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Review

Environmental Aspects of the Combined Cooling, Heating, and Power (CCHP) Systems: A Review

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Abstract: Expanding cities means increasing the need for energy in the residential sector. The supply of this energy must be in environmentally friendly ways; one method of meeting demand in the residential sector is the use of combined cooling, heating, and power (CCHP) systems. The current review paper shows that due to the high cost of gas and electricity, CCHP can be used in various sectors, such as hospitals and airports, to reduce energy consumption with lower environmental impacts by using renewable energy systems as the main driver. While CCHP systems are not feasible in tropical regions with high cooling demand, a solar hybrid system is a superior candidate for regions with sufficient radiation. CCHP can also be used in sectors such as wastewater treatment units, desalination systems, and hydrogen production units to improve performance and increase productivity. The carbon and water footprints of CCHP systems are discussed in detail. The main drivers for reducing carbon and water footprints are improving system components such as the combustion engine and increasing productivity by expanding the system to multi-generation systems. Finally, the carbon tax index can help reduce carbon emissions if properly used in the right context. Based on our best knowledge, there is no extensive review of the environmental aspects of CCHP systems in the literature.

Keywords: CCHP; LCA; carbon footprint; water footprint; renewables

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1. Introduction

1.1. Background

In recent years, three combined cooling, heating, and power (CCHP) systems, also known as trigeneration systems, have received more attention due to their lower greenhouse gas emissions and high energy efficiency [1–6]. CCHP systems are the same as combined heating and power (CHP) systems (also known as cogeneration systems) with an added unit for cold water production. Cold water can be used in refrigeration and air conditioning [7]. Figure 1 shows the capability of the CCHP system compared to a traditional power plant with the same fuel consumption. In a traditional power plant, approximately 30% of the input fuel can be used to generate electricity, while the excess energy is dissipated into the environment as waste heat. For a CCHP system, however, produced heat is recovered, and the efficiency of the system can reach about 90% [8–10]. Many commercial and industrial sectors can benefit significantly from the installation of a CCHP system.

As can be seen in Figure 1, the CCHP system generally includes the prime mover/driver (power generation unit), the heat-recovery system, the cold-production system, the heating system, and the management and control system. The most common prime movers utilised in CCHP systems are gas or steam turbines, internal combustion or Stirling engines, and high-temperature fuel cells, such as solid-oxide fuel cells (SOFC) [7]. The most common heating unit is the boiler. The most common cold-production system is the absorption chiller [11]. Details about different parts/units of CCHP systems are presented in Section 2. The main advantages of CCHP systems can be summarised as:

- It uses one fuel source to generate three energy outputs (electricity, heat, and cooling).
- A higher level of energy security is achieved through the generation of all energy onsite.
- Trigeneration can improve the overall efficiency of CHP systems by utilising heat that would otherwise be rejected to serve absorption chillers to generate cooling.
- There is limited noise pollution as absorption chillers produce no noise compared to the traditional chiller plants.
- Flexible solutions that are customised to meet individual needs and maximise efficiencies.
- It has lower CO_2 production compared to electricity produced from coal, whilst delivering the same amount of energy.
- It can be used as a backup power system.

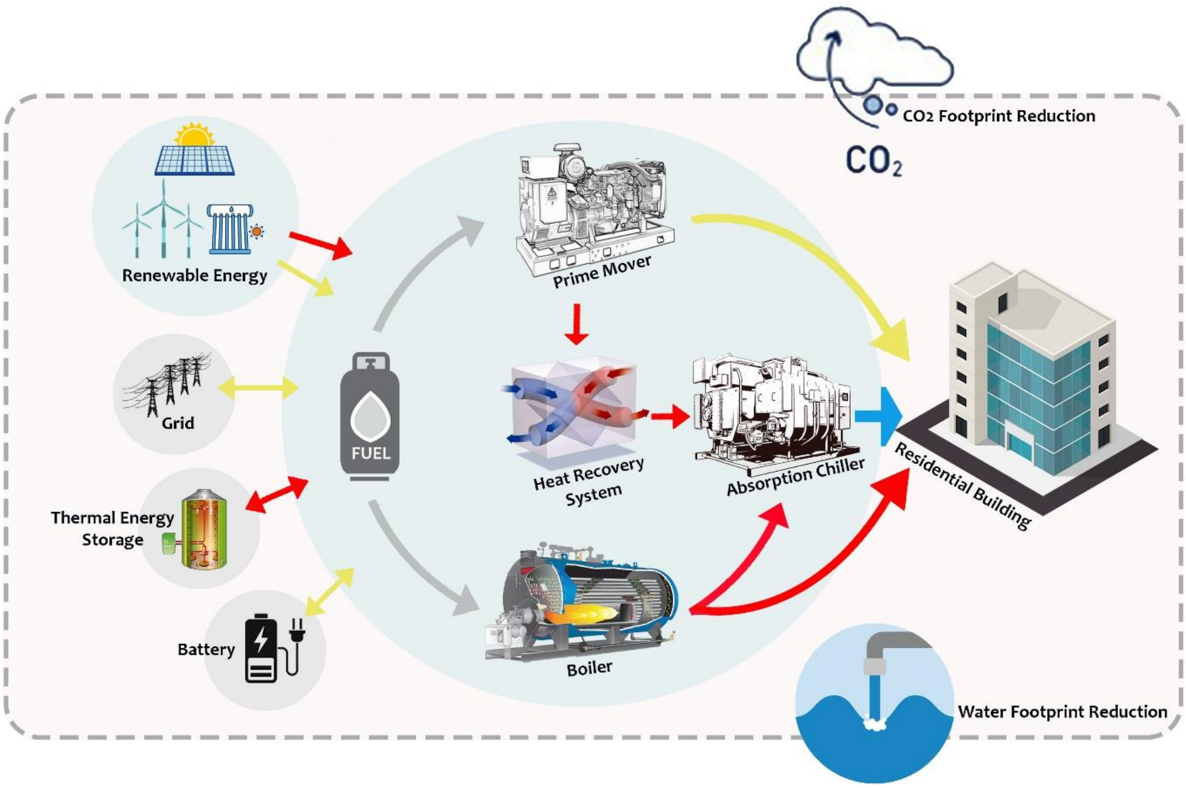

Figure 1. Multi-functional CCHP with application in the residential sector.

The main disadvantages of CCHP systems are their high up-front capital costs, the required space for CCHP installation, and administration costs. CCHP systems are suitable for end-users where power, heating, and cooling are essential for them. Moreover, CCHP systems are not quite sustainable when the main driver is based on fossil fuel.

