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Review

Eco-Sustainable Energy Production in Healthcare: Trends and Challenges in Renewable Energy Systems

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Abstract: The shift from fossil fuels to renewable energy systems represents a pivotal step toward the realization of a sustainable society. This study aims to analyze representative scientific literature on eco-sustainable energy production in the healthcare sector, particularly in hospitals. Given hospitals' substantial electricity consumption, the adoption of renewable energy offers a reliable, low-CO_2 emission solution. The COVID-19 pandemic has underscored the urgency for energy-efficient and environmentally-responsible approaches. This brief review analyzes the development of experimental, simulation, and optimization projects for sustainable energy production in healthcare facilities. The analysis reveals trends and challenges in renewable energy systems, offering valuable insights into the potential of eco-sustainable solutions in the healthcare sector. The findings indicate that hydrogen storage systems are consistently coupled with photovoltaic panels or solar collectors, but only 14% of the analyzed studies explore this potential within hospital settings. Hybrid renewable energy systems (HRES) could be used to meet the energy demands of healthcare centers and hospitals. However, the integration of HRES in hospitals and medical buildings is understudied.

Keywords: eco-sustainable energy production; hospitals and healthcare facilities; renewable energy systems; hydrogen production; statistical analysis

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1. Introduction

Nowadays, it is of crucial importance to develop innovative and environmentally sustainable solutions for energy production with low environmental impacts, achieved through the implementation of renewable energy systems instead of fossil fuels [1–3] Recent years have seen a surge of interest in renewable energy systems, driven by a growing awareness of the need to reduce environmental impacts and improve energy efficiency in the building sector [4–6]. Among the various types of buildings, hospitals and health centers represent a particular challenge in the context of adopting renewable energy systems. Indeed, these facilities have a unique energy consumption profile, as they operate 24 h a day, 365 days a year, providing continuous medical care. Consequently, their energy demand is constant, and they cannot afford interruptions. The use of renewable energy systems in hospitals and health centers not only helps to reduce their environmental impacts but can also provide greater reliability in their energy supply [7].

The spread of the COVID-19 pandemic has significantly impactedon the energy systems of healthcare facilities worldwide. This impact was primarily observed due to substantial increases in the consumption of energy and medical gases by hospitals and healthcare facilities during the critical period of the pandemic. This situation has led to a heightened focus on the topic of green energy production applied to these environments. First and foremost, it is important to underline that hospitals and healthcare facilities require a substantial amount of energy to ensure the operation of medical equipment, cooling systems, lighting, emergency electricity, heating and cooling, and more. During the pandemic, the pressure on the healthcare system increased exponentially, resulting in a considerable rise in energy demands. The critical aspect of this situation is that many hospitals and healthcare facilities rely on conventional energy sources, such as coal, natural gas, or oil, which not only contribute to environmental pollution but can also be susceptible to supply disruptions. The growing awareness of these issues has prompted many healthcare facilities to explore more sustainable energy solutions, such as the installation of solar panels, wind turbines, combined heat and power systems, and the adoption of energy monitoring and management technologies.

A promising application could be hybrid systems combining different renewable energy sources [8,9]. Izadi et al. [10] proposed a hybrid renewable energy system with hydrogen energy storage to cover the energy demand from the units of a hospital caring for COVID-19 patients. The inclusion of hydrogen for power generation in the energy mix is gradually gaining commercial attention globally [11]. To study the feasibility of the transition to a hydrogen economy, the main step is to assess and estimate the potential of renewable hydrogen for each country [12]. Hydrogen production is still a major challenge with high costs, and often, environmental burdens [13]. Today, various methods are available for hydrogen production. It can be considered a sustainable alternative to fossil fuels when derived from renewable and sustainable sources [14,15]. Hydrogen is classified based on the production method and process, including steam reforming [16], water electrolysis, biomass gasification [17], thermochemical hydrogen production [18], or photocatalysis [19]. Grey hydrogen is produced by emitting CO_2 from fossil fuels; blue hydrogen emits CO_2 during the production process but subsequently recovers and stores it underground, while green hydrogen is generated by water electrolysis powered by renewable energy [20]. Bartels et al. [21] conducted an economic evaluation of different production methods and found that as of the date of the analysis, gray hydrogen was the least expensive option. Currently, approximately 96 percent of the world's hydrogen production is primarily derived from fossil fuels [22]. Green hydrogen is considered a promising energy carrier to support the energy transition and help achieve climate change goals, but the intermittency of renewable energy does not allow it to meet the increasing energy demand [23]. Photovoltaics and wind power are affordable modes of power generation. The power output varies significantly based on location and weather conditions. Investigating suitable system configurations and operational parameters involves understanding the natural intermittence of photovoltaic and wind power generation, along with the factors that accelerate the degradation of water electrolyzers' performances [24]. Touili et al. [25] demonstrated that water electrolysis, the electrochemical conversion of water to hydrogen and oxygen using a direct electric current, combined with renewable energy, represents an optimal approach for large-scale green hydrogen production.

