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Systematic Review

The Economic and Environmental Evaluations of Combined Heat and Power Systems in Buildings with Different Contexts: A Systematic Review

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Abstract: Cogeneration systems—also known as combined heat and power systems—form a promising technology for the simultaneous generation of power and thermal energy while consuming a single source of fuel at a site. A number of prior studies have examined the cogeneration systems used in residential, commercial, and industrial buildings. However, a systematic review of the economic and environmental evaluations of the system is not found in the literature. The present study aims to address this research gap by reviewing the most relevant studies on the cogeneration systems applied to buildings in different contexts (e.g., residential, commercial, and industrial) and provides systematic evaluation approaches from economic and environmental perspectives. Results show that the cogeneration system can significantly reduce energy consumption, operating costs, carbon dioxide equivalent emissions, and positive performance on other relevant parameters. The present study provides extensive evidence to show that the cogeneration system is simultaneously economically profitable and environmentally friendly in various application contexts. To achieve the maximum benefits from cogeneration systems, several practical suggestions are provided for their successful installation and implementation in real-life situations.

Keywords: cogeneration system; economic evaluation; environmental evaluation; systematic review

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1. Introduction

Advanced industrial development and world population growth have led to a remarkable increase in energy consumption in the past decades [1–3]. Data from the United States Environmental Protection Agency show a 6.8% increase in greenhouse gas emissions from 2020 to 2021 [4]. According to the report released by the International Energy Agency [5], when energy consumption levels remain unchanged and a sustainable development scenario is considered, the demand for global electricity consumption will increase by 2.1% annually until 2040. As a result, the consumption of fossil fuels and the emission of greenhouse gasses will substantially increase and will exacerbate global warming and ozone depletion problems, becoming a main global concern [6,7]. For the minimization of climate change threats and the enhancement of sustainable development goals, the use of high-efficiency energy generators is promising solution. Because of the increase in energy prices and uncertainty in fuel supply, engineers have become dedicated to developing more efficient systems for electricity production. Replacing conventional power generators with combined heat and power (cogeneration) systems (CHP) is a cost-effective way of improving energy efficiency [8].

Cogeneration systems refer to energy generation units that can simultaneously produce power and heat by consuming a single fuel source with a prime mover and a heat recovery system (Figure 1) [9,10]. During the process of electricity production, much energy

is wasted as thermal energy. To save the wasted thermal energy, cogeneration systems make use of it to generate heat by utilizing resources such as fuel cells and micro turbine [11]. The heat can be utilized for heating or cooling purposes in various industrial sectors. Cogeneration systems are not new technology; they have been used in industrial plants since the early 1880s. They were prevalent when engineers used pulley mechanisms and steam belts to generate electricity by motors. Steam turbine generators and coal-fired boilers were used to generate electricity with exhaust steam, which was an industrial byproduct that can be used for different applications, such as heating water [12]. Cogeneration systems are also suitable for use in buildings, including institutional buildings, hospitals, hotels, single- and multi-family residential buildings, and office buildings [13].

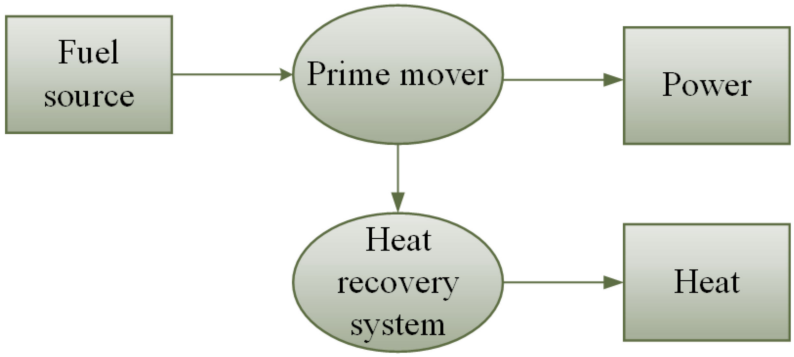


Figure 1. A schematic view of a simple cogeneration system.