1.2. Motivation of This Study

Several review papers and books have been published about CCHP systems, but the focus of them was on the system configuration, management, and optimisation [2,5,11–14]. None of these papers' focus was on the environmental aspects of CCHP systems. Cho et al. [2], Shi et al. [13], and Ebrahimi and Keshavarz [14] reviewed the modelling, performance improvement, and optimisation of CCHP systems. Meanwhile, Liu et al. [5], Roman et al. [11], and Wu and Wang [12] presented a more general review, considering other aspects such as economic parameters. In addition to the technical and operational aspects of CCHP systems, attention should be paid to environmental aspects and the impact of these systems.

Therefore, in this review study, the authors would like to review and discuss environmental aspects of CCHP systems, such as their life cycle assessment, CO_2 footprint, and water footprint. In addition, the integration of CCHP systems with different types of renewable energy sources is being reviewed to improve the environmental performance of CCHP systems.

1.3. Research Method in the Current Study

The search for related papers about environmental aspects of the CCHP system was performed using keywords utilised in the titles of the papers, their abstracts, and keywords of published journal articles, such as carbon footprint, water footprint, solar, and renewable energy with CCHP. Table 1 shows the structure of the relevant literature search.

Table 1. Literature search categories, reviewed papers' count, and keywords of the search.

Search Categories	Reviewed Papers' Count	Keywords of the Search
Main drivers of CCHP systems and cooling technologies	43	CCHP, drivers, absorption chiller, COP, steam turbine, gas turbines, micro-turbines, internal combustion engines, Rankine cycle, Sterling engine, fuel cells
Environmental impacts of CCHP and solar energy hybrid systems	33	CCHP, solar, PV, photovoltaic, thermal solar, PV-T, parabolic hybrid system, environmental impacts
Environmental impacts of CCHP and renewable energy hybrid systems	44	CCHP, solar, wind turbine, hybrid system, environmental impacts, geothermal, biomass, Stirling engine
GHG emissions of CCHP systems	30	CCHP, GHG emission, greenhouse gas, emissions, carbon footprint, LCA
Water consumption of CCHP systems	3	CCHP, water consumption, water footprint, LCA

1.4. Outline of the Paper

After the introduction, in Section 2, different parts of CCHP systems will be explained. The main parts are prime movers/main driver and cooling system. Integration of CCHP with a different type of renewable energy is discussed in Section 3. Life cycle assessment (LCA) performed for CCHP systems are reviewed in Section 4. In Section 5, the carbon footprint of these systems is covered. The water footprint is explained in Section 6. In Section 7 is the role of carbon taxation in CCHP development. The important points of this study are concluded in Section 8.

2. Different Components of CCHP Systems

In CCHP systems, there are numerous types of equipment, and there is a coupling relationship between the equipment. The equipment that are used in the CCHP system determine the total efficiency of the system and have a direct impact on the economic and environmental aspects of the system. In addition to the type of equipment, their configuration also has high importance [15]. It can be said that the economic benefits of CCHP systems are greatly reduced due to the mismatch of installed capacity [16]. It should be noted that the atmospheric and seasonal conditions also have significant effects on the performance of CCHP systems. Wang et al. [17] examined a CCHP system for a commercial building in China in different seasons based on the priority of power supply or heat demand. The efficiency of the system is directly related to the consumer's need for electricity, cooling, and heating. The results showed that in summer when more cooling is needed, the CCHP system does not work well, and the most optimal state of the system occurs in summer when the power supply is a priority. The design and operation of CCHP systems depend on the atmospheric conditions. Wang et al. [18] also evaluated the performance of these systems in five different climatic zones based on Thermal Demand management (TDM) and Electrical Demand Management (EDM). Based on the results, the CCHP system in the TDM mode performed better than separate systems and in the cold zone, which requires a higher heating load. Moreover, the EDM model is suitable for temperate regions with stable heating requirements. As main drivers/prime movers and cooling systems are the main and important parts of CCHP systems, they are discussed and explained in more detail in the following subsections.

2.1. Main Drivers/Prime Mover

CCHP systems have different main drivers such as steam and gas turbines [19,20], micro-turbines [21–23], internal combustion engines (ICEs) [24], Rankine cycle [25], Sterling engines [26], and fuel cells [27,28]. Between technologies, fuel cells can have a special place in terms of fewer emissions, higher electrical efficiency, and maintaining efficiency in low-capacity systems [29]. In the paper [30], gas turbines and diesel and gas engines for a CCHP system are compared based on energy, exergy, and economic indicators. The results demonstrated that exergy efficiency and the power supply of the CCHP system raised by 10% by integrating two drivers at the same time compared with one driver. Moreover, the integration of gas and diesel engines is recognised as the best scenario due to its energy efficiency of 87%, exergy efficiency of 62.8%, and lower operating costs of about 80%.

ICEs are another suitable main driver that, due to high electrical efficiency and low investment cost, work better than similar options [31]. These engines save 16.7% more energy than the conventional CHPs. The study [26] investigated a system with a gas turbine as the main driver. The system includes an air compressor, combustion chamber, gas turbine, heat recovery steam generator (HRSG), and absorption chiller. By examining the effects of various features such as turbine inlet temperature, pinch point temperature in HRSG, and steam generator inlet pressure on fuel consumption, cost, and energy generation, it is shown that the integration of gas turbine with HRSG and absorption chiller increase efficiency.

This is because the flue gas from the turbine can be used as a heat source for steam required for the absorption chiller and the process. In the study [32], diesel engines, gas engines, gas turbines with recuperators, and combined gas turbine cycle (CGTC) were investigated. According to the results, the diesel engine has the lowest energy consumption and carbon emission. The gas engine is selected as the best case based on energy consumption and system simplicity. The research [33] examined the primary drivers for a residential building micro-CCHP system under five different climatic conditions. The paper compared four scenarios of separate production (SP), ICE, gas micro-turbine, and Sterling engine based on the technical, economic, environmental, and social evaluation. The results for all weather conditions indicated that the ICE is more suitable than the other options, followed by Sterling engine, SP, and gas micro-turbines.

In a steam driven CCHP system, high-pressure steam is drawn from the steam turbine and then used for heating or as an absorption chiller inlet. Due to the high loss of heat transfer, CCHP systems are mainly located near large cities or industrial areas [34–38]. Recovering and reusing waste heat causes significant savings in energy use as the fuel is used for multiple purposes. The amount of savings varies between different buildings since each CCHP system is unique and sustainable, but overall, a reduction in energy consumption of up to 25% has been reported [39]. Therefore, the CCHP system significantly reduces the carbon footprint of facilities. In addition to saving energy, the CCHP system gives the building reliability and integrated flexibility [40–44]. Further, air conditioning is always available when the waste heat of CCHP is used alongside absorption chillers, which is very crucial in moments of adverse weather disasters, such as hurricanes. Consequently, CCHP provides backup generation services with day-to-day services and is always in service [45].

