic diagram of a single-effect absorption chiller is illustrated in Fig. 14. Qg, Qe, Qc, and Qa represent the amount of heat transfer in the generator, evaporator, condenser, and absorber, respectively. LiBr/water and ammonia/water are the common working pairs of absorption chillers. A generator, a condenser, an evaporator, and an absorber are the main components of a single-effect absorption chiller. When the hot water heats the working fluids in the generator, water vapour is then generated and flows into the condenser (7).

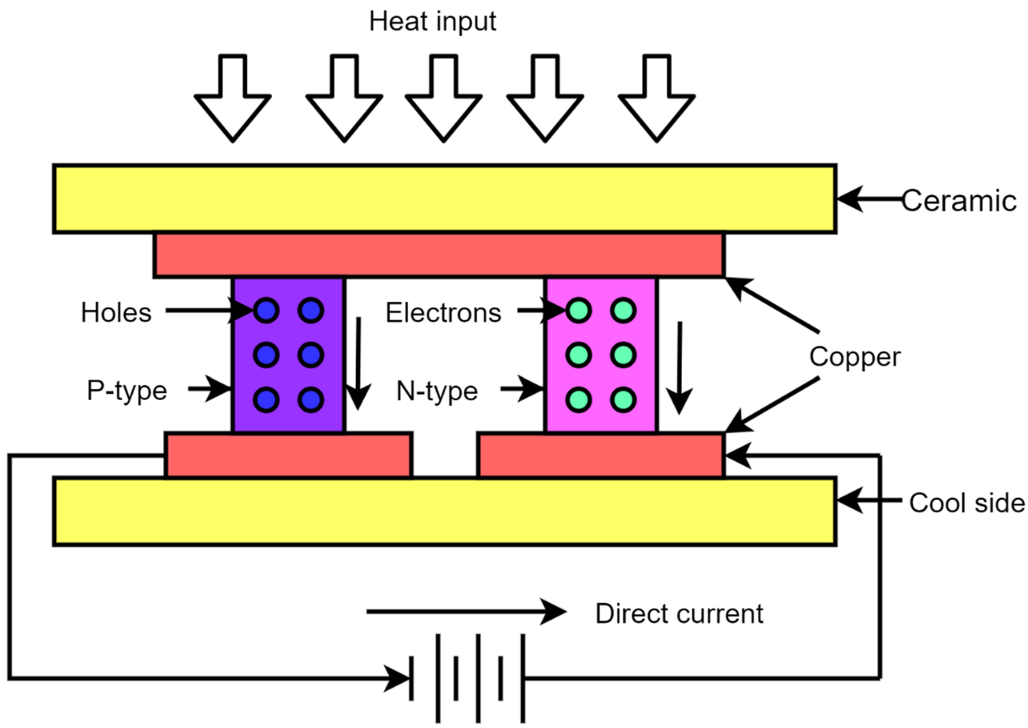

Fig. 13 Schematic diagram of a thermo-electricity system

The generated strong LiBr solution flow into the absorber (4–5–6). The condensed LiBr/water in the condenser is further sprayed into the evaporator by utilizing a throttle valve (8–9). The vapor then constantly flows into the absorber (10). The strong LiBr absorber the vapor and then is pumped into the generator (1–2–3). The chilled water's outlet temperature decreases dramatically, since the sprayed vapour absorbs a significant amount of heat during the evaporation process. Double-effect and triple-effect absorption chillers are also adopted to recover waste heat from the superheated exhaust. Greater details on the working principles and cycle process of the single/double/triple-effect absorption chillers are well documented in the literature [34]. The inlet and outlet temperature ranges of a single-effect absorption chiller are around 85–100 °C and 75–90, respectively.

(b) Adsorption chiller

Adsorption chiller is a promising technology that feeds on waste heat to produce potable and chilled water [30] simultaneously. A schematic diagram of a four-bed two-evaporator adsorption chiller is presented in Fig. 15. The main components of the adsorption chillers are condenser, evaporator, and chambers with desiccant coated heat exchangers. During the adsorption process, beds 3 and 4 are connected to the low-pressure evaporator and high-pressure evaporator, respectively. Consequently, the vapour is able to enter the beds from the evaporators. In contrast, beds 1 and 2 are connected to the condenser so that the vapour can flow into the condenser during the desorption process [35]. There is no vapour flowing from evaporators to beds or from the beds to the condenser during the switching process, because the connecting valves are closed. Unlike absorption chillers that use erosive working pairs, the adsorption chillers typically employ silica gel/vapor or zeolite/vapor as working pairs. Thus, the adsorption chiller does not encounter erosion issues. However, the COP of adsorption chillers is comparatively lower than the absorption chiller due to the silica gel's vapor sorption capacity being lower than LiBr. This limits the wide-scale deployment of the adsorption chillers. The inlet and outlet temperature ranges of an adsorption chiller are around 65–90 °C and 55–80, respectively.

(c) Desiccant dehumidifier

Thermal-driven desiccant dehumidifiers remove moisture from humid air, resulting in a significant energy-saving performance of cooling systems [37]. Figure 16 shows a schematic diagram of a solid desiccant coated heat exchanger dehumidifier system. The solid desiccant dehumidifier includes two chambers. Each chamber has two heat exchangers coated with silica gel (Type RD). The central working principle is the alternation of humidification and dehumidification processes between the desiccant materials at different temperatures. Consequently,