Some past studies have evaluated cogeneration systems from economic and environmental perspectives. For instance, Oh, et al. [14] conducted a study to economically assess a cogeneration system installed in a Korean hospital in terms of payback period and internal rate of return on the initial investment. Asaee, et al. [15] evaluated the use of cogeneration systems in Canadian houses considering greenhouse gas emission reduction and tolerable capital cost as environmental and economic performance metrics, respectively. Recent review studies on cogeneration systems, such as De Souza, et al. [16], Ahmed and Kumar [17] and Özgür and Yakaryılmaz [18] have mainly focused on the technical aspects of cogeneration systems. However, a systematic review on the environmental and economic evaluations of cogeneration systems in buildings with different contexts is not found in the literature. Therefore, this study aimed to address this research gap by conducting a systematic review on these evaluations in order to answer two research questions: (1) what are the common approaches to economic and environmental evaluations of cogeneration systems used in various contexts? and (2) what is the economic and environmental feasibility of cogeneration systems? By answering these two research questions, this study aims to provide evidence to prove that cogeneration systems are simultaneously economically profitable and environmentally friendly in various application contexts. Based on the evaluation approaches used in the selected studies, the present study shall give some practical suggestions for the installation and implementation of cogeneration systems in real-life situations.

2. Methods

A systematic review was conducted to answer the two research questions. In the systematic review, a literature search was undertaken to collect data. Five databases were used for the literature search, including Web of Science, Google Scholar, ScienceDirect, PubMed, and Scopus, to identify the studies that describe the environmental and economic evaluations of cogeneration systems. The keywords used for the literature search included (cogeneration OR cogeneration system OR heat and power system OR power and heat system) AND (environmental evaluation OR economic evaluation). Studies published in the past 20 years (i.e., published after 2000) were identified to obtain the recent characteristics of cogeneration systems and to ensure sufficient literature.

Subsequently, four inclusion criteria were used to select the articles suitable for this systematic review. First, the studies where full text could be obtained were included. Thus, the studies without the full text were excluded. Second, the studies that clearly stated how to evaluate cogeneration systems in terms of economic and environmental performance were included. Thus, the studies that failed to report the evaluation details were excluded. Third, the studies that were peer-reviewed were included. Fourth, if the studies used the same data, only one of the studies was selected for this systematic review to prevent overlapping. The first two authors evaluated the full text of the selected articles. If there were disagreements that could not be resolved, the third author was invited for their viewpoints.

3. Results

3.1. Study Selection

The presentation of the systematic study selection process is shown in Figure 2, following that of Natsky, et al. [19]:

(1) Identification: after searching the keywords, as listed in the previous section, a total of 1373 studies, published after 2000, were identified. An additional seven studies were retrieved from a search of the reference lists included in the present work. Eight studies without the full text were removed. Thus, 1372 studies were left.

(2) Screening: the 1372 articles were screened with titles and abstracts to see whether they were closely relevant to the current topic. One thousand two hundred fifty articles that were not closely relevant to the current topic were excluded. One hundred twenty-two articles remained.

(3) Eligibility: the 122 full-text articles were assessed for eligibility. One hundred three studies were excluded for the following reasons: 77 studies failed to report evaluation details; 26 studies were not peer-reviewed; and no studies involved duplicated data. This left a total of 19 articles.

(4) Included: the 19 shortlisted articles were thus included for systematic review.

3.2. Study Characteristics

A summary of the characteristics of the 19 included studies is presented in Table 1. A list of all abbreviations is added in Table 2 for readers' convenience in reading the manuscript.

3.2.1. Geographical Location

The included studies analyzed data from different countries/regions, namely, Brazil [20], Canada [15], Greece [21], Italy [22–24], Korea [14], Malaysia [25], Portugal [26], Spain [27–29], Thailand [30], Japan [31], Germany [32], China [33], the United Kingdom [34], and the United States [35,36].

3.2.2. Settings of Cogeneration Application

The selected studies included cogeneration systems applied to various contexts (i.e., residential, commercial, and industrial). Five studies reported evaluation details of the system in the residential sector [15,22,26,28,32], eight studies in the commercial sector [14,21,25,27,29,30,35,36], four studies in the industrial sector [20,23,24,34] and one study in the hotel sector [33]. One study did not clearly mention the specific sector in which the data were obtained [31].