Problem Statement

The purpose of this study was to analyze the key scientific articles that represent the state of the art in eco-sustainable energy production for hospital facilities. The aim is to illustrate the trends and results in the development of experimental, simulation, and optimization designs for facilities focused on achieving sustainable production. Data were processed to obtain statistical analyses for each category or each combination of categories.

2. Literature Review

The articles under review focus on implementing innovative solutions to reduce the environmental impact of energy consumption in hospitals worldwide. These facilities, located in different regions, each possess unique characteristics, necessitating tailored approaches to enhancing energy performance. The literature explores diverse plant configurations, energy storage systems, and strategies for optimizing energy costs. This review aims to capture the essence of these studies, providing insights into the state of the art and emerging trends, especially regarding the use of hydrogen and sustainable energy technologies in hospital environments. The following sections will analyze the literature, categorizing the content into distinct thematic areas, and ensuring a comprehensive understanding of innovative energy solutions for hospitals.

2.1. Techno-Economic Evaluations

A significant strand of research focuses on the technical and economic feasibility of renewable energy solutions. Normazlina and Himadry [26] explored a combined power generation system using photovoltaic modules, fuel cells, and batteries for a Malaysian hospital. Their study, like that of Bornand and Girardin [27] for a Geneva hospital complex, relies on techno-economic evaluations to gauge the viability of the proposed systems. Buonomano and Calise [28] delved into a polygeneration system, revealing substantial energy savings and reduced operating costs, albeit influenced by weather conditions.

2.2. Emission Reduction and Environmental Impacts

Eco-friendliness is paramount in today's energy solutions. Prada and Cristea [29] assessed energy efficiency solutions for Romanian hospitals from the 70s and 80s, revealing significant economic and environmental benefits. The simulation of Alotaibi and Akrami [30] for a Saudi Arabian hospital emphasized reduced carbon emissions, resonating with the examination of Chen and Zhang [31] of multiple combined heat and power (CHP) systems for a Chinese hospital. Zaza and Sepetis [32] delineated the energy costs of 125 Greek public hospitals, highlighting significant factors that influence their consumption.

2.3. Optimization and Efficiency

Optimization remains a central theme in hospital energy research. Ma, Zhang, and Sun [33] proposed an interval planning method, while Ascione and Bianco [34] took an optimization approach for a southern Italian hospital, revealing significant energy savings. Innovative strategies were also put forth by Sigarchian and Malmquist [35]; Jahangir and Eslamnezhad [36], who used the HOMER Pro software to simulate various scenarios, emphasizing the efficiency of hybrid systems in reducing emissions and costs; Luo and Hongqiang [37]; and Dursun [38], with a shared emphasis on efficiency.

2.4. Resilience, Storage, and Microgrids

Lagrange and Simon-Martín [39] explored sustainable microgrids to enhance the energy resilience of critical facilities like hospitals. Their findings, highlighting the tangible benefits of additional micro-grids, echo Mahmoudza and Rezaee [40]'s emphasis on renewable energy systems incorporating photovoltaic modules and wind turbines. Mustafa and Huang [41] delved into the feasibility of an electricity storage system for a Belfast hospital, indicating the challenges of using BESS for arbitrage due to economic constraints.

2.5. Regional and Case Studies

Region-specific studies offer insights into localized challenges and solutions. Oliveira and Santos [42] developed guidelines for São Paulo hospitals, while Burch and Anstey [43] explored Australian public hospitals' energy consumption trends. Kahwash and Barakat [44] took a granular look at a hybrid system in a southeast England hospital, emphasizing CO_2 emission reductions. Further, Alamoudi and Taylan [45] focused on the design and optimization of a PV system; Ogunmodede and Anderson [46] optimized the design and dispatch of a renewable energy system, assessing the feasibility of a wind and solar energy storage system with grid-connected batteries; and Bardineh and Mohamadiano [47] highlighted the merits of renewable energy in medical and dental applications. Regional investigations also spanned Greece [48], Spain [49], Poland [50], Malaysia [51], and more.