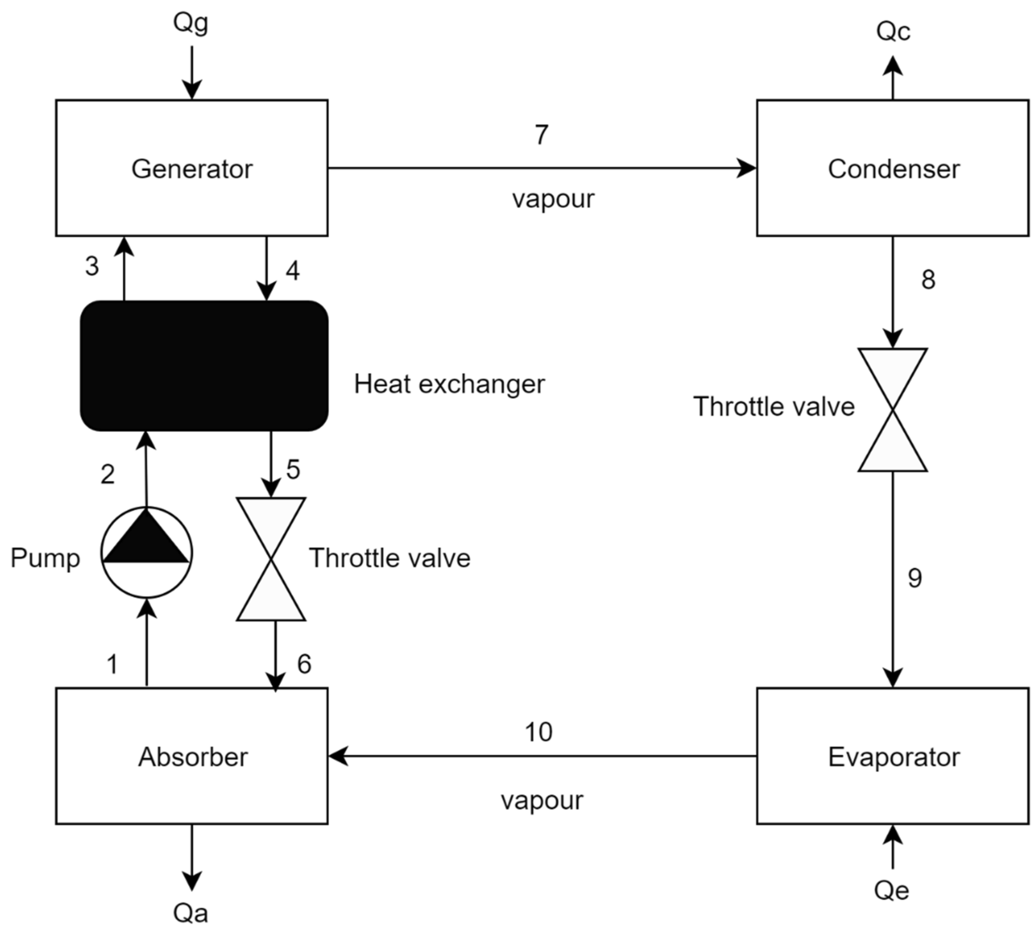

Fig. 14 Schematic diagram of a single-effect absorption chiller

the moisture in the air is removed. The dehumidified air can then be efficiently cooled down with a vapor compression system with lower energy consumption. Figure 17 shows the schematic diagram of the liquid desiccant dehumidifier system. A regenerator and a dehumidifier are the main components of a liquid desiccant dehumidifier. The working principle is the switching of adsorption and desorption processes between liquid desiccant material and vapor. LiCl, $CaCl_2$, and LiBr are the commonly employed liquid desiccant material.

Comparisons between different waste heat recovery technologies and their working conditions are summarized in Table 2.

Recovering waste heat to produce useful heating (a) Heat pump

Both electric heat pumps and sorption heat pumps utilize low-grade waste (hot water, geothermal heat, solar energy) to produce heating [44]. Figure 18 portrays a schematic diagram of a vapor-compression heat pump system. It comprises an evaporator, a compressor, a condenser, and an expansion valve. During the vapor compression cycle, the liquid refrigerant absorbs heat in the evaporator (4–1) and releases heat in the condenser (2–3). The heat from the condenser is used to heat air or water.

Thermal storage systems Thermal storage systems play essential roles in utilizing waste heat [45]. This is because the location of many industries that generate waste heat are sometimes far away from the consumers' location. Therefore, the recovered waste heat needs to be stored and then transported to meet the user's demand. The thermal storage system is likened to a thermal battery and can shift heating and cooling peak loads. Thermal storage systems employ a variety of energy storage materials to store heat energy. Figure 19 depicts the distribution of different energy densities of materials at different temperatures [46]. It is apparent that thermochemical energy storage has the highest energy density. In other words, to recover the same amount of waste thermal energy, the

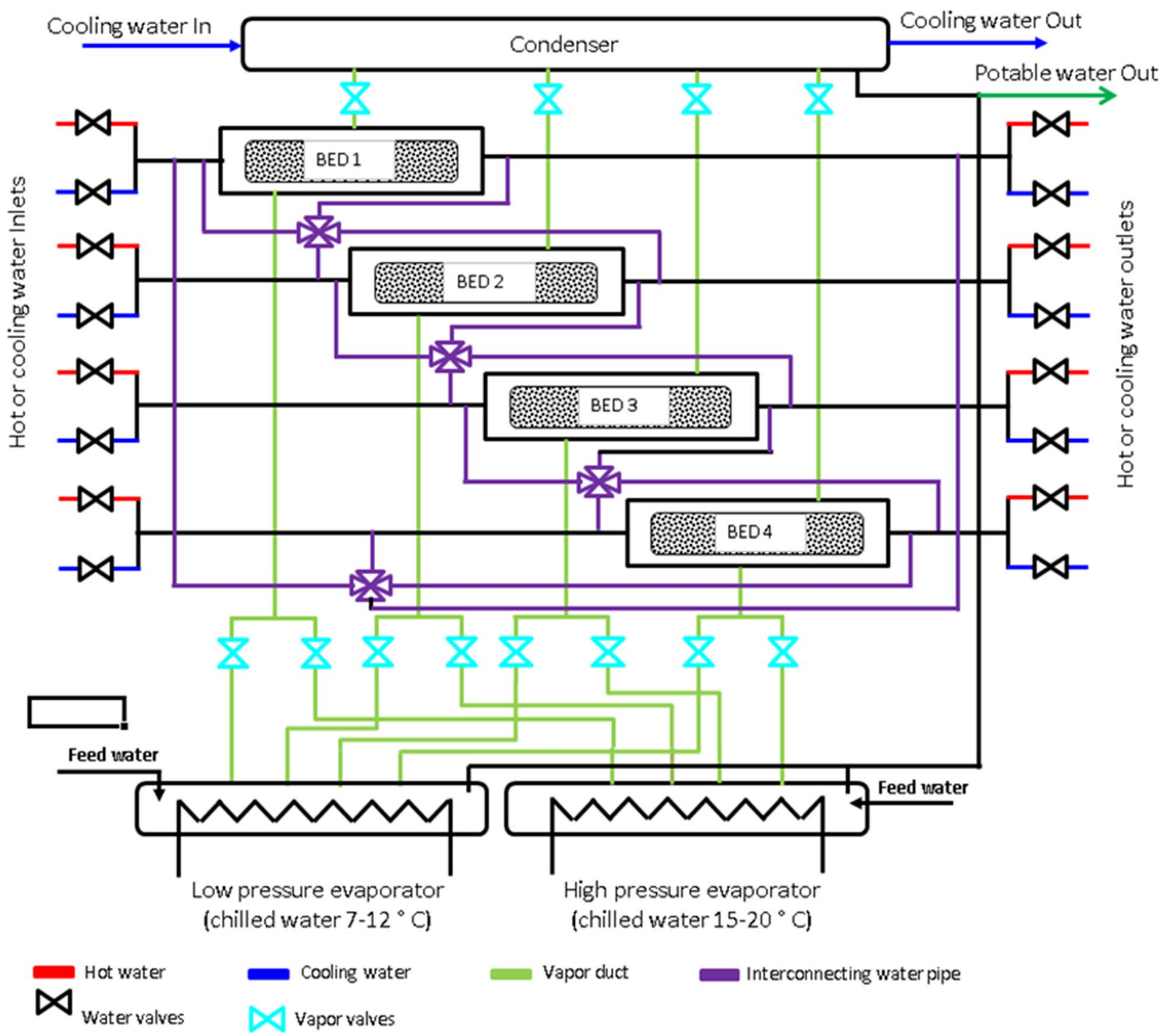

Fig. 15 Schematic diagram of an adsorption chiller [36]

volume required for thermochemical energy storage is the smallest.