3.2.3. Methodology

It was found that the 19 studies were conducted through two main methods: comparative analysis and model-based simulation analysis. With the former, four studies compared multiple types of cogeneration systems [21,23,24,27]. For example, in Renedo, Ortiz, Manana, Silio and Perez [27], the authors compared two cogeneration types, one with diesel engines and the other with gas turbines. Three studies compared the proposed or installed cogeneration with conventional separate energy generation [28,30,34]. Ten of

the remaining studies used model-based simulation methods to assess the economic and environmental merits of the cogeneration systems [14,15,20,22,25,26,29,32,33,35]. There are also two studies combining both operational data of the cogeneration in actual sites and transient modeling to evaluate the system [31,36].

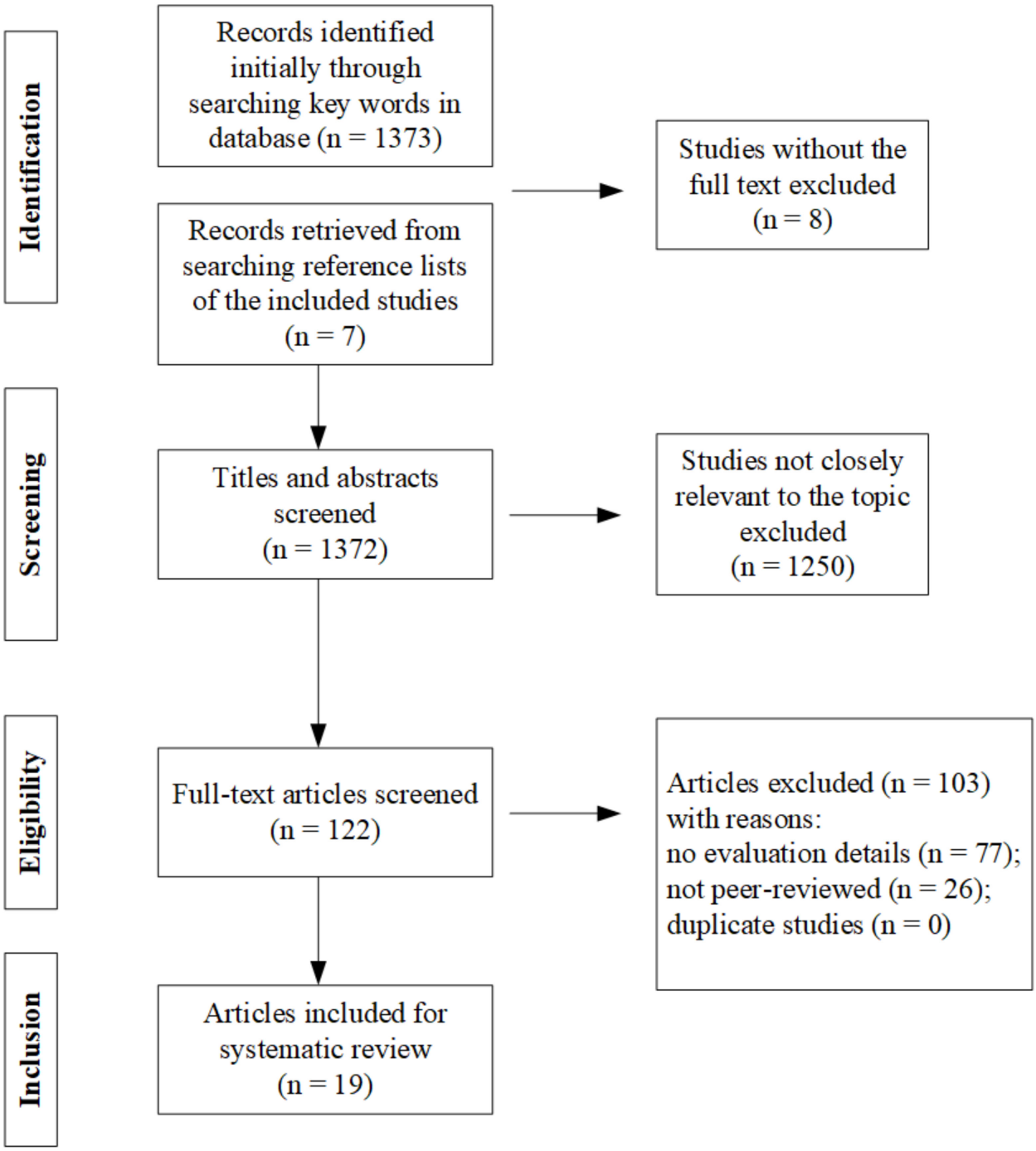


Figure 2. Flow chart of study selection process.