2.2. Cooling Technologies

Several different types of cooling technologies such as absorption chillers, adsorption chillers, and Desiccant dehumidifiers [5] can be used in CCHP systems, but in most cases, absorption systems are selected. The most commonly known cooling systems are absorption systems, adsorption systems, and ejector refrigerators. These systems generate less noise and emissions than conventional compression systems that use electricity but are more expensive and less efficient. The coefficient of performance (COP) in these systems, i.e., the ratio of cooling to energy consumption, is lower than in compression systems (COP = 2.5–5). In absorption systems, different combinations of refrigerants are used. For example, an ammonia-water refrigerant with a low COP (0.2–0.65) is suitable for medium-or large-scale applications (industrial applications up to several megawatts) at temperatures below 5 °C. Lithium bromide-water refrigerant is used for air conditioning (temperatures greater than 5 °C) of buildings and has a higher COP (0.7–1.7). There are different absorption systems, and the choice of an appropriate technology depends on the criteria of investors, especially in terms of cost and efficiency (Table 2).

Table 2. Characteristics of refrigerants used in absorption systems.

Refrigerant Absorption System	COP	Temperature	Application
Ammonia-water	0.2–0.65	<5 °C	Industrial and large applications
Lithium bromide-water	0.7–1.7	>5 °C	Air conditioning in the building

In adsorption systems, refrigerants such as silica gel-water are used, which can supply cold water up to 3 °C. It has a higher COP at low hot water temperatures (65–85 °C) than single-stage lithium bromide absorption systems. New technologies such as vapour ejector refrigeration [46] or desiccant cooling [47] are also being developed and used. A compression system can be combined with the refrigeration system to balance the generation and demand for cooling. The CCP or CCHP system, in this case, usually ensures the base demand and the compression system covers the peak demand times [48].

Liu et al. [49] showed that the performance of a CCHP system depends on the system structure, operation strategy, and facility capacity. They designed a CCHP system with a hybrid chiller, a combination of absorption and electric chillers, in which the ratio of electrical cooling to cooling load changes hourly based on the thermal and electrical load. After obtaining the optimal performance algorithm and conducting a case study of a hypothetical hotel, the study shows that the designed system is more efficient than conventional SP systems and the annual costs were reduced by about 50%. Li and Wu [50] investigated a micro CCHP system based on a silica gel-water absorption chiller. The analysis of the simulated results of this research shows that the COP of the chiller and cooling capacity are directly affected by the mean and rate of change of electric load and the mean amount of cooling load. Moreover, the water tank has a significant impact on the performance of the chiller and is best used when the electric charge is low. A cold accumulator can also be used for better performance and higher safety.

Li and Wu [51] investigated the performance of absorption chillers in conjunction with ground source heat pumps (GSHP), electric chillers, and gas-fired absorption chillers (GFC). The authors determined the optimal state of the systems using a genetic algorithm based on the priority of electricity or heat supply. They have selected carbon dioxide emission reduction rate (CDERR), primary fossil energy-saving rate (PFESR), and annual total cost savings rate (ATCSR) as the criteria which were used to compare the mentioned systems with SP systems. The results of a case study on a commercial building in Shanghai demonstrated that a combination of the CCHP system and GSHP with a priority on power supply had the best performance among all options. In addition, the absorption cooling system and the electric compression refrigeration system in terms of energy efficiency and exergy are compared. According to the results, the distance between the cooling centre and the power plant, i.e., the distance that the steam must travel, affects the performance of the absorption cooling system. While absorption cooling is suitable for distances of less than 5 km, the electric compression system is a better option for distances of more than 9.3 km [52].

3. Combining CCHP System and Renewable Energy

One way to increase energy efficiency with fewer environmental effects is to combine CCHP systems with renewable energy sources such as solar [53,54], wind [41], Stirling engine [55], biomass [56,57], geothermal [58], and fuel cell [59]. Table 3 shows methods used in the literature to analyse, evaluate, and optimise the integration of different renewable energy sources with CCHP systems. Moreover, in this table, integrated energy renewable energy sources, the country or region, and the sector details of each study are demonstrated. Among the various renewable sources that have been considered for use in cogeneration systems (such as solar panels, wind generators, biomass, or a combination thereof), solar energy and biomass have attracted the attention of academics due to their availability and low destructive environmental effects [60]. As one of the main benefits of biomass, it can be used steadily, and changes in environmental conditions (e.g., the absence of the sun at night) do not affect the energy supply. For this reason, it is a proper option for use in hybrid energy supply systems. In the following subsections, some important studies about the integration of the CCHP system with different renewable energies are reviewed. China is one of the successful countries in CCHP systems implementation. Cogeneration was highlighted in the 13th Five Year Plan of China [61]. For example, technical regulation for the development of CCHP systems was issued by the government of China [62]. Mobasseri et al. [63] studied multi-energy microgrids. In this study, the uncertainties of renewable energy supply and unpredictable demand were evaluated. A hybrid energy management tool was presented in this study for multi-energy microgrids.

Table 3. Methods, geographical locations, renewable energy types, and sector details of studies related to CCHP systems.

Method Used	Integrated Renewable Energy	Country/Region	Sector			Ref.
			Industrial	Residential	Commercial	
NPV optimisation, MINLP model, IRR optimisation	Wind turbine, PV	Shanghai		✓	✓	[42]
Optimal planning and operation strategies	Wind turbine, PV	China		✓		[64]
Information gap decision theory	Wind turbine, PV	Iran	✓	✓		[65]
Nested optimisation design, genetic algorithm, and nonlinear programming algorithm	Solar and biomass energy	Jinan City, China		✓		[66]
Energy, exergy, and economic analysis	Photovoltaic thermal and parabolic trough collectors	Iran		✓		[67]
CC-MOPSO algorithm	Photovoltaic module, Wind turbine, solid oxide fuel cell	Kermanshah, Iran			A hypothetical hotel	[68]
Exergetic and exergoeconomic evaluation	Biomass gas and ground source heat pump	China		✓		[69]
Genetic algorithm	Biogas and solar Dish/Sterling power system	Lhasa Tibet, China	✓			[70]
Operational optimisation model (nonlinear optimisation model)	Solar thermal collector and photovoltaic	Shanghai, China			A five-star hotel	[71]
Exergy-ecological analysis	PV and biogas	Poland	✓			[72]
Exergy analysis	Geothermal energy	Iran	✓			[73]
Multi-objection optimisation (non-dominated sorting genetic algorithm-II)	Solar collector	China	✓			[74]
The thermodynamic and economic analysis	Biomass and ground source heat pump (GSHP)	Rural China		✓		[75]
Optimisation based on quantum genetic algorithm	Ground source heat pump (GSHP)	China		✓		[76]
Parametric life cycle assessment	Solar PVs arrays	Atlanta, USA			A medium office	[77]
Energy and exergy analysis	Geothermal	Iran		✓		[45]