System applications on waste heat recovery

In Table 3, the performances and characteristics of different prime movers and waste heat recovery systems are consolidated. Typically, the system integrates a prime mover and a waste heat recovery system, which can produce multiple utilities. It is noteworthy that employing various operating strategies [47] to optimize the thermal energy utilization efficiency [48–50] is not within the scope of this study. It is observed that some waste heat recovery subsystems are purposefully designed to enhance electricity generation performance. In comparison, others are adopted to produce multiple outputs, such as hot water, chilled water, and potable drinking water. Efficient multigeneration systems are known to play key roles in future decentralized energy landscapes. It is noteworthy that renewable electricity typically comes from wind energy, tide energy, and solar energy. Renewable electricity can be utilized to generate Hydrogen [51]. The typical devices for seawater electrolysis to generate hydrogen include (1) Direct seawater electrolyzer (DWE); (2) Proton exchange membrane water electrolyzer (PEMWE); (3) Anion exchange membrane water electrolyzer (AEMWE). The operating temperature for DWE, PEMWE, and AEWME are 20 °C, 58–80 °C, and 40–60 °C, respectively. The temperature of produced

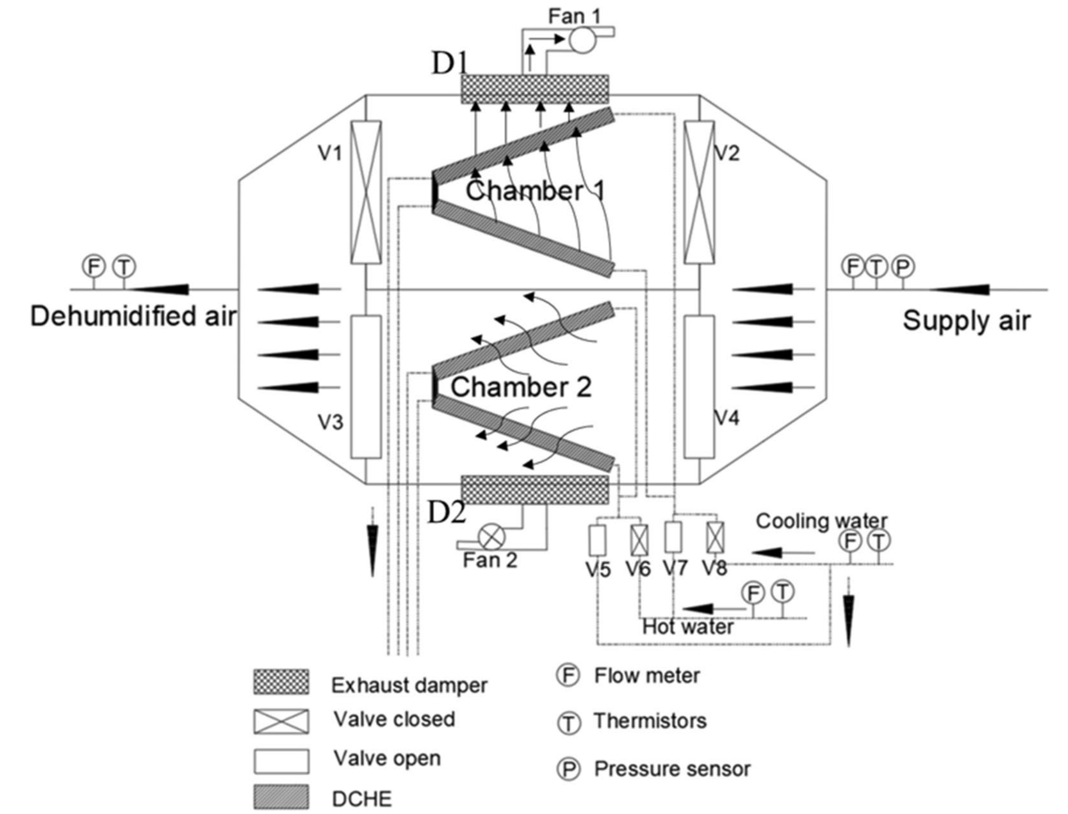

Fig. 16 Schematic diagram of a solid desiccant coated heat exchanger dehumidifier [37]

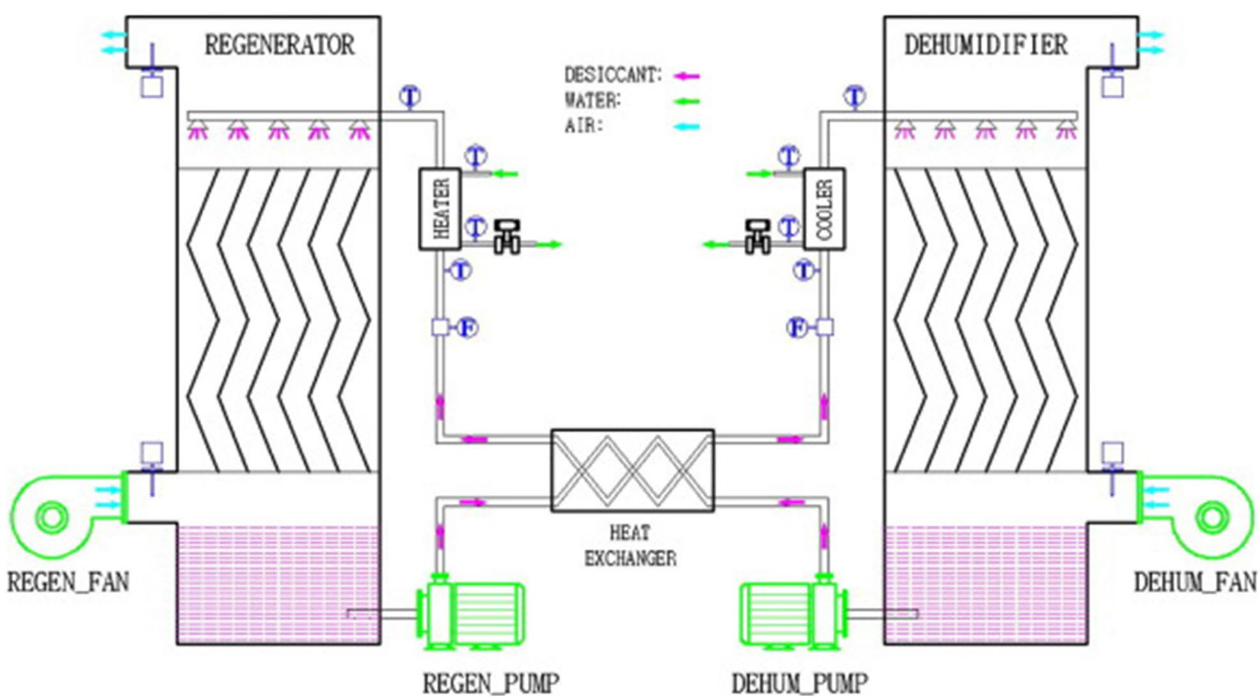

Fig. 17 Schematic diagram of a liquid desiccant dehumidifier [38]

Table 2 Typical working conditions and performance of waste heat recovery technologies

Technology	Working temperature (°C)	Source types	COP (–)	Product
RC [39]	> 400	High-pressure exhaust gas	0.2–0.3	Electricity
ORC [40]	200–450	High-pressure exhaust gas	0.05–0.2	Electricity
KC [31]	200–400	High-pressure exhaust gas	0.08–0.27	Electricity
TEG [33]	50–730	–	0.05–0.08	Electricity
TABC [41]	200–300	Steam or hot water	1.4–1.7	Cooling
DABC [42]	120–270	Steam or hot water	1.0–1.2	Cooling
SABC [41]	80–120	Steam or hot water	0.6–0.8	Cooling
ADC [36]	60–90	Hot water	0.4–0.6	Cooling
AHP [43]	60–240	Steam or hot water	0.4–1.8	Heating
DH [43]	> 60	Condensing heat or hot water	> 0.8	Heating
VCHP [43]	10–30	Condensing heat	3–5	Heating
SDD [37]	50–70	Hot water	0.15–0.3	Dehumidified air