2.6. Miscellaneous Innovations

Several studies explored diverse avenues to innovate hospital energy solutions. For instance, Carnero and Gomez [52] proposed a multi-criteria model for energy system maintenance in a Spanish hospital. Sánchez and González [48] evaluated solar thermal systems, while Maggio and Squadrito [53] merged renewable energy with medical gas production.

3. Literature Analysis

This study aims to analyze representative scientific literature on eco-sustainable energy production in the healthcare sector, with a particular focus on hospitals. The analyses are categorized as follows:

- Geographical distribution of articles;
- System configurations and auxiliary components;
- System installation modes;
- Analysis typology.

3.1. Geographical Distribution of Articles

Table 1 presents an overview of the countries covered in the studies.

Table 1. Overview of countries. "Not Specified" has been used where data is not provided.

Article	Country	Location	Facility Specifications (Size, Volume, Floor Surface, Beds)	Type and Category of the Facility
[26]	Malaysia	Cheras, Selangor	Number of beds: 873	University Hospital
[27]	Switzerland	Geneva	Area: 332,311 m^2, Number of beds: 1224	Private Hospital
[28]	Italy	Naples	Area: 270,000 m^2, Volume: 1,130,000 m^3, Number of beds: 2800	University Hospital
[29]	Romania	Oradea	Not Specified	Public Hospital
[30]	Saudi Arabia	Neom	Not Specified	Hospital
[31]	China	Not Specified	Not Specified	Hospital
[32]	Greece	Data from all public hospitals in Greece	Not Specified	121 Public Hospital
[33]	China	Jinan	Total area: 33,000 m^2, Average floor height: 3.5 m, Number of floors: 19	Hospital
[34]	Italy	Naples	Volume: 90,828 m^3, Area: 22,711 m^2	Public Hospital
[35]	Italy	North Italy	Not Specified	Hospital
[36]	Iran	Tehran	Not Specified	Hospital
[37]	China	Changsha	Not Specified	Hospital
[38]	Somalia	Mogadishu	Not Specified	Hospital
[39]	USA (California)	Palmdale	Area: 30,000 m^2, Number of beds: 171	Private Hospital
[40]	Iran	Not Specified	Number of beds: 900	Hospital
[41]	UK (Northern Ireland)	Belfast City	Number of beds: 2058	6 Public/Private Hospitals/Clinics

Table 1. *Cont.*

Article	Country	Location	Facility Specifications (Size, Volume, Floor Surface, Beds)	Type and Category of the Facility
[42]	Australia	Not Specified	Not Specified	Hospital
[43]	UK	South-east England	Not Specified	Hospital
[44]	Saudi Arabia	Jeddah	Number of beds: 715	University Hospital
[45]	USA	San Diego—Cheyenne	Not Specified	Case 1: Hospital—Case 2: Campus
[46]	Poland	Bydgoszcz	Not Specified	Hospital
[47]	Spain	Region of Extremadura—Cities of Badajoz/Cáceres	Total area: from 533 to 87,118 m^2, Number of beds: from 15 to 529	25 Private/Public Hospital in the region of Extremadura, Spain
[48]	Spain	Region of Extremadura	Total area: from 13,300 m^2 to 66,326 m^2, Number of beds: from 43 to 508	13 Private/Public Hospital in the region of Extremadura, Spain
[49]	Poland	Hospital A: Bydgoszcz—Hospital B: Province	Hospital A: Number of beds: 715, Volume: 160,849 m^3, Usable area: 27,586 m^2, Hospital B: Number of Beds: 810	A: University Hospital /B: Provincial Hospital
[50]	Malaysia	Not Specified	Not Specified	Public Hospital
[51]	Spain	Ciudad Real	Not Specified	Hospital
[52]	Not Specified	Not Specified	Number of beds: up to 500	Hospital
[53]	Finland	Espoo	Not Specified	Hospital
[54]	Country	Location	Facility Specifications (Size, Volume, Floor Surface, Beds)	Type and Category of the Facility

The geographical locations of the energy systems play a pivotal role in their performance. The discrepancy between the location of system installation and the location of the study's development often arises due to researchers analyzing data from systems in regions different from their own. This divergence can be attributed to various factors such as the availability of data, collaborative projects across countries, or specific climatic or operational interests in certain regions. Such differences can influence the findings as the local climatic and operational conditions might differ from the assumptions or models used by the researchers. In most articles, the physical location of the system installation is declared, which often does not coincide with the location where the study was developed. In other articles, the data used for the analysis came from historical data that described the habits of the analyzed system.

