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Advances in Cogeneration and Trigeneration Systems: A Review on Conventional and Bio-inspired Approaches

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Abstract*– Climate change impacts have become a concern of all countries, and research on mitigation actions has increased in the last decades. One of the solutions implemented, which has proven benefits, is the installation of cogeneration and trigeneration plants in buildings. Likewise, interest in the search for technical solutions inspired by nature has increased, leading to the development of more sustainable systems. Thus, this work presents a systematic review on conventional and bio-inspired cogeneration and trigeneration systems at building scale to show the current available advances. For this, a bibliometric analysis is carried out using the VOSViewer software to present the current knowledge state and research trends. Results show that conventional systems achieve energy savings and reduce CO_2 emissions. Also, these systems can be improved by using renewable energy sources or making modifications to the components of the system based on nature strategies.

***Keywords*— Biomimetic, cogeneration, energy, sustainability, trigeneration.**

I. Introduction

Due to industrialization and urbanization, mainly in developing countries, there has been an increase in energy demand and, consequently, in pollution levels. Multigeneration systems such as cogeneration and trigeneration have therefore been developed.

Cogeneration and trigeneration systems have been implemented for decades to generate two or three forms of useful energy simultaneously by burning a single fossil fuel because they have higher yields than electricity and heat obtention through separate technologies [1].

In the 1970s, the scientific community became more interested in improving the efficiency of these systems. Since 2000, using renewable sources in cogeneration and trigeneration systems has emerged as a scientific research topic [2].

It has been estimated that about 73% of greenhouse gas emissions come from electricity generation and consumption [1], because only 33% of primary energy is transformed into useful energy, while the remaining 67% are losses caused by power generation and transport systems [3]. For this reason, conventional cogeneration and trigeneration systems are viable solutions to the problem described above, with efficiencies of 85% and 90%, respectively [1].

Some renewable sources that have recently been studied and evaluated to be integrated into multigeneration systems are solar energy and biomass.

In 2019, researchers from the University of Electronic Science and Technology of China, in collaboration with Cyprus International University, developed a trigeneration system powered by biogas made of chicken and corn silage. The system was designed to generate cooling, electricity, and hot water, through two steam cycles, a gas cycle, a hot water chamber, and an absorption cycle [4], prioritizing electricity production as the most versatile form of energy. By using biogas produced with 70,000 kg of poultry and 30,000 kg of corn silage, the trigeneration system was able to produce 1460 kW of electricity, 280.8 kW for cooling, and 122.6 L/min of hot water, obtaining an efficiency of 64%, that matches the values found in literature for multiple generation systems that rely on renewable energy. It was highlighted that the main challenge to using this type of system is the production of biogas due to all the specifications and the large quantities of raw material required.

In a similar study, researchers from North China Electric Power University proposed and simulated a cogeneration system that relies on solar energy, as this is a flexible resource that allows generating both electricity and heat, depending on the demand. A 330 MW solar-aided cogeneration plant was simulated, and its results showed that the feasible operation region is 74% larger than that of a cogeneration plant powered by fossil fuel [5].

The case studies presented above show that cogeneration and trigeneration systems where renewable energy sources are used can have even higher efficiencies than systems powered by fossil fuels.

It was in 1997 that Professor Janine Benyus proposed the term biomimicry and defined it as a new science that studies and imitates existing models, systems, and processes from nature to solve problems faced by human beings [6]. Using a biomimetic approach, architects, designers, and engineers can take information about how organisms have related to their

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environment throughout their evolution and try to emulate these natural processes in their designs [7].

Nowadays, biomimicry is mainly used to improve building sustainability through the design of innovative materials, the application of renewable energy sources, and the reduction of energy consumption [6]. For example, the Pearl River Tower case, where biomimetics, trigeneration, and renewable energies were applied to its design, is presented.

The Pearl River Tower, built between 2005 and 2013, is a skyscraper located in Guangzhou, China, whose structure is inspired by the sea sponge. Sea sponges can circulate through them thousands of gallons of water a day, obtaining their food from this flow, and are home to different micro-organisms; these characteristics were considered by architects to create a design capable of producing the same amount of energy that the building demands [8].