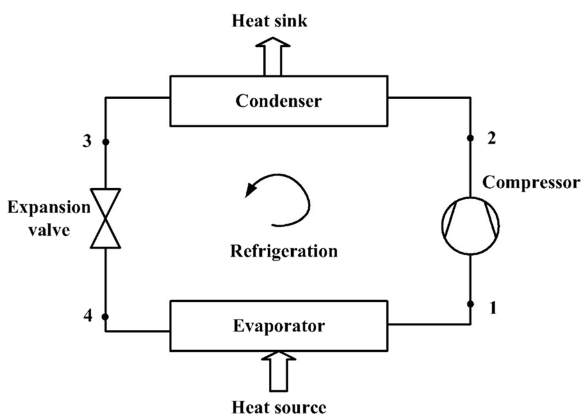

Fig. 18 Schematic diagram of a vapor compression heat pump system [44]

waste heat is low than 100 °C. Thus, part of waste heat can be utilized by absorption chiller, adsorption chiller, or desiccant dehumidifier. Recent reports have indicated that hydrogen generation from renewable means accounts for 5% of the overall global hydrogen produced [52]. In addition, the main applications of renewable produced hydrogen are in the transportation and industry which account for 51% reduction in global CO_2 emission [53].

Cold energy recovery

Current popular LNG cold energy utilization strategies include power generation, combined cooling and power, air separation, cryogenic CO_2 capture, and cold warehouse provision. A list of cold energy recovery technologies is provided in Table 4. For power generation units, the LNG cold energy is often employed as the heat sink for the power generation cycle. In other cases, the LNG cold energy is directly converted to cooling effects. These applications' progress and challenges are reviewed and analyzed in detail in the ensuing sections.

Power generation

Power generation is one of the most favoured LNG cold energy utilization methods, since electricity can be delivered efficiently by power line. Based on Japan's commissioned LNG cold energy utilization facilities, about 76% of them are power generation [66]. The commonly adopted power generation technologies are the Rankine cycle (RC), direct expansion (DE), and combined cycle (RC + DE) [67]. The schematic diagram of a combined cycle is illustrated in Fig. 20. LNG is pumped to a pressure that is higher than the distribution network. The high-pressure LNG firstly becomes the heat sink for the Rankine cycle and then expands in the direct expansion turbine. Seawater is often adopted to be the heat source, since the receiving terminal is usually adjacent to the port area. Liquid with low boiling and freezing points, such as propane, is a good working medium of the Rankine cycle [68]. It is worthy to note that the power output of the direct expansion unit deteriorates for increasing distribution pressure due to a lower expansion ratio. Hence, the direct expansion unit is rarely adopted when the distribution pressure is more than 2 MPa [67]. Even when a combined cycle configuration is employed, the cold energy utilization efficiencies are still low. According to the performance of several commissioned plants, most systems' exergy efficiency spans 10–20% [67].

Some improved configurations have been proposed to improve the cold energy utilization efficiency. Sun et al. [69] compared the two-stage Rankine cycle-based systems with the single-stage Rankine cycle-based system in harnessing cold energy for power generation. They

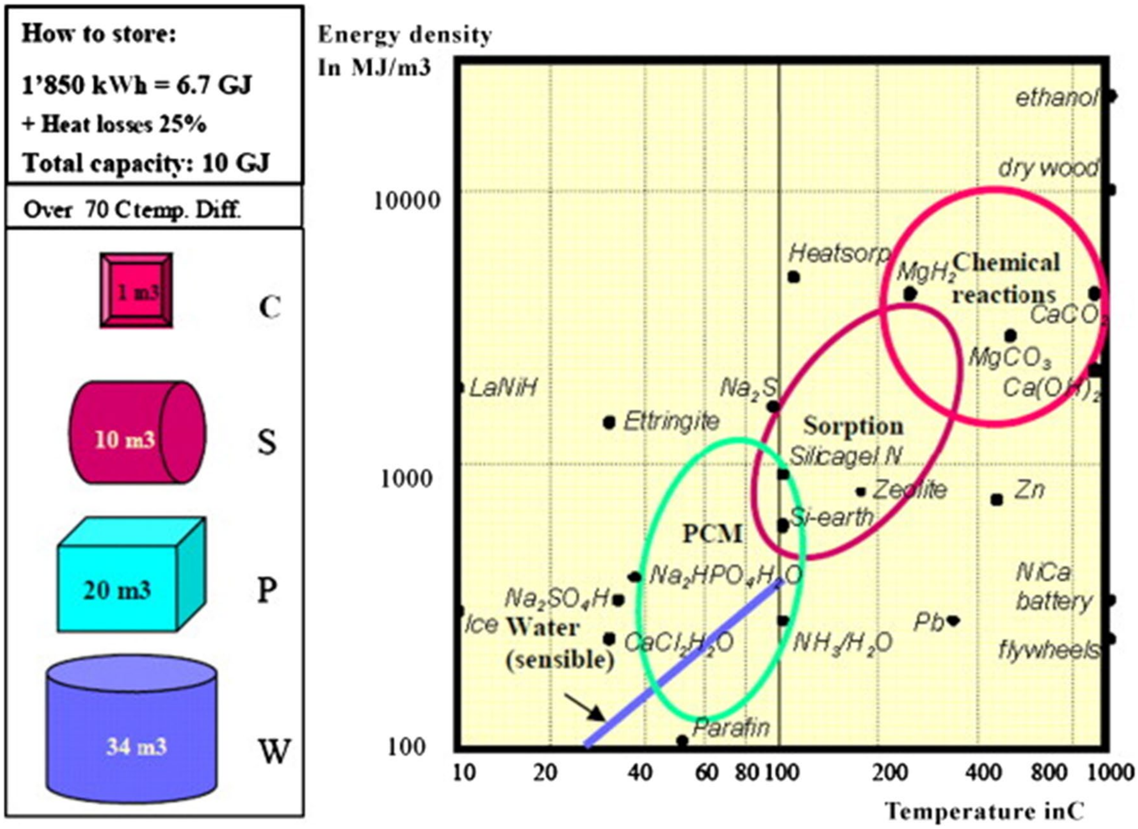

Fig. 19 Distributions of energy storage materials and their energy density at different temperatures [46]

observed that the two-stage Rankine cycle system always achieved a higher exergy efficiency due to better thermal matching between the heat source and working mediums. In addition, the cascade two-stage Rankine cycle system performs better than the parallel system when the heat source temperature is above 100 °C. Atienza-Márquez et al. [70] proposed a three-stage Rankine cycle-based LNG cold energy utilization system. They reported that the exergy efficiency of the proposed system is capable of reaching as high as 34.7%. Establishing a better thermal matching between the cold or heat source and working mediums is the key to achieving efficiency improvement. However, it should be noted that as the stage of the Rankine cycle increases, the system configuration becomes more complicated. This may lead to poorer economic viability and system reliability. In addition, the Brayton cycle [71], Kalina cycle [72], and Stirling cycle [73] have also been proposed to generate electricity by harnessing the LNG cold energy in recent years.