Specifically, 24 articles (82.75% of the sample) explicitly state the country in which the system's physical location is based. In 8% of the articles, similar systems are found in multiple areas within the same country. Out of the 24 articles that specify a single country, five (20.8%) consider cities located in different regions of the same country, while five articles do not mention the country where the system was investigated. Overall, the data indicates that the analyzed publications cover studies conducted within the national boundaries of 17 countries.

Figure 1 shows the countries and continents represented in the sample of articles with the highest number of occurrences.

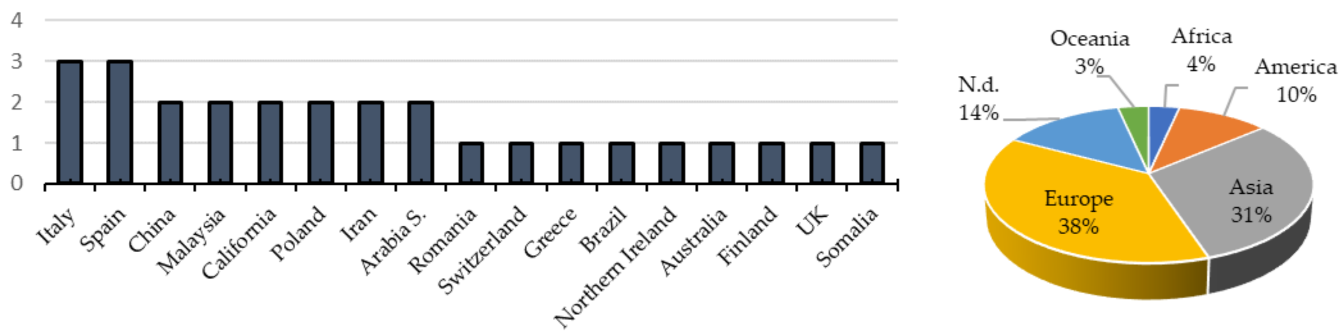

Figure 1. Number of publications by country and percentage distribution by continent.

Globally, Europe hosts the highest number of studies, accounting for 38% of publications, followed by Asia at 31%. Research in Africa and Oceania is less frequent, indicating that these regions are still in the early stages of development.

Figure 1 demonstrates that China and Iran, among Asian countries, lead in conducting research within their respective national boundaries, particularly emphasizing advanced plant configurations for energy production. The prominence of Asian countries in this research field can be attributed to several factors. For China, rapid industrialization, urbanization, and the nation's commitment to green energy have spurred significant advancements and research into eco-sustainable energy solutions. Iran, with its vast natural resources and strategic push towards energy diversification, has also seen a surge in related research. Both countries have government-backed initiatives and funding opportunities that promote research in sustainable energy, driving these numbers.

These configurations can be efficiently employed in a variety of ways and under various usage conditions, without the system's complexity posing a disadvantage. In certain cases, the complexity of the analyses conducted surpasses that of other publications, as they involve optimization analyses that necessitate the creation of bespoked mathematical models.

Nevertheless, publications describing cold climates also assessed optimal plant solutions, technological limitations, and strengths. In these cases, the assessment covered renewable energy sources, hybrid plants based on wind production, cogeneration plants, and mixed plants incorporating geothermal and heat pump components.

The implications of these geographic tendencies are vast. The leadership of certain countries in specific research areas can shape global trends, standards, and technological advancements. For instance, innovations and breakthroughs in China might influence global production methodologies due to the country's significant manufacturing base. Similarly, research trends in Europe, with its stringent environmental standards, can set benchmarks for eco-sustainability that other nations might aspire to emulate.

3.2. System Configurations and Auxiliary Components

Table 2 presents an overview of renewable energy technologies and their applications in various countries and climates.