The tower has a curved shape that minimizes the pressure exerted by the wind, which reduces the amount of structural steel and concrete used for its construction. In addition, it has openings that emulate the sponge's pores, where four wind turbines are located to generate energy. It is important to highlight that these turbines are responsible for powering the trigeneration system from which electricity, ventilation, and air conditioning are obtained [6].

The building envelope presents innovations such as the installation of solar panels in large parts of the roof and facade, and a double-layered glass whose exterior has high solar permeability, while the interior prevents heat gain. The heat trapped in the facade is used for the heating system [8]. The description of this design fits into what is known as ecosystem biomimicry, an approach that emulates ecosystem strategies in which the product of one process is the primary source of another one [9].

This research performs a systematic literature review on the existing cogeneration and trigeneration systems at building scale, aiming to provide an overview of current advancements and present how biomimetics are applied to these systems.

II. METHODOLOGY

The methodology consists of a bibliometric analysis based on cogeneration and trigeneration systems, performance indicators used to evaluate them, and the implementation of biomimetic strategies to improve those systems.

A. *Search strategy*

The literature search strategy implemented consists of a combination of keywords related to the main topic. Two databases, Google Scholar and ScienceDirect, were used to implement the search strategy, applying no year limit.

The following keyword combinations were applied: “cogeneration OR trigeneration AND building,” “cogeneration OR trigeneration AND biomimicry,” “cogeneration OR trigeneration AND renewable energy,” “system-level biomimicry AND innovation.”

However, some of the publications found when the first filter was applied did not provide important information, such as performance indicators that allow comparisons or the application of biomimicry strategies on designs. For this reason, a second filter was applied by setting some exclusion criteria, i.e., characteristics used to identify which references should not be included in this paper. Fig. 1 shows the steps followed in the search strategy described above.

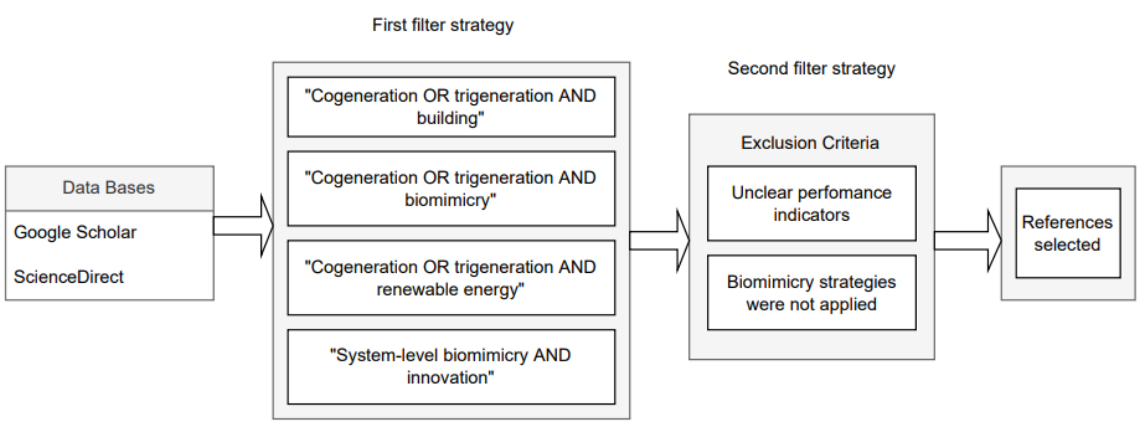

Fig. 1. Steps of search strategy implemented.

B. *Bibliometric analysis*

For the bibliometric analysis, the software VOSviewer was used. It creates links between colored bubbles of different sizes representing terms’ occurrence. The size of each bubble depends on the occurrence of each word.

A total of 2124 references were connected by co-occurrence of terms, extracted from keywords field, using the complete count method, with a minimum number of five occurrences. Of the 3281 keywords identified by the software algorithm, 324 met the threshold. The resulting overlay map based on keywords is presented in the following section.

III. RESULTS ANALYSIS AND DISCUSSION

A. Current state and tendency of the specific fields

Fig. 2 shows the map generated in the overlay visualization. With this map, it is possible to see how keywords related to the main topic of this paper have been used and have changed over the last few years.