Combined cooling and power

Besides increasing the number of stages of the Rankine cycle, combined cooling and power (CCP) is another strategy to improve the LNG cold energy utilization efficiency. The schematic diagram of the CCP system for LNG cold energy utilization is illustrated in Fig. 21. After power generation, the LNG still contains a considerable amount of cold energy. In addition, the evaporator of the cryogenic power generation cycle is also a potential cold source. It is, therefore, intuitive to continue to harness the remaining cold energy to supply cooling effects. Ning et al. [74] proposed a CCP system to utilize the cold energy from the LNG regasification process. The system continued to recover the LNG cold energy after the Rankine cycle and direct expansion unit for air conditioning. Li et al. [75] designed an ammonia–water absorption refrigeration/power system to utilize LNG cold energy. The absorption cycle produced not only electricity but also cooling effects. Chilled water was produced from the absorption cycle's evaporator, generator, and absorber. The comprehensive energy utilization efficiency for such a system was capable of reaching as high as 81.63%. Atienza-Márquezet et al. [76] proposed a CCP system to recover the LNG cold energy. The LNG cold energy was temporarily stored using the CO_2 and then distributed to a district cooling network. Subsequently, the LNG cold

Table 3 Combined systems designed to recover waste heat energy

System(s)	A: Experimental analysis; B: Simulation analysis	Feature(s)	Product(s)
ICE + ORC + KC [13]	Coupled (A & B)	1. The combined cycle's efficiency was 0.21; 2. Two different working fluids were considered	Electricity
ICE + PERC + ORC + LNG [54]	B	1. Six kinds of PRC working fluids were discussed; 2. PERC's exergoeconomic performance was better than the ORC and LNG system	Electricity and hot water
GT + SAB + EC + PT [55]	B	1. An optimal CCHP design was proposed; 2. Eight different application cases were employed to test the proposed system	Electricity, hot water, chilled water, and cool air
ABC + transcritical CO_2 cycle [56]	B	1. The proposed system aimed to recover waste heat at 90–150 °C; 2. Two optimization strategies were employed to investigate optimal design	Electricity, chilled water
ICE + QLC + ABC + CRS [57]	B	1. The proposed novel trigeneration system included QLC system; 2. Parametric analysis of the proposed system was also performed	Electricity, hot water, chilled water
A cascade ABC system [58]	B	1. The proposed system consisted of an NH_3–H_2O and LiBr–H_2O systems; 2. Maximum exergy efficiency was 0.23	Chilled water
A cascade ADC system [59]	B	1. Five kinds of working pairs of the system were considered; 2. Maximum COP was 0.08	Chilled water
A cascade LDD system [60]	B	1. 92.29% energy could be saved by employing the proposed system; 2. Payback period of the proposed system was 3.39 years	Dehumidified air
A cascade AHP system [61]	Coupled (A & B)	1. Utilize waste hot water at 45 °C; 2. Heating COP was 1.77	Hot water
ICE + ABC + ORC [62]	B	1. The model was developed based on MATLAB/SIMULINK platform; 2. Off-design performance of the proposed system was also discussed	Electricity, hot water, chilled water
A cascade absorption–compression system [63]	B	1. The proposed system was able to produce chilled water at -60 °C; 2. COP of the proposed system was 0.277	Chilled water
KC + ABC [64]	B	1. A multi-objective optimization of the proposed system was investigated; 2. Life cycle time of the proposed system was assessed	Electricity, chilled water
GT + ABC + ADC [65]	Coupled (A & B)	1. The proposed system was able to produce potable water; 2. Cooling COP of the proposed ABC–ADC system was 0.59	Electricity, hot water, chilled water, and potable water

energy becomes the heat sink for the low-temperature Rankine cycle to produce electricity. According to their calculations, the exergy and energy efficiencies of the system approached 40% and 64%, respectively.

Despite many multigeneration systems having reported higher efficiency, most studies often do not consider the downstream users and their demand scenarios. In other words, the performance of these systems is only evaluated from the system perspective. Energy mismatching occurs if the LNG regasification rate is not judiciously synchronized with the cooling demands. Accordingly, the energy mismatch between cold energy recovery systems and users is the underlying problem that needs to be properly addressed.

Air separation

Air separation is one of the energy-intensive industries. The atmosphere air is first compressed and cooled to a

Table 4 Summary of popular LNG cold energy utilization technologies

References	System types	Configurations	Function of LNG
[66]	Power generation	RC + DE	Heat sink and expansion
[69]		Two-stage RC + DE	Heat sink and expansion
[70]		Three-stage RC + DE	Heat sink and expansion
[71]		Brayton cycle	Heat sink
[72]		Kalina cycle	Heat sink
[73]		Stirling cycle	Heat sink
[74]	Combined cooling and power	RCs + DE	Heat sink, expansion, and cool down working mediums
[75]		Absorption refrigeration/power + DE	Heat sink and expansion
[76]		RCs + DE	Heat sink, expansion, and cool down working mediums
[77]	Air separation	Two distillation columns	Precool inlet air
[78]		Single distillation column	Precool inlet air
[79]		Three distillation columns	Precool inlet air
[71, 81, 82]	Cryogenic CO_2 capture	–	Cool down CO_2
[85–87]	Cold warehouse	–	Cool down working mediums