In most articles, the energy efficiency, the economic viability of the production system, and the environmental impact were studied (Figure 2).

Table 2. Renewable energy systems in different countries.

Article	Country	PV	WIND	Geothermal	Flat Solar Collector	Concentrating Solar Collector	Electrolysis System	Fuel Cell	Biomass
[26]	Malaysia	Yes	No	No	Yes	-	Yes	Yes	No
[39]	California	Yes	No	No	Yes	-	No	No	No
[29]	Romania	Yes	No	Yes	-	-	No	No	No
[30]	Saudi Arabia	Yes	No	No	-	-	No	No	Yes
[33]	China	Yes	Yes	No	Yes	-	No	No	No
[27]	Swiss	Yes	No	No	-	-	Yes	Yes	No
[34]	Italy	Yes	No	Yes	Yes	-	No	No	No
[32]	Greek	No	No	No	-	-	No	No	No
[42]	Brazil	Yes	No	No	-	-	-	-	-
[41]	North Ireland	Yes	Yes	No	-	-	No	Yes	No
[28]	Italy	Yes	No	No	No	Yes	No	No	No
[52]	Spain	No	No	No	No	No	No	No	No
[37]	China	No	No	No	No	No	No	No	No
[48]	Spain	Yes	No	No	Yes	No	No	No	No
[49]	Spain	Yes	No	No	Yes	No	No	No	No
[53]	-	Yes	No	No	Yes	No	Yes	No	No
[46]	California—Wyoming	Yes	Yes	No	-	-	No	No	No
[47]	Poland	Yes	No	No	Yes	No	No	No	No
[45]	Saudi Arabia	Yes	No	No	-	-	No	No	No
[43]	Australia	-	-	-	-	-	-	-	-
[54]	Finland	Yes	No	Yes	-	-	No	No	Yes
[44]	UK	Yes	No	No	-	-	No	No	No
[36]	Iran	Yes	Yes	No	-	-	No	No	No
[40]	Iran	Yes	Yes	No	-	-	No	No	No
[31]	China	Yes	Yes	No	Yes	No	Yes	No	No
[35]	Italy	Yes	Yes	No	-	-	No	No	No
[50]	Poland	No	No	No	No	No	No	No	No
[51]	Malaysia	Yes	No	No	No	No	No	No	No
[38]	Somalia	Yes	Yes	No	Yes	No	No	No	No

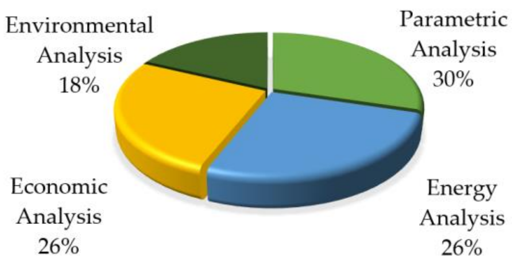

Figure 2. Types of analysis by number of total publications.

Out of the 29 analyzed articles, 25 conducted a parametric analysis for sizing the system using suitable parameters to best approximate the optimal system size based on the provided input. In most cases, the aim was to assess the economic feasibility of the plant and compare the economic advantages of different plant solutions. Additionally, 15 articles conducted an environmental analysis to determine the emissions produced by the system.

Auxiliary components encompass additional systems and components that support the main renewable energy generation and storage systems, ensuring uninterrupted energy supply and optimal system performance. These auxiliary components fall into two macro-categories:

- Energy Generation Auxiliary Systems: These components generate electrical energy in case of renewable sources or other generation system failures, forming single or multiple cogeneration systems (electricity, heat, air conditioning, hot water, hydrogen, etc.).
- Energy Storage Systems: These systems store excess energy from renewable sources using electrical, thermal, hydrogen, or other storage methods.