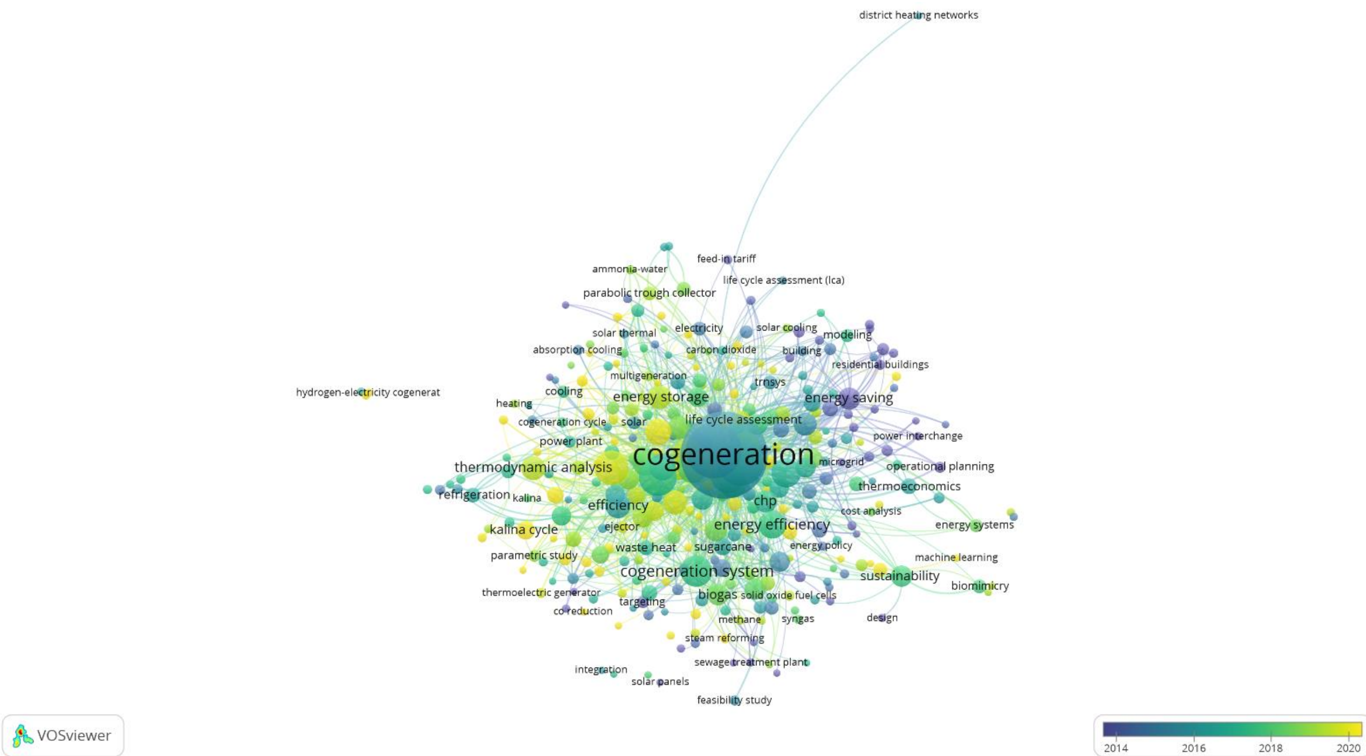

Fig. 2. Overlay visualization of keywords organized by publication years.

According to the analysis made by VOSviewer, “cogeneration” and “trigeneration” were the most repeated words, with a total of 621 and 260 occurrences, respectively. By seeing the size of the colored bubble for the word “cogeneration”, it is possible to make a visual comparison of this term occurrence with any other item that appears on the map.

On the overlay map, terms such as “electricity,” “cold storage,” “latent heat storage,” “micro-cogeneration,” and “residential building" are the oldest (in purple) and were mostly used in 2014 and 2015 publications. Later, between 2015 and 2017, terms such as “cogeneration,” “feasibility study,” and “energy efficiency” began to be used as keywords. This shows that at first, the production and storage of energy forms were studied separately, but then researchers became more interested in evaluating the feasibility of multigeneration systems.