3.2.4. Cogeneration Type

The types of cogeneration systems differ across the involved studies. Ten studies examined the cogeneration system with gas engines [14,20–22,26,28–30,34,35]. Seven of the rest examined the system with various other types, such as with biomass engine in Giacchetta, Leporini and Marchetti [24], internal combustion engine in Asaee, Ugursal

and Beausoleil-Morrison [15], natural gas and electricity consumed engine in Xu and Qu [36], a system consisting of photovoltaic, battery and fuel cell in Isa, Das, Tan, Yatim and Lau [25], a solar-driven cogeneration system in Wu, Li, Xiang, Wang, Wang and Li [33], and hydrogen-based cogeneration systems with fuel cells in Endo, Shimoda, Goshome, Yamane, Nozu and Maeda [31] and Knosala, Kotzur, Röben, Stenzel, Blum, Robinius and Stolten [32]. Additionally, there are two studies involving different types of cogeneration systems. In the study of Renedo, Ortiz, Manana, Silio and Perez [27], a system with diesel engines and one with gas engines were considered. In the work of Badami, Camillieri, Portoraro and Vigliani [23], three systems with an internal combustion engine, gas turbine, and combined cycle power plant were analyzed.

3.2.5. Evaluation Approaches

Seven of the studies adopted an economic evaluation perspective, while the remaining 12 studies adopted both economic and environmental evaluation perspectives. Studies that employed the former perspective assessed energy consumption, operating costs (e.g., maintenance cost and procurement cost of primary energy), system efficiency, and other relevant factors (e.g., net present value, payback period) [14,20,23,24,27,31,32]. However, each study may not include all these parameters (see Table 1). Studies employing both economic and environmental perspectives assessed pollutant emissions additionally, such as CO_2, NOx, CH_4, and SO_2 [15,21,22,25,26,28–30,33–36]. Note that each study may not include all these pollutants (see Table 1).

3.3. Summary of Results

The main results regarding the economic and environmental feasibilities of the CHP configuration in residential, commercial, and industrial buildings are summarized in Table 1.

3.3.1. Economic Feasibility

All included studies indicated that installing an optimal cogeneration plant was an effective method to improve the economic return. Such a positive effect was mainly reflected in a reduction of primary energy consumption and operational costs, increasing energy production and net present values, and shortening payback periods. For example, Xu and Qu [36] compared the CHP configuration with the conventional separate energy generation and found that the former delivered a higher overall efficiency than the latter. Even though the CHP plant might cost relatively high operational investments, it was still a favorable system in, for example, the textile sector in Brazil [20].

3.3.2. Environmental Feasibility

Twelve studies, considering the environmental aspect, indicated that a suitable cogeneration plant was environmentally friendly [15,21,22,25,26,28–30,33–36]. This was reflected in the aspect that the CHP system could significantly reduce annual pollutant or greenhouse emissions and increase environmental benefits. Furthermore, Soltero, Chacartegui, Ortiz and Velázquez [28] reported that the CHP system could reduce nuclear radioactive waste. If the carbon emission savings were monetized, the annual worth would be higher [26].

Table 1. Summary of the included studies.