3.1. Integration of CCHP with Biomass

In recent years, many researchers have worked on the integration of biomass as an important renewable and sustainable feedstock and CCHP systems. Wang et al. [78] analysed the energy and exergy of a CCHP system combined with biomass gasification. Biomass in the gasification sector is converted to gas, which is used as a fuel in the CCHP system for electricity generation, heating, and cooling. Based on the results of this study, energy efficiency for a CCHP system and gasification in summer is at its highest (37% for the case study). This rate decreased in autumn and spring due to increased heat output (16%), and the annual energy efficiency was reported as 28% [78]. The annual performance also showed that the biomass-fired CCHP system reduced biomass consumption by 4% compared to the case without heat recovery. Wegener et al. [79] developed an innovative modelling approach to design the biomass-based, solar-assisted CCHP and heat pump (HP) systems for various climate scenarios. They used this dynamic model to evaluate the economic, energy, and ecological performance of biomass-based CCHP/HP systems of various sizes compared to an individual HP system. Based on their case study, the authors mentioned that climate change will have small impacts not just on the energy demand of the building but also on the operation strategies and efficiencies of HP and CCHP systems. The case study's findings show that the model can be used to determine at what scale a small-scale CCHP system can be a viable choice for a more renewable and autonomous energy system for culture, tourist, and accommodation parts. Jalili et al. [80] studied a combined biomass/natural gas-fed CCHP system from exergetic and thermo-economic standpoints. The authors investigated the effects of the gas turbine inlet temperature pressure, the gas mass ratio, and the split ratio on the performance of this system. They reported the optimum operating conditions of the system.

3.2. Integration of CCHP with Solar Energy

Photovoltaic panels can be used to supply electricity and solar collectors to provide heating [81,82]. To increase the advantages of CCHP systems, they can be used in conjunction with solar systems. Ebrahimi and Keshavarz [83] examined a solar-assisted CCHP in different cities of Iran. The authors showed that the size of CCHP is significantly larger for cities with higher cooling loads and therefore requires higher investment costs. As a result, the use of CCHP systems in the tropics is not efficient and economically justified, and these systems are efficient for areas with temperate climates. The operation mode of the CCHP system determines its economic, environmental, and energetic performance.

Yamano [24] reported that biomass systems have better performance than solar systems in terms of energy and exergy. Moreover, the increase in output power causes a linear increase in output cooling, a slight increase in COP, and an improvement in exergy and energy efficiency. High radiation intensity will also increase the cooling output. In this case, due to the share of heating in the absorption chiller increasing simultaneously, the COP and, consequently, the exergy and energy efficiency of the system will also decrease.

In general, a high percentage of biomass energy consumption and a decrease in the percentage of solar energy increase energy efficiency. In addition, at high biomass consumption rates, increasing the percentage of solar energy increases the exergy efficiency. This will be the opposite at low biomass energy consumption rates. Different indicators must be considered when comparing CCHP systems combined with renewable sources and conventional systems. Wang et al. [54] examined a solar-assisted hybrid system from the aspects of energy, exergy, exergoeconomic, and environment. According to the findings, the energy efficiency and exergy efficiency of the system are, respectively, 66 and 25.7% in heating mode and 83.6 and 24.9% in cooling mode. Compared to a system without solar energy, carbon emissions were reduced by 41% per unit of energy generated.

It should be noted that, if the system is only examined in terms of energy and exergy, the effect of solar energy on the system cannot be determined. In addition to solar-assisted CCHP systems, there are photovoltaic hybrid systems (PV-T) that are more efficient than conventional solar systems and can meet the needs of the household. In these systems, the overall efficiency can exceed 70%, and the electrical and thermal efficiencies can reach up to 20 and 50%, respectively. Ramos et al. [84] studied PV-T systems in several European cities. According to the results, this system can meet 60% of the heating needs for hot water and ambient heating and almost 100% of the cooling needs of houses. Moreover, the energy cost of the PV-T system is about 30–40% lower than the PV system. To achieve the desired result, these systems can be coupled with heat pumps and absorption refrigerators.

3.3. Integration of CCHP with Geothermal Energy

Mohsenipour et al. [85] performed the optimisation of a geothermal-assisted CCHP system using the genetic algorithm (GA). The efficiency of this system, water consumption, and CO_2 emissions were reported as 46.4%, 688,151.21 L, and 13,439 CO_2 kg eq, respectively. The results also demonstrated that the highest water consumption belongs to the construction sector and the highest CO_2 emissions are emitted from the steam generator.

To calculate the CCHP-GSHP hybrid system's actual working conditions, Zeng et al. [86] presented an optimal model concerning carbon taxation. The power generation unit capacity and the monthly energy ratios of the system are the variables, and 3E analysis is performed. Compared to the E-GSHP, the results demonstrated that the CCHP-GSHP hybrid system has an annual energy saving ratio of 31.79%. The annual reduction in carbon dioxide emissions was 51.34%, the annual total cost decrease was 25.64%, and the optimisation rate was 36.26%.

3.4. Integration of CCHP with Wind Energy

Regarding the intermittent nature of renewable energies, utilisation of energy storage systems is inevitable. For this purpose, wind energy together with compressed air energy storage systems in combination with CCHP systems was studied [87]. The system included a gas turbine, a Rankine cycle, and an absorption chiller. The results demonstrated that this system could supply 33.67 kWh of electricity, 2.56 kW of cooling load, and 1.82 tons of hot water per day and has an energy efficiency of 53.94%. Exergy analysis also indicated that wind turbines, combustion chambers, and compressed air storage systems have the highest rate of exergy destruction, respectively. Lastly, the sensitivity analysis demonstrated that the performance of the system strongly depends on the gas turbine parameters.

Table 4 demonstrates the advantages and disadvantages of integrated CCHP systems with different renewable energy resources.

Table 4. Comparative table about the integration of the CCHP systems with different renewable energy sources.

Integration of Different Renewable Energy Sources with the CCHP System	Advantages	Disadvantages
High-temperature solar thermal systems integrated with CCHP systems based on Rankine cycle (1. Parabolic trough, 2. Linear Fresnel, and 3. Central receiver tower) [88,89]	• Rankine cycle is a mature technology • High energy efficiency • High CO_2 reduction • Suitable for district energy supply • Solar energy is clean, free, abundant, and widespread	• Large space occupation • A large number of components • High maintenance costs • Slow ROI • Not suitable for small-scale projects
High-temperature solar thermal systems integrated with CCHP systems based on gas turbine [90]	• Low technical risks • Low economic risks • Solar energy is clean, free, abundant, and widespread	• No experimental studies • Large space occupation