Publications from 2017 and 2018 were mainly focused on studying sustainable approaches to improve cogeneration and trigeneration systems. This is proven by seeing that researchers started to use terms such as “biomimicry,” “sustainability,” “natural gas,” and “biomass” as keywords during that period.

The most recent studies show that there is an interest in improving existing systems by the application of “multi-objective optimization” or "circular economy” and the study of “thermodynamic cycles” involved in the functioning of these systems.

It also stands out that current research is focusing on nature-inspired solutions rather than searching for the concept of biomimicry. A possible reason for it might be the fact that in recent years, terms such as “bio-inspiration,” “biomimetics,” “bio-replication,” and “biomimicry” were given a standardized definition by the International Organization for Standardization (ISO) [10].

Besides, among recent keywords, “tall building” and “high-rise building” appear. This shows that there has been more research on the feasibility of cogeneration and trigeneration systems to a building level rather than to a residence level, which may be due to the size of these systems, as well as the investment required for installation and operation.

B. Study of conventional cogeneration and trigeneration systems

The implementation of cogeneration and trigeneration systems at building level has been shown to have multiple advantages that can be maximized with the integration of renewable sources.

Spain is one of the countries with more contributions to research related to multigeneration systems. As an example, there is an article that was presented in 2012 by [11] at the XVI International Congress of Project Engineering that took place in Valencia.

This project is a comparison of the results of 3 alternatives proposed to meet the energy needs (heating, air conditioning, and sanitary hot water) of a hotel located in Logroño. The first solution proposed is a conventional system that generates each of the resources independently; the second proposes using biomass to produce sanitary hot water (SHW) and heating, and the third consists of a trigeneration system along with the installation of a green roof.

Results show that the third option is the most convenient since it has a payback period of 12 years and would generate profits by selling electricity to the municipality's grid.

A similar publication studies the economic feasibility of a cogeneration plant in a hospital in the municipality of Fuenlabrada, Madrid. The results show that the investment of the cogeneration plant could be recovered in 5 years, while, for the trigeneration plant, it would take between 14 and 17 years [12].

Based on the results obtained, the best solution proposed to generate the energy needed for heating and air conditioning is the installation of a cogeneration system along with an independent system of solar collectors to obtain the hot water that is needed in the building.

There is also a graduate work entitled "Micro energy generation", which presents a compilation of the results obtained in projects of cogeneration and trigeneration systems installed in residential buildings in several cities such as Barcelona, Seville, and Madrid. With the implementation of these systems, both energy consumption and carbon dioxide emissions are reduced, and the average time in which the initial investment is recovered is 7 years [13].

One of the most recent articles found is a publication made by researchers of the National Technical University of Athens, in which three systems are compared. Those systems are different configurations of the following components: Rankine cycle powered by parabolic cylindrical collectors and heat sinks.

Each one of the thermodynamic models was designed and evaluated using EES and FORTRAN, obtaining an energy efficiency of 78.17%, 43.30%, and 37.45%, and a PBP of 5.62, 7.82 and 8.49 years [14].

When reviewing the literature of the last 8 years, it stands out that many publications are from educational institutions in Asia, where researchers are looking for the best energy sources to power up trigeneration systems, comparing the performance of systems that use diesel with those using natural gas, biomass, and even solar energy.

For example, in 2016, collaborative research between Korean Institute of Energy Research (KIER) and Natural Resources Canada was made to analyze the behavior of a solar-aided trigeneration system at residential level under the climatic conditions of two cities: Incheon in South Korea and Ottawa in Canada.

Results obtained using TRNSYS show an annual energy saving of 45% for the case evaluated in Incheon and 42% for Ottawa, as well as a reduction of CO_2 emissions of 43% and 82% respectively [15].

Another important research found is an evaluation of the effect of variations in climatic conditions on the performance of trigeneration systems. The efficiency of these systems is affected when they work in part-load conditions, which are mainly caused by the changes in the climatic conditions of the region. Results show that variation on the amount of fuel required ranges between 61.9% and 83.8%, and the reduction in energy consumption only varies from 0.4 to 7.5% during the year, so the impact of the stations is not so drastic [16].

To obtain those results, a simulation of a trigeneration system powered by natural gas was performed in an office building under the annual climatic conditions of Beijing, Hong Kong, Shanghai, and Singapore. And it was compared to trigeneration systems powered by diesel in the same cities.