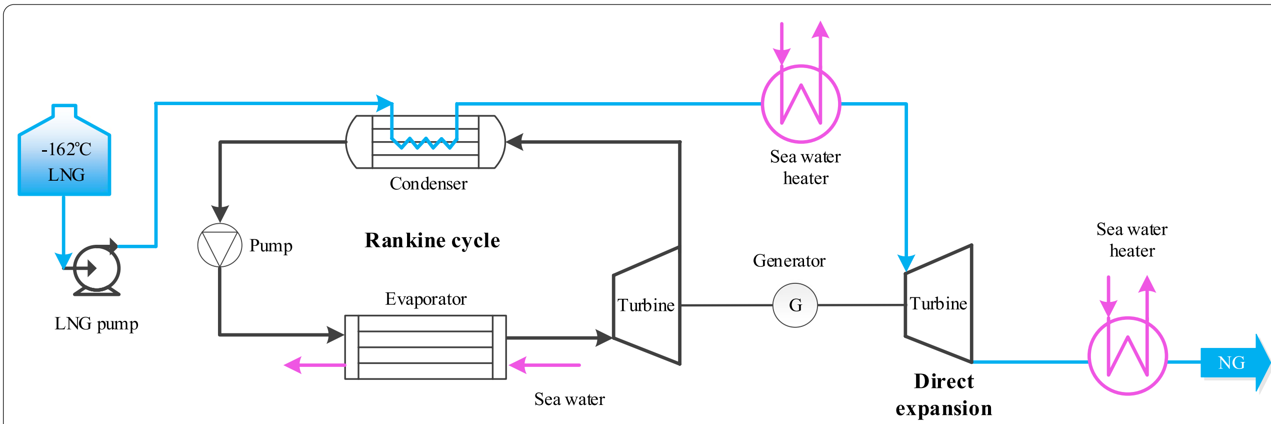

Fig. 20 Schematic diagram of the combined cycle for LNG cold energy utilization

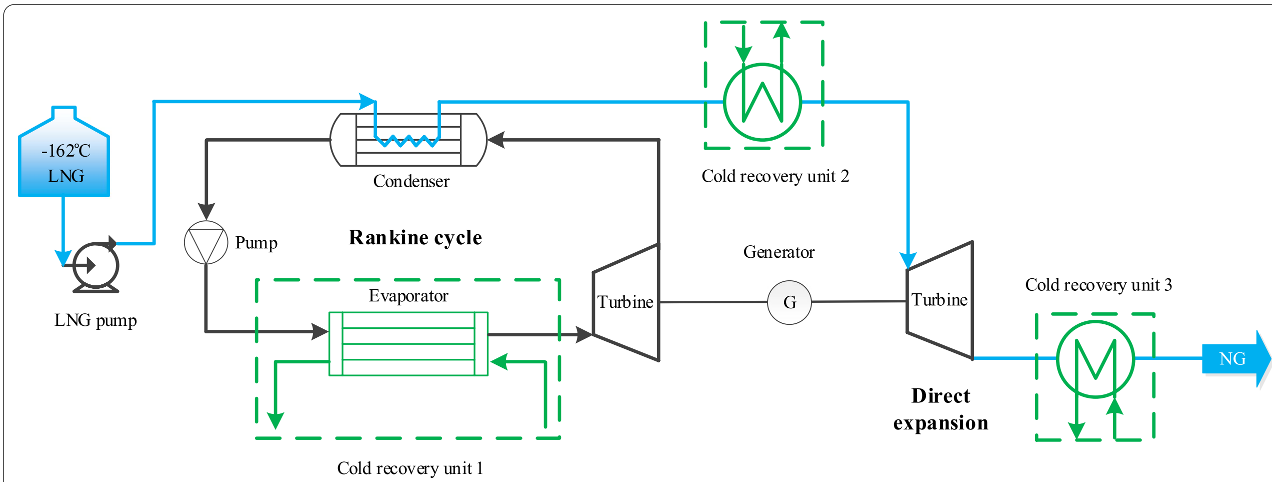

Fig. 21 Schematic diagram of combined cooling and power system for LNG cold energy utilization

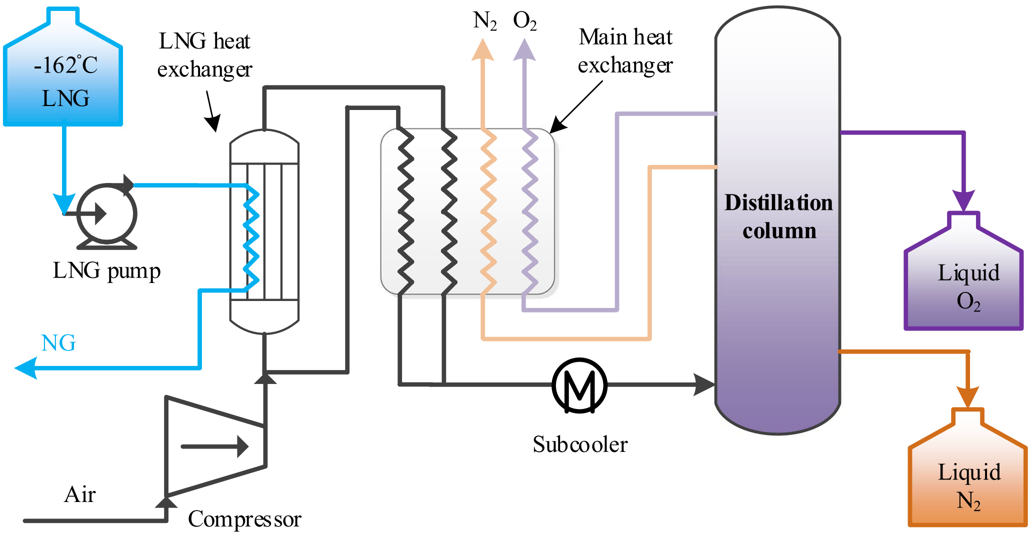

Fig. 22 Schematic diagram of the air separation incorporating LNG cold energy utilization

liquid state. Then, the liquified air is sent to the distillation column to separate nitrogen, oxygen, etc. During the liquefication process, a large amount of electricity is used to drive the external refrigeration cycle and generate cooling effects. Replacing the external refrigeration system with the LNG cold energy refrigerating process is an excellent option to reduce electricity consumption. The basic principle behind the air separation process employing the LNG cold energy is shown in Fig. 22. The electricity demand of the electric chiller is significantly reduced because of the use of LNG cold energy for air pre-cooling. Chen et al. [77] investigated the novel coupling of two distillation columns with the LNG cold energy for air separation. The electricity consumption of producing vapour oxygen was reported to be about 72% less than the conventional air separation unit (without LNG cold utilization). Han et al. [78] designed a single distillation column air separation system. Four different schemes were compared while incorporating LNG cold energy. Their results revealed that the proposed system cut 66% energy consumption compared to the traditional air separation process (without LNG cold utilization). Wu et al. [79] proposed a three distillation columns air separation system. In this system, the LNG cold energy cooled down circulating nitrogen in a cascade manner. Although the power consumption is marginally higher than the system designed by Chen and co-workers [77], the power consumption is still lowered by 54% with respect to the system without LNG cold energy utilization as far as the production of liquid oxygen is concerned.

In comparison to pure power generation, the air separation process is a more efficient way to utilize LNG cold energy. This is because the LNG cold exergy has been directly passed to the working mediums with similar low temperature. However, two key points have to be carefully considered before its adoption: (1) the air separation plant has to be close to the receiving terminal as the LNG is not suited to experience long-distance transportation; and (2) the safety aspects of air separation plant may be compromised as LNG is a flammable medium. But the second issue can be resolved by employing intermediate working mediums, such as nitrogen, to transport the cold energy. All in, both economic viability and safety impact must be seriously considered.

Cryogenic CO_2 capture

Excess CO_2 emission is recognized as another urgent matter that needs addressing as it markedly impacts global warming and climate change. Carbon dioxide capture and storage (CCS) is an important process to reduce excess CO_2 emission [80]. Typically, CCS involves three steps: capture, transportation, and storage. For the first step, cryogenic carbon dioxide capture is considered to be one of the popular methods for implementation. This method employs cold energy that is often generated by the external refrigeration cycle to condense CO_2 from fuel gas. However, the major barrier that deters the development of cryogenic CO_2 capture is its high-energy consumption. Incorporating LNG cold energy into this process will significantly reduce energy consumption. A schematic diagram of the cryogenic CO_2 capture process using LNG cold energy in a combined cycle gas turbine (CCGT) plant is shown in Fig. 23. The fuel gas exhausted from the plant is cooled down by the LNG cold energy