Figure 3 shows the percentage occurrences of the main auxiliary components out of the total sample of 29 articles analyzed:

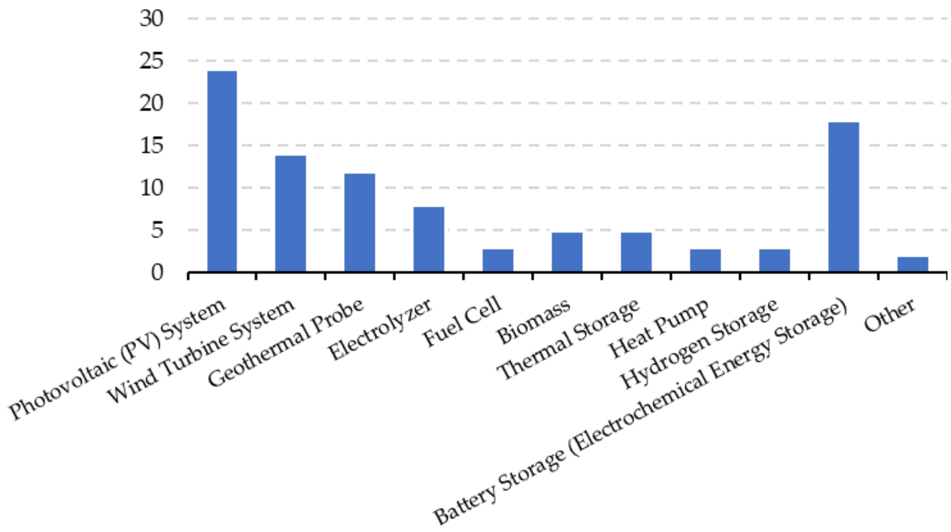

Figure 3. Percentage occurrences of the main auxiliary components out of the total sample.

The survey results reveal that:

- The most used system for energy production is the PV system, with a utilization rate of 25%.
- Wind-based energy production systems come in second place with a utilization rate of 15%.
- Geothermal energy generation systems rank third with a utilization rate of 12%.
- Batteries are the most employed energy storage system, as 18 out of 29 articles describe systems incorporating a battery. In 14 of these articles, the battery is combined with another auxiliary component, and in eight of these cases, it is paired with a different storage system.
- Seven articles describe the operation of hybrid systems by analyzing multiple auxiliary components.
- The diesel generator is one of the most-used auxiliary generation systems, with a utilization rate of 20%.
- Biomass-based systems are the second most-used auxiliary generation systems. They are primarily employed in remote locations where renewable energy production is unfeasible due to unfavorable conditions, such as arctic and polar climates.
- Fuel cells, either standalone or in combination, are the second most-used auxiliary generation system, with three articles, two of which are in combination with a battery. Biomass ranks third.

Three articles analyze systems to produce medical gas, serving as both immediate production and excess quantity storage systems. The analysis of the publications shows that the trend of using renewable energy sources is divided into different applications. These applications span from integrating with existing plants and replacing outdated systems, to establishing new installations for electrical energy or medical gas production based on zero-impact energy sources. A breakdown of the data is as follows:

- In 22 case studies, the contribution of installing a PV system to produce energy from renewable sources is analyzed.
- In 6 case studies, energy production comes from systems other than PV, such as wind systems, biomass, single or multiple CHP cogeneration plants, diesel generators, and geothermal and heat pump hybrid systems.
- In 1 case study out of the twenty-nine analyzed, it was not possible to obtain information on the use of PV as an energy production plant since it was not specified.

The findings suggest that PV systems are predominantly used for large-scale electrical energy production, either supplementing existing plants or as primary installations. These systems align with most climatic classifications of the discussed subgroups, making them a favored choice across diverse climates.

However, implementing PV systems in regions with prolonged snowy or boreal climates, marked by long winters or brief summers, would not be optimal. The insufficient solar radiation in these areas may not yield energy outputs that justify the costs. On the contrary, tropical, arid, and temperate climates provide suitable conditions for PV system installation, enabling micro-grids to operate independently from the national grid.

The articles detailing the use of PV systems delve into the benefits and challenges associated with these installations. Various analyses have been employed to weigh the costs against the benefits of the system:

- Economic analysis: the break-even point (BEP) is determined, factoring in the primary installation costs and projecting the time required for cost recovery. This analysis also highlights the savings accrued from autonomous renewable energy production over direct electricity purchases from the national grid.
- Energetic analysis: the potential energy production and storage throughout the system's life cycle, either through hands-on experiments or simulations.
- Optimization analysis: the system's energy output for enhanced economic and environmental returns. It emphasizes the strategic use of renewable energy during peak pricing periods and the leveraging of the national grid during off-peak hours for cost efficiency.