An analysis of the feasibility of using woody biomass for a cogeneration system connected to a district heating system was conducted by [17]. The process consisted of using an official map that indicates heating demand in the region of Fukushima, Japan. The area of greatest need was identified, and a diagram of the network system to be implemented was designed, with the respective pipe sizes according to the demand of the different buildings.

After calculations and simulations were made, it was observed that, by using woody biomass, the percentage of carbon dioxide emissions is reduced to 70% [17].

C. Performance indicators of conventional cogeneration and trigeneration systems

To compare the efficiency or convenience of installing conventional cogeneration or trigeneration systems on buildings, indicators such as payback period, percentage of CO_2 emissions reduced, and the amount of energy consumption reduced are frequently used.

Tables I, II, and III were made to summarize and classify the chosen publications based on the performance indicator used.

TABLE I
SUMMARY OF PUBLICATIONS WHERE THE PAYBACK PERIOD IS THE PERFORMANCE INDICATOR

Country, City	Köppen climate classification	Type of generation system	Amount of energy generated	Indicator	Ref.
Spain, La Rioja	Cfb	Trigeneration (SHW, heating, cooling)	1985.44 kW/day	12 years	[11]
Spain, Madrid	Bsk	Trigeneration (SHW, heating, cooling)	2090 kW/day	14 -17 years	[12]
Spain, Barcelona	Csa	Trigeneration (SHW, heating, cooling)	65 kW/day	7 years	[13]
Spain, Sevilla	Csa	Cogeneration (SHW, heating)	10 kW/day	7.5 years	[13]
Spain, Madrid	Bsk	Cogeneration (SHW, heating)	685 kW/day	5 years	[12]
-	-	Solar-aided trigeneration	54.74 kW	5.62 years	[14]

		(SHW, heating, cooling)	30.3 kW	7.82 years	
			26.21 kW	8.49 years	

TABLE II
SUMMARY OF PUBLICATIONS WHERE CO_2 EMISSIONS REDUCED IS THE PERFORMANCE INDICATOR

Country, City	Köppen climate classification	Type of generation system	Amount of energy generated	Indicator	Ref.
Japan, Koriyama	Cfa	Cogeneration with biomass (SHW, heating)	9000 kW	70%	[17]
South Korea, Incheon	Dfa	Solar-aided trigeneration (SHW, heating, cooling)	122 $kWh/m^2 \cdot year$	43%	[15]
Canada, Ottawa	Dfb	Solar-aided trigeneration (SHW, heating, cooling)	156 $kWh/m^2 \cdot year$	82%	[15]

TABLE III
SUMMARY OF PUBLICATIONS WHERE ENERGY SAVINGS IS THE PERFORMANCE INDICATOR

Country, City	Köppen climate classification	Type of generation system	Indicator	Ref.
China, Hong Kong	Cwa	Trigeneration (SHW, heating, cooling)	Reduction of 119MWh	[18]
Spain, Madrid	Bsk	Trigeneration (SHW, heating, cooling)	Reduction of 264,000 kwh per year	[13]
Singapore	Af	Trigeneration (SHW, heating, cooling) powered by natural gas	2.20%	[16]
China, Hong Kong	Cwa	Trigeneration (SHW, heating, cooling) powered by natural gas	1.50%	[16]
China, Shanghai	Cfa	Trigeneration (SHW, heating, cooling) powered by natural gas	0.40%	[16]
China, Beijing	Dwa	Trigeneration (SHW, heating, cooling) powered by natural gas	2.70%	[16]
Singapore	Af	Trigeneration (SHW, heating, cooling) powered by diesel	7.10%	[16]
China, Hong Kong	Cwa	Trigeneration (SHW, heating, cooling) powered by diesel	6.60%	[16]
China, Shanghai	Cfa	Trigeneration (SHW, heating, cooling) powered by diesel	5.50%	[16]
China, Beijing	Dwa	Trigeneration (SHW, heating, cooling) powered by diesel	7.50%	[16]

The indicators that were chosen to categorize the publications are useful to evaluate if a project of a cogeneration or trigeneration plant will have adequate efficiency and if it will generate long-term benefits.