Table 4. *Cont.*

Integration of Different Renewable Energy Sources with the CCHP System	Advantages	Disadvantages
CCHP systems based on Supercritical CO_2 Brayton Cycle integrated with solar thermal cycle [91]	• Few movable parts • Low installation costs • Low operating and maintenance costs • Solar energy is clean, free, abundant, and widespread	• Early commercial stage • High investment and technical risks
CCHP systems based on ORC integrated with solar thermal cycle [92,93]	• Low working fluid temperature • Efficient for small-scale utilisation • Low operating and maintenance costs • Zero CO_2 emission • Solar energy is clean, free, abundant, and widespread	• A low number of experimental studies
CCHP systems integrated with PV panels [94]	• Acceptable supply–demand correlation • High CCHP fuel efficiency • Low maintenance costs • Fuel consumption reduction • Government subsidies in many countries • Solar energy is clean, free, abundant, and widespread	• Larger invertor size
CCHP systems integrated with PV-T [95]	• Lower emissions • Energy saving • Solar energy is clean, free, abundant, and widespread	• Low ROI
CCHP systems based on Rankine cycle using biomass [96]	• Proper for district energy supply • CO_2 reduction	• Not proper for small-scale CCHP systems
CCHP systems based on ORC using biomass [97,98]	• Operating in lower temperatures • Proper for small-scale CCHP systems • Low up-front capital costs • Low maintenance costs • Good partial efficiency	• Flammable working fluid • Higher safety needs • Still in the research and development stage
CCHP systems based on the steam engine using biomass [99]	• It is possible to use solid biomass	• Loud noise of the system
CCHP systems based on gas turbines using biomass [99]	• High efficiency • Low costs • Easy operation • High availability • Small size	• Sensitive ambient condition • Loud noise • Fuel quality issues
CCHP systems based on externally fired gas turbines using biomass [99]	• Low fuel quality issues • Atmospheric combustion	
CCHP systems based on the internal combustion engine and gasifier using biomass [78]	• Commercially available • Proper for a small-scale operation	• High exergy loss in the gasifier

Table 4. *Cont.*

Integration of Different Renewable Energy Sources with the CCHP System	Advantages	Disadvantages
CCHP systems based on Stirling engine using biogas [100]	• High efficiency • Low pollution • Less noise • Low maintenance costs • Reliable operation	• A low number of Stirling engines suppliers • High capital costs
CCHP systems based on fuel cells using biomass [101]	• High efficiency • Low pollution • Low noise level • Clean • Quiet	• High investment costs • High maintenance costs • Low fuel availability
Wind energy source integrated with CCHP systems [102]	• Clean • Free • Low maintenance costs • No fuel costs • Size flexibility • Commercial availability • Inexpensive • Operate with the wind at low speeds	• High initial investment costs • Unstable output • High dependency on wind speed and weather conditions • In many countries, the proper sites are not abundant
Geothermal energy source integrated with CCHP systems (1. ORC, and 2. Kalina cycle) [103,104]	• Low level of air pollutants • Not impacted by weather conditions	• Availability in particular regions

4. LCA and CCHP System Optimisation

Life cycle assessment (LCA) is a method to predict the total impact of a product or process by considering all stages of the life cycle, from the extraction of raw materials during production, transportation, consumption, until waste disposal [105]. This method is sometimes called "cradle-to-grave" analysis. The results of these analyses can be used in decision making. Using this analysis, processes or products can be compared and evaluated to see which one is more efficient. It can also be used to design new products and materials or to improve the environmental performance of existing products. This technique is used as a method for environmental management and does not consider the economic aspects of a product and it is a useful tool for predicting the potential impact of a system on the environment. This method is simple but sometimes depends a lot on the assumptions made for the process. For example, in the CCHP system of a coal-fired power plant in China [106], the combustion process has the greatest impact on the environment (92%). This process, due to the high emission of carbon dioxide, plays an important role in global warming as well as biological pollution (terrestrial and water) caused by elements such as copper.

In addition to coal combustion, mining (5%) and transportation (3%) also affect the environment. The main GHG from this plant is CO_2 (43.5%), followed by NO_x (23.7%) and SO_x (19.3%), and the rest are methane emissions (in the extraction process) and trace elements (in the combustion process) [106]. A CCHP system comparison with a stand-alone coal-fired system demonstrates that the CCHP system is not only more efficient but also more environmentally friendly. Using a CCHP system instead of a stand-alone system can reduce coal consumption, resulting in an 11% reduction in environmental damage.

Figure 2 shows the difference between two stand-alone and CCHP systems. Coal (F) feeds the CCHP system for electricity generation, cooling, and heating, and in the stand-alone system, coal (F_t) enters the boiler as heating fuel for heating and F_e enters the power plant as fuel for electricity generation. De Felice et al. [107] examined the integration of the two approaches of LCA and multi-criteria decision analysis (MCDA). The first allows researchers to analyse the system's environmental impact, and the second is used to select the best path for progress. The main purpose of this research was to develop a systematic and easy method to achieve useful and practical results. To this end, existing methods were reviewed with a new approach and for continuous improvement.

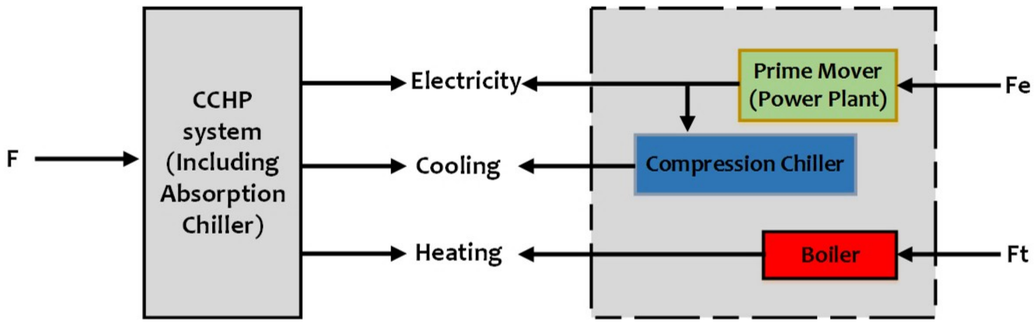

Figure 2. Comparison of conventional and CCHP power systems [106].

In a recent study, Chaiyat et al. [108] studied the LCA of the cascade geothermal-based CCHP system, which uses the ORC, absorption cooling, and centralised drying systems. They presented a novel microscale CCHP unit and performed a life cycle impact assessment (LCIA) to realise the environmental burdens, human health impacts, and resource impacts. Their system's LCA values were lower than those of combined cycle gas turbine and coal power plants. The authors advised that the hot fluid and hot water loops be combined into a single cycle for future research to improve net electrical power, system efficiency, and environmental impacts.