Study	Country	Context/Setting	Methodology	Cogeneration Type	Economic Parameters	Environmental Parameters	Findings
Renedo, Ortiz, Manana, Silio and Perez [27]	Spain	Hospitals	Comparing two cogeneration types	Cogeneration systems with either diesel engine or gas turbine	Electricity production, time of use at full load, and installation and operating cost	NA	The system with diesel engines was more efficient than the ones with gas turbines. This was determined based on the former having a higher electrical performance, which was suggested as the most significant parameter when considering the economy of the cogeneration installation.
Oh, Lee, Jung and Kwak [14]	Korea	Hospitals and apartments	Programming calculation with the branch and bound algorithm	Gas engine-based cogeneration system	Energy demand, operational cost, PB period, and IRR	NA	The study demonstrated that the installation of an optimal cogeneration plant to hospitals and apartments was determined by considering the annual energy demand, which crucially affected the payback period and IRR on the initial investment.
Mago and Smith [35]	USA	Seven types of commercial buildings	Modelling-based simulation analysis	Natural gas-fuelled cogeneration system	Primary energy consumption and operational cost	Carbon equivalent emissions (e.g., CO_2, NO_x, CH_4)	The analyses revealed that the cogeneration could reduce primary energy consumption, operational cost, as well as emissions. Moreover, high fractions of the thermal load could provide better emissions, cost, and primary reduction from the CHP system.
Alexis and Liakos [21]	Greece	Hospital	Comparing cogeneration units with various operating hours	Natural gas engine-based cogeneration system	Annual energy cost, annual primary energy consumption, BCR, NPV, and PB period	Pollutant emissions (e.g., CO_2, NO_x, SO_2)	The study showed that, when using a cogeneration system with appropriate operations and backups, the total annual energy cost would be reduced. The BCR became greater than one, and the NPV was positive. Moreover, there was a significant reduction in annual primary energy consumption and annual pollutant emissions.
Rosato, Sibilio and Ciampi [22]	Italy	Residential building	Modelling-based simulation analysis	Natural gas-fired cogeneration system	Energy consumption and operating cost	CO_2 emissions	The study demonstrated that the proposed system allows for a reduction of primary energy consumption, CO_2 emission, and operating cost, in comparison with the conventional separate system.
Xu and Qu [36]	USA	Data centres in commercial buildings	Operational data of actual sites and transient modelling	Natural gas-driven cogeneration system	Primary energy consumption, operational cost, and system efficiency	CO_2 equivalent reduction ratio	The results show that the cogeneration system reduced primary energy consumption, carbon dioxide equivalent emissions, and operational costs, with higher overall efficiency, compared with conventional systems.
Badami, Camillieri, Portoraro and Vigliani [23]	Italy	Industrial sectors	Comparing different cogenerations	Cogeneration systems with either ICE, GT, or CC power plants	Primary energy saving, investment cost,	NA	The analyses have highlighted the advantages of CPH plants. All CPH plants allowed for saving primary energy consumption, compared to separate systems. The plant with an ICE spent the lowest investment costs.

Table 1. *Cont.*

Study	Country	Context/Setting	Methodology	Cogeneration Type	Economic Parameters	Environmental Parameters	Findings
Ferreira, Nunes, Martins and Teixeira [26]	Portugal	Residential building	Modelling-based simulation analysis	Micro-gas turbine-based cogeneration system	Investment and operational cost, primary energy saving	Carbon emission savings	The case study proved that the cogeneration system represented a more efficient way to produce heat and power, and reduced gas emissions. The annual worth would be higher if the carbon emission savings were monetized.
Giacchetta, Leporini and Marchetti [24]	Italian and European level	Manufacturers of small and medium size	Comparing different energy generations with data in literature	Biomass-fired cogeneration system	Energy consumption and generation, PB period, NPV, and system efficiency	NA	The results show that the CHP is economically viable with a high NPV and a shorter PB period, and also technically performing with a high global efficiency and low biomass consumption.
Kelly, McManus and Hammond [34]	UK	Industrial sector	Environmental lifecycle assessment	Gas-fired cogeneration system	Energy gain ratio and energy PB period	Global warming potential	The study showed that the CHP was proven to deliver a total energy saving and a global warming potential saving, in comparison with separate heat and power generations.
Kritsanawonghong, Gao, Iamtrakul and Kuroki [30]	Thailand	Convenience stores	Comparing the CHP with a conventional system	Natural gas engine-driven micro-cogeneration system	Primary energy saving	CO_2 emissions	The results show that selecting an appropriate micro-cogeneration system depended on the characteristic of the load profile and the objective of the utilization of the system. Moreover, the electrical and thermal efficiencies of the system had a significant effect on increasing both energy savings and environmental benefits.
Asaee, Ugursal and Beausoleil-Morrison [15]	Canada	residential	Modelling-based simulation analysis	ICE-based cogeneration	Primary energy consumption, tolerable capital cost	Greenhouse gas emission	The ICE-based cogeneration is an effective system to approach net zero energy status in existing Canadian houses. It also enabled a reduction in greenhouse gas emissions. The tolerable capital cost analyses indicated that a large storage tank is not a suitable option in most Canadian cities; thus, smaller storage tanks are preferable.
Isa, Das, Tan, Yatim and Lau [25]	Malaysia	Hospital	Modelling-based simulation analysis	Cogeneration system consisting of photovoltaic, battery and fuel cell	NPV, levelized energy cost, energy production	Pollutant gas emissions	The analyses showed that the cogeneration system projected the lowest net present cost, levelized cost of energy, and operating cost. Furthermore, the system had been proven environmentally friendly, as it would produce less pollutant gas.
Soltero, Chacartegui, Ortiz and Velázquez [28]	Spain	Residential buildings	Top-down/bottom-up analysis	Natural gas fired cogeneration system	Energy demand and generation, benefit-cost ratio	CO_2 emissions, contaminants dispersion	The case study showed a potential for more fully viable cogeneration district heating systems. Results show that the CHP system would not increase the energy cost, and would reduce CO_2 emissions and nuclear radioactive waste.