The payback period calculates the time in which an investment can be recovered [19]. And financially speaking, this has a huge impact when deciding whether a project will be executed.

Regarding CO_2 emissions, using this percentage as a performance indicator of an energy generation system is important in this era, where it is vital to take action to mitigate climate change. It is known that due to the increase in energy demand and existing generation processes, the so-called greenhouse effect has occurred due to the emissions of polluting gases to the atmosphere, such as methane and CO_2. This has triggered an increase in Earth's temperatures with irreversible consequences such as melting glaciers and rising sea levels.

By installing systems that generate multiple forms of useful energy from a single fuel, it is possible to reduce CO_2 emissions since these occur when carbon stored in fossil energy sources such as oil, coal, or natural gas is released into the atmosphere by combustion.

Energy savings allow people to compare the energy demand before and after installing the cogeneration or trigeneration plant on a building. Considering that the building sector is one of the largest consumers of energy [20], knowing the savings that could be achieved by implementing these systems is useful.

D. *Nature-inspired cogeneration and trigeneration systems*

Cogeneration or trigeneration systems designed using biomimicry strategies were not found in literature, so it is not possible to make a comparison with conventional systems. For this reason, system-level biomimicry was studied instead.

A heat recovery ventilation system (HRV) innovative configuration was proposed by [21], using as inspiration the tuna *rete mirabile*, which is a system that acts as a heat exchanger between the arteries and veins of this animal, and blocks the heat flow to its gills [22].

Three configurations were compared in this study: the first one has an HRV for each one of the two adjacent rooms; the second case uses the extracted air removed from one room to preheat the fresh air that will be injected into the other room; and the third case, consists of a device that performs the function described on the second case with no need of having two ventilators.

After running simulations of the three configurations previously described on Autodesk CFD 2015, selecting Pamplona, Berlin, and Helsinki as the location of the building studied, the following results were obtained: 32-39% of energy savings when comparing the first case with the second one, and 44.5%, 42.7% y 41.3% for each city when comparing the first and third case [21].

Another interesting study found in literature proposes the design of a heat dissipation system inspired by an elephant's pinna, which helps this animal to cool down its temperature [23]. The nature-inspired solution would solve the common problems that conventional heat sinks present, such as noise, vibrations, and high operations and maintenance costs [24].

The design consists of a cooling panel that could be integrated into the whole cooling system of a building, as shown in Fig. 3.

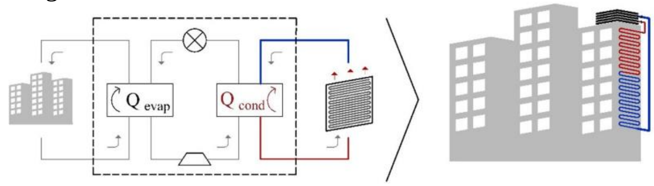

Fig. 3 Schema of proposed cooling panel design [24].

The prototype designed, shown in Fig. 4, was simulated to determine the amount of heat removed per square meter when the system is put under certain temperature conditions. Results show that it is possible to remove up to 479.6 W/m^2.

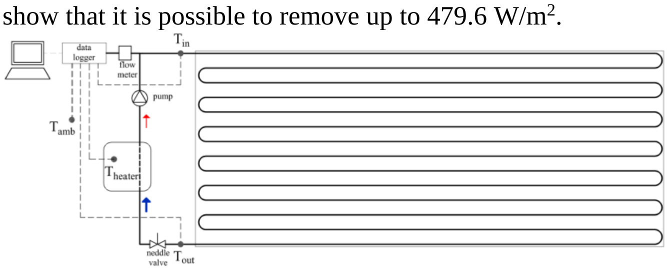

Fig. 4 Prototype setup [24].

This solution based on biomimetics is great because it is an alternative that could be implemented on existing infrastructure.

One last example is a solar cell array inspired by the shape of the fovea centralis, an array of cone cells located on the retina [25]. The design proposed is shown in Fig. 5.

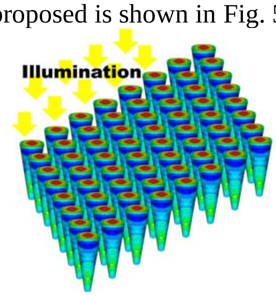

Fig. 5 Tridimensional representation of light-funnel arrays [25].