5. Carbon Footprint

The use of CCHP systems usually emits fewer greenhouse gases than conventional systems because fewer primary resources are consumed. In addition, a CCHP system can be considered a multi-product generation system because it regularly generates electricity, heating, and cooling concurrently. Carbon footprint can be used to evaluate the systems [109]. Carbon footprint assessment is an approach for all carbon life cycle processes with a comprehensive assessment of total greenhouse gas emissions. There is a set of international regulations and standards that help users to better calculate the carbon footprint and thus make progress in reducing carbon emissions [110,111]. It should be noted that, in multi-product systems, applying total GHG emissions as an evaluation indicator cannot help recognising the contribution of each product of the emissions. For a comprehensive evaluation of a system, source allocation of carbon emissions by different products seems necessary. ISO 14067 states that output and input data may be divided between the common products of a system corresponding to the products' economic value. In CCHP systems, common products, namely electricity, cooling, and heating, have dissimilar energy levels, so assignment principles must be observed in assessing the CCHP systems' carbon footprint. However, no information is available on compliance with ISO 14067 for the allocations [5,12,112–114]. Chicco and Mancarella [115] proposed an indicator named trigeneration CO_2 emission reduction to quantify GHG emission reduction by CCHP system with respect to separate production. The case studies showed that the CCHP system can bring considerable benefit to countries with fossil fuel-based power generation systems [116].

Jiang et al. [117] utilised the Multi-Product Carbon Footprint (MPCF) technique to evaluate the carbon dioxide emission of a CCHP system. The capacity of the system is 1183 kW, and the natural gas consumption rate is 303.85 m^3/h. The MPCF is calculated and analysed for the mentioned CCHP system, and a potential approach is presented to reduce MPCF by optimising the system. Results indicate that the optimised CCHP system's MPCF decreases by 7.5% compared with the initial system. Table 5 lists the values of the factors utilised in their study.

Table 5. Factors used in calculating greenhouse gas emissions by Jiang et al. [117].

Procedure	Item	Unit	Emission Factor
Energy producing	Methane	kg CO_2/m^3	16.5
Utilities	Electricity	kg CO_2/kWh	0.8

Su et al. [118] studied the integration of a biogas steam reforming unit and solar energy with a CCHP system. The proposed approach reduces the separate system's direct carbon footprint by more than 18%. Kishor Johar et al. [119] carried out a comparative study about CHP systems, CHP systems with thermal energy storage, and CCHP systems with thermal energy storage. The internal combustion engine was the prime mover of the system. The carbon footprint of the CCHP system with thermal energy storage was more than 54% lower than the single generation system. Wang et al. [120] studied the performance of biomass powered CCHP systems for 100 m^2 isolated houses in China. It showed the thermal efficiency of the system can reach 55.26% which results in low GHG emissions and lower costs. Chen et al. [121] compared the performance of a full load small scale gas turbine-based CCHP system with the same system with a 30% load. The GHG emissions of the full load system were more than 66% lower than the 30% load system. Wu et al. [122] carried out a multi-criteria assessment of CCHP systems in Japan. It was demonstrated that in mild climates, the CCHP systems have a lower potential for energy saving and GHG emission reduction than other climate zones.

The study [123] deals with the optimisation of CCHP systems through carbon regulatory policies. This paper defines a nonlinear optimisation model based on operating costs taking into account variable carbon tax. Experimental results show that appropriate carbon tax policies can effectively reduce emissions. In the following, the topic of the carbon tax is addressed specifically. The research [124] studied the CO_2 emissions of gas-fired CHP systems. Conventional energy-saving models were developed. Equivalent efficiencies have also been defined to assess CO_2 emissions and used in the development of the PCO_2ER (Poly-generation CO_2 Emission Reduction) index, which is specifically developed to assess environmental impacts.

Mago and Hueffed [37] studied the incorporation of tax credits to demonstrate how carbon credits can result in carbon footprint reduction. The authors showed, in the case study, that the CCHP system can reduce carbon footprint by more than 40% in comparison to conventional technologies. Lu et al. [125] performed a 3E analysis for CCHP systems located on a remote island in the South China sea. Two different kinds of absorption chillers were analysed for the proposed CCHP system. The double effect absorption chiller had lower carbon dioxide and economic performance than a single one. Zhao et al. [126] carried out a 4E analysis for the PEM fuel cell-based CCHP system. The results demonstrate that high inlet pressure and an increase in mass flow of chilled water can lower GHG emissions of the system. On the other hand, high cooling water mass flow increases the GHG emission of the system. Chang et al. [127] studied a PEMFC and solar energy-based CCHP system. The addition of solar energy to the PEMFC-based CCHP system can decrease GHG emissions by 8.4–23.5%. Li et al. [128] studied natural gas-fuelled CCHP systems in China. It demonstrated that CCHP systems with a gas engine as a prime mover have better performance than CCHP systems with a gas turbine. It also showed that the CCHP systems operation lower GHG emission for all the case studies.

Ahn et al. [129] studied the operation of CCHP systems in cooling and heating seasons. It was demonstrated that CCHP systems have better performance in lowering GHG emissions in the cooling season than in the heating season. According to the results, the more heat used to supply the cooling load, the higher the energy consumption and CO_2 emissions. Co-production of multiple products by CCHP increases the challenge of allocating carbon footprint to each energy stream, especially when these products are sold to different customers. Ubando et al. [130] introduced a fuzzy fractional programming model to design a CHP system and identify carbon footprints in each energy stream. The model determines the minimum amount of carbon footprint for each stream so that it also provides the specified amount of energy. Table 6 demonstrates common methods used in the literature to analyse, evaluate, and optimise different environmental aspects of CCHP systems. Moreover, in this table, the country or region and the sector details of each paper are shown.

Table 6. Methods, demographic, and sector details of studies related to environmental aspects of CCHP systems.

Method Used	Country/ Region	Sector			Ref.
		Industrial	Residential	Commercial	
Hybrid IGDT-stochastic optimisation approach	China	✓			[131]
Epsilon constraint and fuzzy methods	China	✓	✓		[132]
Energy and exergy analysis	Iran		✓		[133]
Exergoeconomic analysis method	China		✓		[54]
TRNSYS thermal models	China	✓			[134]
TRNSYS thermal models	Remote island in the south of China		✓		[125]
Energy analysis	Iran	✓			[135]
Genetic algorithm	China			✓	[51]
Multi-objective optimisation algorithm	Iran		✓		[136]
3E analysis	Singapore and Shanghai			✓	[137]
Multivariate regression, multivariate statistical analysis	7 climate zones in the U.S.			✓	[138]
Weighted sum technique and max-min fuzzy technique	Iran	✓			[139]

Zhang et al. [140] compared the performance of the CCHP system with the solar assisted CCHP system. The presented system components were a chemically recuperated gas turbine, absorption chiller, and heat exchange. The integration of solar heat reduced GHG emissions by 33%.

6. Water Footprint

Water footprint indicates the amount of water utilised to produce each of the goods and services we make use of [141]. There are two direct and indirect ways to trace the water footprint of a process, product, or department, which include water consumption and water pollution during the generation life cycle from the supply chain to final consumption.