Considering generation systems, diesel generators, though reliable, come with the baggage of higher emissions and increased fuel consumption. Conversely, fuel cells emerge as a progressive solution. Their combustion-free operation boosts efficiency and significantly reduces emissions, promoting environmental sustainability. The inherent modularity of fuel cells supports scalability based on demand. Moreover, when hydrogen-powered, their primary byproduct is water, underscoring their environmental benefits. The rising adoption of fuel cells in energy production systems can be attributed to these advantages. Among storage solutions, batteries dominate, while hydrogen tanks, especially when paired with components like electrolyzers, hold significant value. Thermal and hydraulic storage mechanisms feature in 52% of the discussed articles.

3.3. System Installation Mode

Table 3 shows the different system installation modes employed in healthcare facilities in various countries.

Table 3. Overview of system installation modes in healthcare facilities.

Article	Country	Description	Stand Alone	Grid Connected	Size	Type (Clinic or Healthcare Building, Private and Public Hospital)
[26]	Malaysia	Grid-connected PV with battery, fuel cells, cogenerative system	-	Yes	Number of beds: 873	University Hospital
[39]	California	Stand-alone PV + Battery storage	Yes	-	Area: 30,000 m^2, Number of beds: 171	Private Hospital
[29]	Romania	Stand-alone PV + battery + Heat Pump + Geothermal Probes	Yes	-	-	Public Hospital
[30]	Saudi Arabia	Hybrid system: diesel generators + photovoltaic PV + batteries	Yes	-	-	Hospital

Table 3. *Cont.*

Article	Country	Description	Stand Alone	Grid Connected	Size	Type (Clinic or Healthcare Building, Private and Public Hospital)
[33]	China	RES-CCHP system		Yes	Total area 33,000 m^2, Average floor height: 3.5 m, Number of floors: 19	Hospital
[27]	Swiss	Five different types of combined systems based on the production of electrical energy with storage, generation of thermal energy with storage, use of fuel cells, heat pumps, and cogeneration in accordance with pre-existing ventilation systems.	-	Yes	Area: 332,311 m^2, Number of beds: 1224	Private Hospital
[34]	Italy	Analysis of different configurations systems: Gas boiler, heat pump, geothermal, chiller, CHP system, CCHP system, solar thermal collectors, PV photovoltaic solar panels.	-	Yes	Volume: 90,828 m^3 Area: 22,711 m^2	Public Hospital
[32]	Greek	-	-	-	-	121 Public Hospital
[42]	Brazil	Solar thermal panel for hot water production and heating, PV photovoltaic solar panel	-	-	Number of beds: 2058	N° 6 Public/Private Hospitals/Clinic
[41]	North Ireland	Battery energy Solar System (BESS), with/without PV, grid-connected	-	Yes	Number of beds: 900	Hospital
[28]	Italy	SHC system based on a field of CPVT solar collectors coupled with a single-stage LiBr–H_2O absorption chiller, supporting the cogeneration plant CHCP system + ST (solar trigeneration).	-	Yes	Numbers of beds: 2800, Area: 270,000 m^2, Volume: 1,130,000 m^3	University Hospital
[52]	Spain	- Syst. 1: Boilers with a modulating burner - Syst. 2: Rotary coolers + Screw coolers - Syst. 3: Cooling towers	-	-	-	Hospital
[37]	China	Solar arc shading reflector plates, vacuum heat collection tubes, sanitary water tank, and cold-water supply unit.	-	-	-	Hospital
[48]	Spain	Solar thermal system to produce sanitary hot water intended for hospital use.	-	-	Total area: from 533 to 87,118 m^2—Number of beds: from 15 to 529	25 Private/Public Hospital in the region of Extremadura, Spain
[49]	Spain	Solar thermal system to produce hot water intended for hospital use.	-	-	Total area: from 13,300 m^2 to 66,326 m^2 Number of beds: from 43 to 508	13 Private/Public Hospital in the region of Extremadura, Spain
[53]	/	Photovoltaic system to produce hydrogen and oxygen for hospital use. PV + electrolyser + batteries + tanks	Yes	-	Number of beds: up to 500	Hospital
[46]	California—Wyoming	PV system + Electrical Storage—WIND system + Electrical Storage	-	Yes	-	Case 1: Hospital—Case 2: Campus