Opto-electronic simulations were performed using the software Sentaurus Process. Results demonstrated that the light-funnel arrays proposed have efficiencies 60% higher than common silicon arrays, as well as an absorption enhancement of 65% [25].

The examples mentioned do not have the same efficiency indicators, so it is not possible to compare them. However, Table IV was made to summarize the information.

TABLE IV
SUMMARY OF PUBLICATIONS OF BIOMIMICRY APPLIED AT SYSTEM-LEVEL

System/Device improved	Pinnacle	Indicator's name	Indicator's value		Ref.
Heat recovery ventilation system	Tuna *rete mirabile*	Energy savings	Comparing first and second configuration	32-39%	[21]
			Comparing the first and third configuration	41.3-44.5 %	
Heat sink (cooling panel)	Elephant pinna	Heat removed	479.6 W/m^2		[24]
Solar cells array	Fovea centralis	Efficiency	60%		[25]
		Absorption enhancement	65%		

Other innovative ideas where biomimicry strategies are applied at system-level were found. Although performance indicators are not provided in the publications, these ideas shall be mentioned because it is important to have a bigger understanding of how nature serves as an inspiration for the improvement of many devices or processes that could be integrated into cogeneration or trigeneration systems.

Beehives have been used as a source of inspiration for the optimization of conventional HVAC system designs that use Peltier cells. Temperature control strategies implemented by bees in their hives are useful to improve the functioning of Peltier cells, which work in such a way that heat is transferred from one cell junction to the other when electricity flows through it [26].

The suggested biomimetic strategy is known as a "heat shield". When the outside temperature of the hive is higher than the interior temperature, bees place themselves between the outside and honeycombs, acting as a protective shield for these cells. In this way, bees absorb heat, preventing the inside of the hive from heating up, and when they are no longer able to absorb more heat, they fly to release it into the air [27].

The bioinspired design proposed is a ventilated façade with Peltier cells that extract excess heat from the enclosures into an air chamber or cavity during the summer. During the winter, the air of this chamber would be heated, taking advantage of the solar radiation to perform the opposite process [27].

The importance of studying how photosynthesis occurs has become a topic of interest. According to [15], the fact that plants use sunlight to produce their own food (energy) can be used as inspiration to improve photovoltaic systems because sunlight is also what powers their functioning. Both are energy generation processes that have the same input in common, which is solar energy.

A nanoscale device capable of converting sunlight into chemical energy, inspired by the photosynthesis performed by purple bacteria, was proposed by [28]. At reaction-level, the photosynthesis performed by purple bacteria is easier to understand than what plants do.

The device performs this energy conversion with high efficiency, including the basic processes that occur during photosynthesis, such as light capture, energy conversion by photoinduced electron transfer, and proton pumping.

In literature, this is known as artificial photosynthesis, a topic that has been discussed for decades [29], and that can be applied in areas of nanotechnology such as sensor design, optoelectronics, and photonics.

In summary, conventional cogeneration and trigeneration systems that were presented in this review have reached energy savings of 264 megawatts per year, and percentages that range between 0.4 and 7.5%; while the heat recovery ventilation system design inspired by tuna's rete mirabile has reached up to 44.5% in energy savings when compared to a conventional HRV system.

Although no studies were found in literature, where nature strategies are directly implemented to cogeneration or trigeneration systems based on the indicators found, it can be observed that modifying certain components or devices of a multigeneration system by applying nature-inspired strategies could be a viable alternative for improving these systems in the future.

IV. Conclusions

The development of innovative ideas to create more systems, such as the multigeneration systems that were studied here, needs to increase in the next few years. It is also necessary to study nature strategies that could improve the processes or components of existing systems.

These systems have a huge impact on the energy sector because significant energy savings can be achieved, as well as reducing emissions of polluting gases. Besides, considering the average lifespan of their main components, the initial investment can be recovered in a short time.

For future research on this topic, the use of performance indicators is recommended to make it possible to evaluate such innovative systems by comparing performances. This is worth mentioning because it was a challenge presented when carrying out this literature review since many of the documents found did not contain any performance information that is necessary to understand the scope of installing such systems.

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