The following is a case study of water use in CCHP systems in Georgia [142]. The water consumption of a system represents the direct water footprint of that system or process. Safari et al. [143] performed water footprint optimisation of CCHP systems. In this study, water and energy footprint was considered to achieve an optimum design. In a three-objective scenario, the energy, environmental, and economic indicators were considered as three objective functions. Besides these objective functions, water footprint was added as the fourth objective function. Optimisation in a four-objective scenario provides better results than a three-objective scenario. The optimum economic and energy objectives were improved by more than 30 and 12 percent in the four-objective scenario. Mohsenipour et al. [85] studied the water footprint of a geothermal based CCHP system. Energy analysis and optimisation are performed. Among the different components of the proposed system, the vapour generator has the highest water footprint.

6.1. A Case Study on Water Footprint

The CCHP system in this case study includes an air turbine micro-turbine for cooling and an absorption chiller for cooling and heating a building. Here, the CCHP system is designed as an FTL model. The reasons for choosing this model were (1) more input FTL (heat-based design) than following electric load (FEL) (power-based design), which increases the optimisation capability of the model in line with environmental concerns, and (2) no need to separately receive heat by burning extra fuel. In the research [142], five scenarios were tested to see which one had the greatest reduction in NO_x pollution and CO_2 emissions and the water need for energy generation.

6.2. Water Consumption to Meet Energy Demand and Greenhouse Gas Emissions

The mean CO_2 and NO_x emissions per kilowatt-hour of power generation in Atlanta in 2012–2013 are shown in Table 7. Water employed for cooling in power generation includes the water that releases in watersheds and the water that evaporates (e.g., in systems where the cooling water cycle is not closed, i.e., once-through cooling systems). Water demand (evaporation loss) for energy generation was computed utilising the mean demand coefficient for the Georgia grid (1.65 gal·$(kWh)^{-1}$). The secondary analysis compares CCHP scenarios with cases in which the energy needed by the grid is supplied by a gas-fired combined cycle power plant utilising the factor (average water consumption coefficient) of 0.2 gal·$(kWh)^{-1}$.

Table 7. Greenhouse gas emissions and water consumption for different sectors of energy generation [142].

	CO_2 Emissions (kg·$(kWh)^{-1}$)	NO_x Emissions (g·$(kWh)^{-1}$)	Water Demand for Energy Generation (gal·$(kWh)^{-1}$)
Micro-turbine	0.768	0.290	-
Conventional electrical grid	0.570	0.408	1.65
Furnace	0.227	0.425	-
Combined cycle natural gas plant	0.515	0.300	0.20

6.3. Savings in Water Consumption for Energy Demand Supply

Figure 3 shows the water consumption of energy generation for an average-size office building under all defined scenarios (FTL), assuming: (1) mean water demand for Georgia electricity generation and (2) all grid energy is supplied employing a combined-cycle power plant. The water used to meet energy demand is lessened to almost zero in the scenarios of monthly operating and the maximum annual heat demand. This was an anticipated result because CCHP generates extra heat while generating more electricity, without the need to receive power from the grid. As mentioned, not consuming the grid electricity means no water use to meet energy demand. For other buildings, the results of water consumption for energy generation were similar (Table 7). Water demand for energy supply in all buildings and CCHP-based scenarios is below the scenario of using the national grid and is zero in all cases where the CCHP system is used to fulfil maximum annual heat demand.

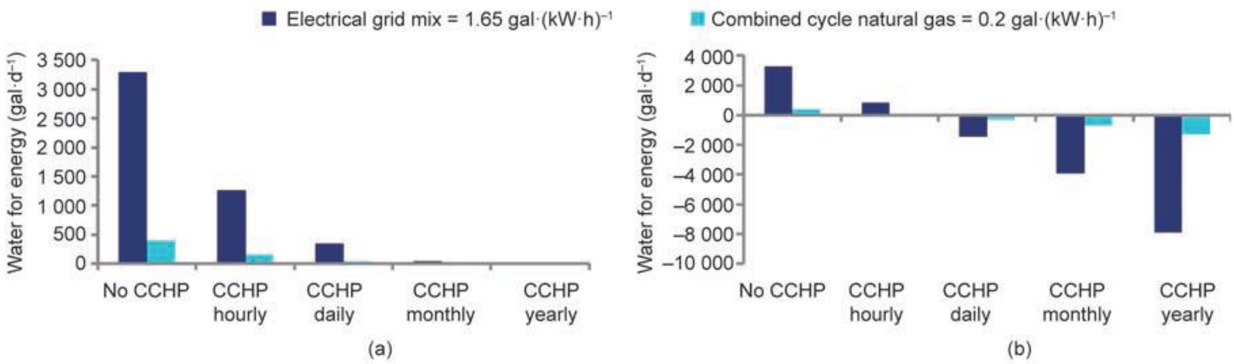

Figure 3. Water demand for the energy supply of a medium-sized office building, a comparison on the consumption coefficient of Georgia grid, a natural gas combined cycle power plant. (**a**) Water consumption for energy generation in mid-size office buildings with CCHP system and without net metering; (**b**) water consumption for energy supply in mid-size office buildings with CCHP system and net metering [142].

7. Role of Carbon Taxation in CCHP Policymaking

Increasing global awareness of global warming and the effects of pollutant emissions has led to a reduction in greenhouse gas emissions. Emissions should have been reduced by 40 to 45% from 2005 to 2020 [144]. CCHP systems are one of the most effective ways to help reduce emissions and increase energy efficiency [145]. Therefore, policies designed to reduce greenhouse gas emissions, such as carbon taxes, can play an important role in the development of these systems.

Chu et al. [123] analysed the performance of the CCHP system under the hybrid electric-thermal load (FHL) operational strategy (a hybrid of the two FTL and FEL approaches) based on costs (including operating costs) and different levels of carbon taxation. To analyse the impact of carbon taxation on the CCHP system, they examined the impact of carbon taxation from USD 1 to 20 per kilowatt-hour using simulation. Figure 4 shows the effect of variable carbon taxes on carbon and energy costs. As the carbon tax increases linearly, so does the overall cost. With the linear increase in carbon taxes, the overall cost also increases. The cost of energy will increase when the carbon tax is between USD 9–11 and 15–17 per kilowatt-hour.