Table 1. *Cont.*

Study	Country	Context/Setting	Methodology	Cogeneration Type	Economic Parameters	Environmental Parameters	Findings
Silva, Dutra, Costa, Ochoa, Dos Santos and Araújo [29]	Brazil	University	Modelling-based simulation analysis	Gas engine-based cogeneration system	Energy demand, NPV, PB period	Pollutant emissions	The results show that the proposed cogeneration system would meet electricity and thermal comfort needs. Thus, it would be technically feasible and environmentally friendly.
Leite, Alcântara, Ochoa, dos Santos, Dutra, Costa, Michima and Silva [20]	Brazil	Textile industry	Modelling-based simulation analysis	Natural gas engine-based cogeneration system	NPV, IRR, PB period	NA	The study demonstrated that the cogeneration was a favorable system in the textile sector, even for the high operational investments.
Endo, Shimoda, Goshome, Yamane, Nozu and Maeda [31]	Japan	Not mentioned clearly	Operational data of actual sites	Hydrogen-based cogeneration system with fuel cells	Energy demand and generation	NA	The results show that the Bench-scale H2 energy utilization system is feasible for zero emission buildings without external heat sources.
Knosala, Kotzur, Röben, Stenzel, Blum, Robinius and Stolten [32]	Germany	Residential buildings	Modelling-based simulation analysis	Hydrogen-based cogeneration system with fuel cells	Operational cost, investment cost, system efficiency	NA	The study indicated that the cogeneration system was a favorable system for residential buildings.
Wu, Li, Xiang, Wang, Wang and Li [33]	China	Hotel	Modelling-based simulation analysis	Solar-driven cogeneration system	Primary energy saving ratio, annual cost–saving ratio	Carbon equivalent emissions (e.g., CO_2, NO_x)	The results show that the solar-driven cogeneration system can reduce greenhouse gas emissions, positively depending on solar irradiation. Additionally, the annual cost–saving ratio of the system is more influenced by electricity prices

Table 2. A list of all abbreviations and their corresponding full names.

Abbreviations	Full Names
BCR	Benefit–cost ratio
CC	Combined cycle
CER	CO_2 emission reduction
CHP	Combined heat and power
GT	Gas turbine
ICE	Internal combustion engine
IRR	Internal rate of return
NA	Not applicable
NPV	Net present value
PB	Payback
PEC	Primary energy consumption

4. Discussion

This systematic review applied strict reporting standards to review economic and environmental evaluation studies investigating the CPH system. A number of previous studies have provided approaches to evaluate the systems. However, they did not incorporate a systematic search strategy and standard reporting, which is addressed in this study.

The present study is the first systematic review focusing on the economic and environmental evaluations of cogeneration systems. We successfully identified 19 studies evaluating the CPH applications and found that they generally had good quality. These studies differed based on evaluation approaches, type of cogeneration, setting, and methodology. For this reason, a direct comparison of the results of the studies was not allowable. Nevertheless, our findings indicate that CPH implementation can lead to economic efficiency and environmental effectiveness. The innovation of this review can be reflected in two aspects. First, this review successfully identified the common approaches to economic and environmental evaluations of cogeneration systems used in various contexts. Second, the results of this review support the economic and environmental feasibility of cogeneration systems in buildings with different contexts. The detailed discussion is presented in the following subsections.

4.1. Economic Efficiency

There are several economic evaluation approaches involved in these studies, including primary energy consumption, energy production, operational costs, and other relevant factors (e.g., net present value, payback period, internal rate of return). According to the selected studies, a suitable CHP configuration will significantly affect the values of these parameters in comparison with conventional separate energy generation.