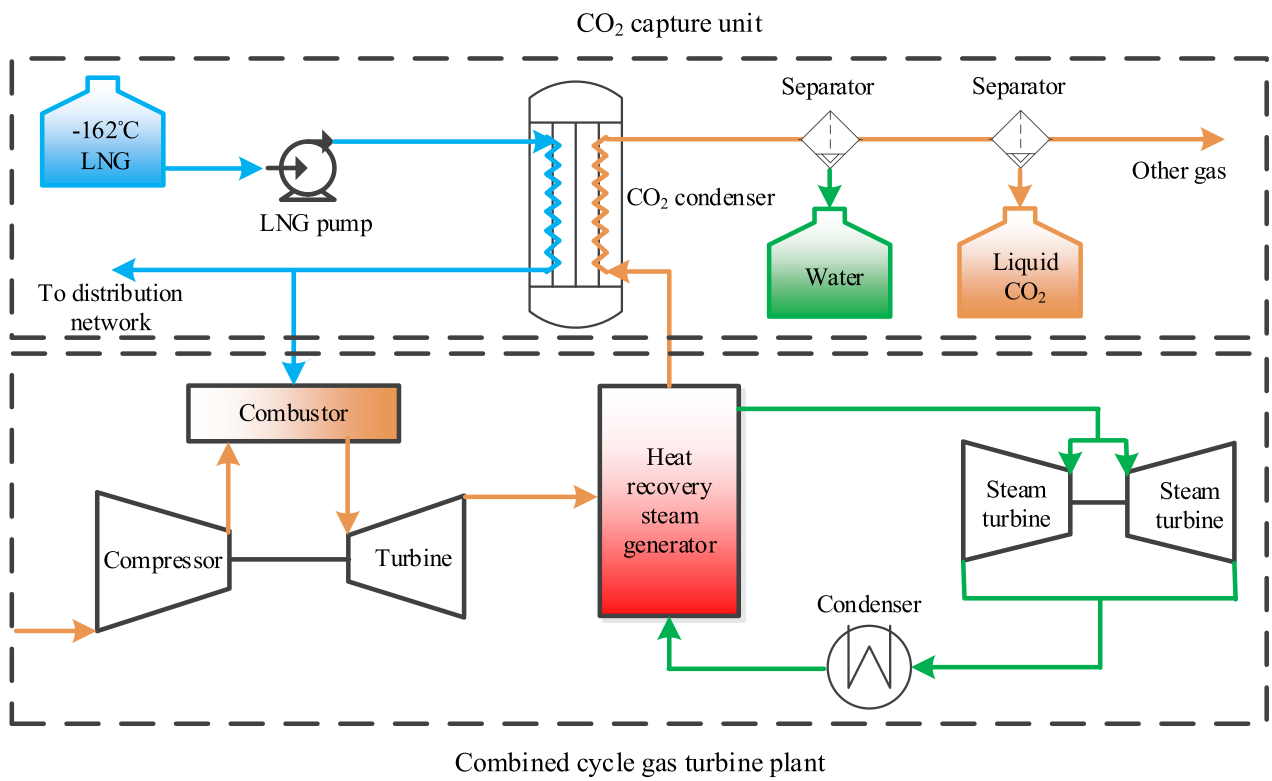

Fig. 23 Schematic diagram of CO_2 capture in CCGT plant

to separate CO_2. The heated natural gas is then sent to the gas turbine or distribution network. One key disadvantage of the method is that it causes relatively large exergy destruction, since the high-quality LNG cold energy is directly converted to liquid CO_2. Zhao et al. [81] designed a combined power and cooling system to capture CO_2 from the fuel gas of a magnesium processing plant. This system employed a set of evaporators from a parallel cryogenic Rankine cycle to cool down the compressed fuel gas. The LNG cold energy played the role of a heat sink for the two Rankine cycles. Consequently, this system can produce electricity and liquid CO_2, operating with an exergy efficiency of about 57%. Goomez et al. [71] proposed a closed Brayton cycle-based system to capture CO_2 from fuel gas. Similarly, the LNG cold energy first act as a heat sink for the Brayton cycle. It then cooled down the fuel gas to capture CO_2. Pan et al. [82] combined a Kalina cycle and an organic Rankine cycle system to capture CO_2 from the fuel gas generated from solid oxide fuel cells and gas turbine (SOFC/GT) plant. The fuel gas forms the heat source, while the LNG cold energy constitutes the cold source for both cycles. After circulating through the two cycles, the LNG cold energy condenses the CO_2 from the fuel gas.

The electricity consumption for cryogenic CO_2 capture is reduced by harnessing the LNG cold energy. However, for a LNG fueled thermal power plant, the LNG cold energy from the power plant itself is insufficient to fully condense the fuel gas. For example, the natural gas mass flow is only about 13 kg/s while the fuel gas mass flow rate approaches as high as 621 kg/s in the CCGT plant [83]. This is attributed to the fact that the fuel gas contains a large portion of non-condensed gas, such as nitrogen and oxygen.

Cold warehouse

Cold warehouses are used to preserve food and are considered to be an important infrastructure in the food supply chain. The required storage temperature varies as it depends on the types of foods. For example, the general temperature for frozen storage is − 18 °C [84]. Some seafood, such as tuna, require storage temperature as low as − 60 °C. Hence, a considerable amount of electricity is consumed to maintain the low-temperature operation. Cold warehouses are usually located in the vicinity of the port area to meet import/export requirements. It is, therefore, possible to incorporate the LNG cold energy to support its operation. A three-stage cooling system using R23 as a working fluid to recover LNG cold energy

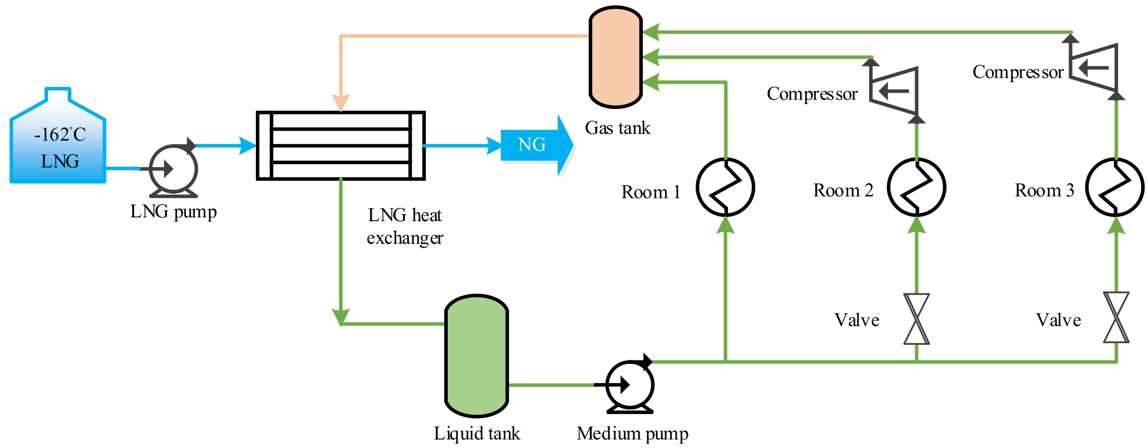

Fig. 24 Schematic diagram of the LNG cold energy utilization in a cold warehouse [85]

was proposed by Li et al. [85]. The schematic diagram of the system is illustrated in Fig. 24. The working medium directly absorbed the cold energy from the LNG. This system was able to provide the cooling effects at different temperature levels (−15 °C, −30 °C, and −60 °C). Messineo et al. [86] presented a case study on utilizing the LNG cold energy for the agro-food industry. The cold energy from the LNG regasification process was recovered and carried by CO_2 to meet users' cooling demand. La Rocca et al. [87] designed a system that utilized the LNG cold energy for hypermarkets. The recovered cold energy is employed to meet cooling needs from various sectors, including air conditioning, display cabinets, and the foodstuffs preparation process. Two main challenges exist, including the location restriction of users and low efficiency. The cold warehouse ought to be constructed adjacent to the receiving terminal, since the cold energy is not appropriate to experience long-distance transportation. In addition, the exergy destruction is significant when the high-quality LNG cold energy is directly converted to shallow cooling effects.

Challenges and prospects for waste thermal energy recovery

Challenges and prospects for heat energy recovery

Financial and governmental policy

Although the importance of recovering waste heat has been emphasized, it is reported that a considerable amount of waste heat is still dissipated directly into the atmosphere [1]. One potential reason is that the payback period of deploying a waste heat recovery system is too long. This is because of a financial burden on the industry investment. That is because the initial installation investment to recover waste heat is enormous. Furthermore, their energy efficiency is relatively low when compared with conventional methods. In addition, it is challenging to realize wide-scale waste heat recovery applications without governmental support policies and stable carbon trading markets.