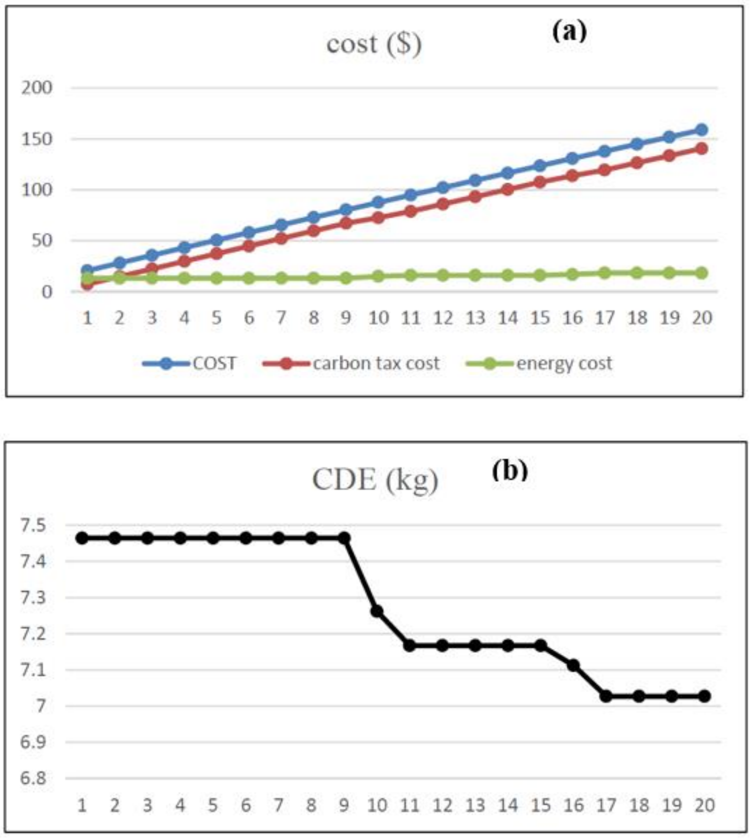

Figure 4. Impact of different carbon taxes on (**a**) total costs and (**b**) carbon taxes on CDE [123].

Figure 4 shows that changing the carbon tax from USD 1–9, 11–15, and 17–20 per kilowatt-hour does not change the CDE (carbon dioxide emission), but the reduction will occur when the carbon tax changes from USD 9–11 to 15–17 per kilowatt-hour. Therefore, Chu et al. showed that the optimal carbon tax is USD 10 per kilowatt-hour. The authors also mentioned that the carbon monitoring mechanism is suitable for capturing the total carbon emission in the CCHP system for the establishment in a specific area. The parameters assigned in the experiments will vary, but the models in their study [123] for carbon emission estimations can be used in other areas.

8. Conclusions and Prospective

This paper examines the CCHP system in various contexts, such as technical, geographical, political, environmental, and the approach of some countries in dealing with this system. In each section, related conclusions are given, but in general, a summary of these conclusions is as follows:

- In general, to meet the same demand, CCHP systems have less greenhouse gas emissions than conventional systems due to less consumption of primary energy sources.
- A comparison of a CCHP system with a stand-alone coal combustion system shows that the CCHP is not only more efficient but also more environmentally friendly. Using the CCHP system instead of the stand-alone system can reduce coal consumption, resulting in an 11% reduction in environmental damage.
- Two general approaches can be used to reduce the carbon footprint in a CCHP system. The first approach is to reduce the carbon emissions of the system. This can be achieved by improving the efficiency of components such as the combustion engine. In this case, less initial energy will be needed to produce the same force. The second is to increase the production of the products with a lower impact factor in calculating the overall carbon footprint of a multi-product system. This product in CCHPs is usually "cooling". This approach can be adopted where high cooling is required.
- In addition to emitting fewer greenhouse gases, CCHP systems use less water than conventional systems. However, attention should be paid to the difference between water consumption and water use. Contrary to the second approach where water is not lost after use, in the first case, water is not reused and, for example, is evaporated by cooling towers and dispersed in the environment.
- Exitance of energy storage tanks for cooling, heating, and energy generation can be among the strategies to optimise the performance of CCHP systems. As a result, energy shortages can be avoided at peak times and more energy can be saved.
- By integrating CCHP and renewable energy, the environmental impacts can greatly be mitigated. In combining the system with solar energy, it should be noted that the more tropical the region, the more radiation and consequently the higher the efficiency of solar panels. However, CCHP systems do not work well in the tropics due to high cooling demand and low heating demand. As a result, this combination can be used in temperate regions.
- This system can also be combined with hydrogen production units [146] and wastewater treatment and desalination plants. In this way, while improving the performance of both parts, the wasted energy can be used to produce more products.
- Cooling technologies used in CCHP systems can directly affect their efficiency and performance. The choice of this equipment depends on various parameters such as the amount of "capital" and "cooling" required. In general, the integration of absorption and electric chillers will improve the performance coefficient of CCHP systems. The use of a water tank can also improve the performance of the chiller. The distance between the power plant and the cooling centre, i.e., the distance that the current must travel, is another condition that affects the performance of the system. Absorption chillers are suitable for distances of less than 5 km, while at distances of more than 9.3 km, electric compression systems are a better option.
- CCHP systems can be used in a variety of industries and buildings to reduce energy consumption. Because of gas tariffs and government subsidies, it can be used in airports and hospitals, as well as in the food industry and supermarkets.
- The development of CCHP systems in various countries is largely dictated by government policy. In France, for example, where the focus is on nuclear power generation, the expansion of CCHP systems is very low, but countries such as Denmark, The Netherlands, Finland, and Austria are among the leaders in expanding these systems in Europe. The expansion of CCHP systems has also been addressed in the development plans of China and the USA. CCHP systems are not suitable in coun-

tries and regions with high gas prices and low electricity prices and may increase running costs.

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Nomenclature

ATCSR	Annual Total Cost Savings Rate	IRR	Internal Rate of Return
CCHP	Combined Cooling Heating and Power	ISO	International Organization for Standardization
CDE	Carbon Dioxide Emission	LCA	Life Cycle Assessment
CDERR	Carbon Dioxide Emission Reduction Rate	LCIA	Life Cycle Impact Assessment
CHP	Combined Heating and Power	PCO_2ER	Poly-generation CO_2 Emission Reduction
CGTC	Combined Gas Turbine Cycle	PEMFC	Proton Exchange Membrane Fuel Cell
COP	Coefficient Performance	PFESR	Primary Fossil Energy Saving Rate
EDM	Electrical Demand Management	MCDA	Multi-Criteria Decision Analysis
FEL	Following Electric Load	MPCF	Multi-Product Carbon Footprint
FHL	Following Hybrid Electric-Thermal Load	MINLP	Mixed-Integer Nonlinear Programming
FTL	Following Thermal Load	NPV	Net Present Value
GFC	Gas-Fired Absorption Chiller	CC-MOPSO	Co-Constrained-Multi-Objective Particle Swarm Optimisation
GHG	Greenhouse Gas	PV	Photovoltaic
GSHP	Ground Source Heat Pump	PV-T	Photovoltaic Thermal
HRSG	Heat Recovery Steam Generator	TDM	Thermal Demand Management
HP	Heat Pump	SOFC	Solid Oxide Fuel Cell
ICE	Internal Combustion Engine	SP	Separate Production
IGDT	Information Gap Decision Theory		

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