Under the CHP mode, there will be a significant reduction in fuel consumption [37]. In the work of Mago and Smith [35], seven different types of commercial buildings (e.g., hotel, school, small office, and supermarket) in the USA were evaluated using a CPH system. Their results show that the primary energy consumptions would be reduced for most of the buildings. The maximum reduction was obtained corresponding to the highest R_h value (fraction of the thermal load) by around 8.8%. Alexis and Liakos [21] compared different cogeneration units with various operating hours in a hospital in Greece. They found that, when using a cogeneration system with appropriate operational hours and backups, the annual primary energy consumption would be reduced by 28%. Additionally, with a simulated optimal CPH system, it was predicted that the consumption reduction in residential buildings in Italy could be up to 13.4% with respect to the conventional system [22]. Furthermore, through operational data and transient modeling, Xu and Qu [36] found that the CPH system reduced almost 14.12 GWh of primary energy consumption. The reduction of energy consumptions primarily helps to reduce net present costs over the

separate energy generations [38,39], and save a great deal of money based on the demanded fuel [37]. It also crucially affects the payback period and internal rate of return on the initial investment [14].

Regarding the energy production, the cogeneration system can generate both electricity and heat energy simultaneously from a single system using a single fuel, differing from the conventional system. In the study of Isa, Das, Tan, Yatim and Lau [25], a cogeneration system, consisting of fuel cell, photovoltaic system, and battery system, was proposed to fulfill the energy demand of a selected hospital building in Malaysia. Based on the simulation results, the proposed CPH system could produce the highest energy (251,760 kWh/yr), and the excess electricity of this system (69,003 kWh/yr) could be stored in the battery. The system has the lowest levelized cost of energy ($0.0841/kWh), which will save up to 30% of the cost on power generation. The effective energy production of the CPH has also been reported by Kelly, McManus and Hammond [34], who showed that harnessing the resource of industrial heat via the CHP configuration can generate electricity with lower associated energy than the current configuration. Thus, an ideal system represents a more effective and efficient way to generate useful heat and electricity [24,26] and, consequently, positive primary energy savings.

The operational costs also benefit from the CPH implementation. Through operational data and transient modeling, Xu and Qu [36] reported that the CPH system reduced $3,364,066 of operational costs for a data center in San Diego, California, with overall system reductions of 46%, in comparison with the existing conventional system. Rosato, Sibilio and Ciampi [22] simulated a CPH system for residential buildings in Italy and demonstrated that such a system enabled a reduction of operating costs of up to 20.9%. In Mago and Smith [35], the operational cost reduction of 5.7% was achieved for an outpatient building. This study further implied that the operational cost could be saved with a higher ratio of the thermal load from the CHP operation and that cost was an important factor when evaluating the performance of a CHP system.

4.2. Environmental Effectiveness

The environmental evaluation of a cogeneration system primarily considers its carbon dioxide equivalent emissions in comparisons with the classical system. By reviewing the included studies, all those considering the environmental effect confirmed that the cogeneration system is environmentally friendly. For example, in the study of Isa, Das, Tan, Yatim and Lau [25], the proposed cogeneration system was predicted to have a low emission of gases, producing 25,708 kg/yr of carbon dioxide, 111 kg/yr of sulfur dioxide and 54.5 kg/yr of nitrogen oxide. It is important for the hospital community to ensure the area maintains healthy and green premises. Therefore, the proposed cogeneration configuration for the hospital is suitable for the environment. Similarly, the results in Mago and Smith [35] show that the modeled CHP system reduced emissions for all seven types of commercial buildings examined, with more than 21% of carbon equivalent emissions reduced for an outpatient healthcare building. In another model-based simulation study, Rosato, Sibilio and Ciampi [22] reported that the optimal CPH system allowed for a reduction of the carbon dioxide equivalent emissions of up to 18.9%. Therefore, as stated in Ferreira, Nunes, Martins and Teixeira [26], an optimal CPH configuration is a more efficient way of reducing gas emission. The demonstration of these desirable results indicates that the CPH implementation is a reliable effort on global climate change [37]. If the carbon emission savings are monetized, the annual worth will be higher [26].