Heat energy storage and transportation

Industries, which produce a large amount of waste heat, are sometimes far away from the consumers. Thus, the storage and transport of thermal energy have become hot research topics in waste heat energy utilization. In addition, even when the waste heat generation site is close to the consumers, a heat thermal energy storage system has to be relied on to store the thermal energy. This is because the consumer's demands frequently fluctuate, making it challenging to utilize waste heat efficiently. Therefore, initial financial investment for thermal heat storage and transport leads to more significant deployment difficulties for waste heat recovery systems.

Improvement of waste heat recovery technologies

Although many waste heat recovery technologies have been proposed, experimentally tested, and commercially deployed, significant shortages of waste heat recovery systems exist. For example, the start-up time of thermal-driven adsorption and absorption chiller is much longer than electric chillers. In addition, the sizes of thermal-driven equipment are comparatively larger than their electric-driven counterparts. As a result, the promotion and application of thermal-driven waste heat recovery systems are challenging.

Prospects on waste heat recovery

(1) Development of advanced materials may contribute to improving the efficiencies of waste heat recovery technologies. For example, the development of more advanced

adsorbent materials promotes the efficiencies of adsorption chillers and solid/liquid desiccant dehumidifiers;

(2) Better thermal storage materials are also key to achieving a low-carbon future [1]. That is because better-performing thermal storage technology not only balances well the load matching between supply and demand but also stables the energy supply considering the seasonal peak and trough of demands;

(3) More advanced waste heat recovery technologies are expected to be designed and engineered. For example, the s-CO_2 cycle has demonstrated better thermal efficiency than the conventional cycle [17]; and

(4) A mature and stable carbon trade market coupled with supportive policy is expected to promote the development of waste heat recovery technology.

Challenges and prospects for LNG cold energy recovery

Low overall recovery rate issue

Fluctuating regasification rate is one of the key issues that restrict the improvement of the overall cold energy recovery rate. LNG receiving terminals are mainly built to meet the natural gas demand of thermal power plants and city usages (including residence and industry). The natural gas demand from these sectors usually appears seasonal or hourly variation. However, the cold energy demand from users may not synchronize well with the changing LNG regasification rate. Therefore, a potential energy mismatch occurs between the cold recovery systems and users. Satisfying the natural gas demand should be prioritized for receiving terminals. Consequently, the capacity of the cold energy utilization setups is usually designed at 20–30% of their baseload [88] to ensure a reliable cold energy supply. This becomes a key factor for the low overall cold energy recovery rate.

Low exergy efficiency issue

Based on the information from the commissioned LNG cold energy recovery plants, the cold energy users are varied but independent of each other [89]. If the LNG cold energy is only used for shallow cold industries, such as chilled water production, the exergy destruction becomes significant. Even for power generation setups, most of their exergy efficiencies linger around 10–20%. Multi-generation systems have been proposed by many researchers [90] to improve cold energy utilization efficiency. However, most of these studies focused on the performance from the system's perspective without considering users' demands. The low-efficiency issue is still not resolved if the energy mismatch between the cold recovery systems and users is not addressed properly.

Inadequate assessment for proposed systems

The environmental impacts, safety risks, and system life cycle are rarely assessed in many cold recovery systems. For example, when the storage pressure peaked as high as 21 MPa in the LNG cold energy utilization-based liquid air energy storage system [90], it became a challenge under contemporary storage technology. Furthermore, the LNG operating pressure peaked at 30 MPa when transferring heat with the air, there may be a severe hazard due to the potential internal leakage of the heat exchangers.

Issues to be addressed

For a newly proposed system, the negative impacts that arise due to fluctuating LNG regasification rates should be carefully investigated. Energy storage technologies and optimal operating strategies can be adopted to mitigate these negative impacts. The users' demand profile is a key aspect when designing a new multigeneration system. The energy match between the cold recovery setups and users should be judiciously considered. Besides thermodynamic and economic analyses, environmental impact, safety assessment, and life cycle assessment are imperative to establish the stability and reliability of a newly proposed system.

Conclusions

Global warming and climate change are existing problems that bring immeasurable consequences to the planet. World primary energy is still dominated by fossil fuels, which are expected to remain a significant part of world energy consumption in the next few decades. At the same time, about 63% of primary energy is wasted due to insufficient energy utilization. Therefore, there are opportunities to develop waste thermal energy recovery technologies to promote a sustainable energy future. A large amount of waste heat and cold energy from different sectors should be recovered to improve the sustainability of energy utilization.

Specifically, this study presents a comprehensive review of sustainable thermal energy recovery technologies considering both waste heat and cold energy utilization. Key features of prime movers and waste heat recovery subsystems are reviewed. Recoverable heat is usually in the form of superheated gas/steam, hot water, or stored in the solid carriers with different temperatures. Accordingly, appropriate waste heat recovery systems can be deployed to harness thermal heat energy fully. The current application status of different multigeneration systems is also evaluated and compared. Consumers can adopt and select a specific multigeneration system based on specific energy and product demands. Waste heat recovery technologies continue to show a promising future, since they can produce multiple utilities to meet consumers' demands, including electricity, heating, chilled water, and potable water.

The cold energy generated from the LNG regasification process is a waste cold energy worthy of being harnessed. Popular LNG cold energy utilization technologies include power generation, combined cooling and power, air separation, cryogenic CO_2 capture, and cold warehouse. Future prospects have been highlighted to facilitate the continuous development of waste energy cold recovery technologies. Optimal operating strategies, improved energy matching, and comprehensive evaluation are keys to developing energy-efficient LNG cold energy harnessing technologies.

It is expected that the prime movers and waste heat utilization technologies reviewed in this paper will play key roles in the decentralized energy market in the future.

Abbreviations

ADC: Adsorption chiller; AHP: Absorption heat pump; CCHP: Combined cooling, heating, and power; CCGT: Combined cycle gas turbine; CCP: Combined cooing and power; CCS: Carbon capture and storage; CNG: Compressed natural gas; CRS: Compression refrigeration system; DABC: Double-effect absorption chiller; DE: Direct expansion; DH: Direct heating; FC: Fuel cell; GT: Gas turbine; HP: Heat pump; ICE: Internal combustion engine; KC: Kalina cycle; LAES: Liquid air energy storage; LDD: Liquid desiccant dehumidifier; LNG: Liquified natural gas; ORC: Organic Rankine cycle; ORV: Open rack vaporizer; PCM: Phase change material; QLC: Quadrilateral cycle; RC: Rankine cycle; SE: Stirling engine; ST: Steam turbine; SDD: Solid desiccant dehumidifier; SABC: Single-effect absorption chiller; TABC: Triple-effect absorption chiller; TEG: Thermo-electric generator; VCHP: Vapor-compressed heat pump.

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Author contributions

WC: Conception, design of the work, the acquisition, analysis, interpretation of data, writing—original draft and review. ZH: conception, design of the work, the acquisition, analysis, interpretation of data, writing—original draft. KJC: conception, design of the work, supervision, project administration, writing—review and editing. All authors compiled the review. All authors read and approved the final manuscript.

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Availability of data and materials

The data sets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Consent for use of images has been granted.

Competing interests

The authors declare that they have no competing interests.

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