In short, the CPH system represents a more efficient way of economically and environmentally producing heat and power. However, the system viability and feasibility are crucially determined by several essential factors, i.e., energy demands (e.g., [14,37]), energy supply (e.g., [14,26]), system unit size (e.g., [15,40]), operational costs (e.g., [21]), and other possible parameters. In reality, these factors will definitely influence the decision to install a suitable cogeneration type.

4.3. Policy Implications

Considering the economic and environmental advantages, the CPH technology is strongly advised to serve various types of buildings worldwide. To achieve the maximum benefits from the cogeneration system, several practical suggestions are provided for the installation and implementation of the cogeneration system in real situations:

First, it was suggested to conduct both economic and environmental evaluations of different CPH technologies rather than conducting only economic or environmental evaluations when selecting the appropriate CPH technology. This is because this approach can provide a comprehensive understanding of the economic and environmental performance of a CPH technology for a certain context [15,21,22,25,26,28–30,33–36].

Second, the use of CPH technology should be promoted for different types of commercial buildings (e.g., hotel, school, small office, and supermarket) as this systematic review found that CPH technology is beneficial to different types of commercial buildings in terms of environmental effectiveness and economic efficiency. Concerned authorities and the government should provide incentive policies or programs to encourage the use of CPH technology for different types of commercial buildings.

Third, the selection of the proper cogeneration configuration size is a must, especially the size of the generator. The right size will generate the right amount of required energy with minimum losses. The suitable size is determined by the potential site condition and requirement. For example, the installation of the system at a school will encounter some challenges with respect to system sizing, plant selection, energy consumption, financial strategy, government policies, etc. To this point, simulation analysis is a necessary step for cogeneration optimization, e.g., [27,40,41].

Fourth, the selection of a suitable prime movers type is of significance. This is because the specific type of prime mover corresponding to the plant configuration can only allow for a certain amount of energy production in maximum to meet the demands. In this case, it is essential to consider some factors relevant to the prime mover, such as prime mover performance, energy demands, electrical performance, gas emissions, and initial investment (e.g., [15,30,42]).

Fifth, the selection of location should also be considered, which will avoid additional costs either in the initial installation or in future maintenance. To this point, the plant is better to be sited in a place where it can remain for long time without disruption or obstruction, and where it should have a large space for maintenance and/or housing supplementary equipment [28,40,43].

Last, economic strategy is another factor that calls for serious consideration. It is evident that economic investigation is the key to ensuring the success of the system's installation and implementation. Therefore, an appropriate financial method to support the project is the objective. The economic strategy relies on the state of the candidate's profile, the government-supported policies (e.g., government subsidy), and other financial supports (e.g., special tariff system) [14,23,25].

4.4. Limitations

This review makes significant contributions to the evaluation of cogeneration systems in theory and in application. Nevertheless, it has several potential limitations to keep in mind. First, it only includes studies that clearly report economic and environmental evaluation parameters and excludes those that do not clearly state the parameters but are also relevant to the topic. This may result in a relatively limited scope of the review. Another potential limitation is the heterogeneity of the selected studies, which covers a wide range of usages of the cogeneration system in various contexts. This may diminish the external validity and the capacity to pool quantitative data. Third, the relatively small number of included studies may limit the generalizability of the reported findings and lead to a lack of statistical information. Thus, it would be ideal to include more relevant and homogeneous studies to provide deeper and more comprehensive insights into the economic and environmental effects of applying cogeneration systems. Fourth, this

review did not cover the disadvantages of various cogeneration systems. More research should be undertaken to review this topic in the future. Last, the existing studies on the evaluations of cogeneration systems rarely used the hotel industry context. It was believed that cogeneration systems are suitable for the hotel industry as hotels consume a large amount of electricity and provide heat-related services, such as space heating and hot water supply [44]. Therefore, future studies should focus on this research area to help promote the use of cogeneration systems in the hotel industry.

5. Conclusions

The present study has provided a systematic review of 19 relevant studies on the economic and environmental evaluations of cogeneration systems to prove that the systems are simultaneously economically profitable and environmentally friendly in various settings. This may result in a significant reduction of primary energy consumption, operational costs, and pollutant emissions. A considerable reduction can be obtained with little/less extra investment [45]. Based on the findings of this study, some practical implications for the installation and implementation of the cogeneration systems in real situations were discussed in order to promote the use of the systems in different settings.

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