Table 3. *Cont.*

Article	Country	Description	Stand Alone	Grid Connected	Size	Type (Clinic or Healthcare Building, Private and Public Hospital)
[47]	Poland	RES system: PV system for electrical production + Electrical Storage and Solar Collector for hot water production and storage.	-	Yes	-	Hospital
[45]	Saudi Arabia	RES system: PV system for electrical production without electrical storage, grid-connected.	-	Yes	Number of beds: 715	University Hospital
[43]	Australia	RES Renewable Energy System	-	-	-	Hospital
[54]	Finland	Biogas, Electricity, Ground heating, Ground cooling, Wood chip, Sun electricity, Compressor cooling, Snow storage cooling, Wood pellet, District cooling, District heating	Yes	Yes	-	Hospital
[44]	UK	HRES Hybrid Renewable Energy System PV + Battery Bank	-	Yes	-	Hospital
[36]	Iran	HRES Hybrid Renewable Energy Systems PV + Wind Turbine+ Battery Bank + Diesel Generator	-	Yes	-	Hospital
[40]	Iran	RES System PV + WIND TURBINE GRID CONNECTED	-	Yes	-	Hospital
[31]	China	Quad Generation System	Yes	-	-	Hospital
[35]	Italy	Small-scale decentralized polygeneration systems	Yes	-	-	Hospital
[50]	Poland	Boiler fired with natural gas	Yes	-	Hospital A: Number of beds: 715—Volume: 160,849 m^3—Usable area: 27,586 m^2 Hospital B: Number of Beds: 810	A: University Hospital/B: Provincial Hospital
[51]	Malaysia	PV-DG System	-	Yes	-	Public Hospital
[38]	Somalia	HRES Hybrid Renewable Energy System PV/WIND TURBINE + Battery storage + Diesel Generator	Yes	-	-	Hospital

The analysis of the distribution of articles in relation to the system installation mode (Figure 4), reveals that:

- Nine articles focus on stand-alone systems.
- A number of 13 articles focus on grid-connected systems.
- Only one article concerns both stand-alone and grid-connected systems to make a comparison or provide the system with various auxiliary components.
- An amount of seven articles do not indicate the system mode.

Research predominantly gravitates towards grid-connected systems, largely because the healthcare facilities scrutinized—ranging from public/private hospitals to medical-university campuses—demand an energy load that standalone solutions simply cannot sustain continuously. This load dependency is further influenced by the facility's size. However, it is essential to acknowledge that 30% of the cases do employ stand-alone technology. Such configurations are often necessitated in remote locales or areas plagued with an inconsistent power supply, ensuring uninterrupted healthcare services.

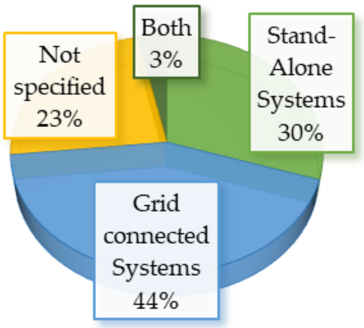

Figure 4. Distribution of articles in relation to the system installation mode.

The articles under review all explore energy solutions tailored for the healthcare sector. Three primary categories of healthcare facilities emerge from this analysis:

- Public/Private Hospitals: These are large establishments that require significant energy loads due to their operations, patient intake, and equipment usage.
- Private Clinics: Typically smaller than hospitals, these facilities still have energy needs, especially if they house specialized equipment.
- Medical-University Campuses: These are expansive establishments, often encompassing a mix of educational facilities and healthcare services, leading to varied energy requirements.

Each of these facilities carries its own unique set of indicators. These indicators can span the physical size (surface and volume), patient capacity, energy requirements, economic considerations, and even the local climate. The type and magnitude of energy loads and outputs, and the efficiency solutions required by the production system, are also tailored according to these indicators.

Having examined the various modes of system installations and their corresponding characteristics, it becomes essential to understand the methodologies and typologies adopted to analyze these systems. As we transition into the discussion on analysis typology, we delve into the various research approaches and tools employed in the literature.

3.4. Analysis Typology

In this section, the discussion includes various types of studies presented in the reviewed articles. These studies range from numerical simulations and experimental investigations on real systems to a blend of both approaches. The articles are further categorized based on the type of analysis conducted, which includes a parametric analysis, non-parametric analysis, energy analysis, economic analysis, and environmental analysis. Table 4 offers an overview of these studies, detailing their respective analysis methodologies and the software employed.

Table 4. Overview of analysis types and software in reviewed articles.

Article	Parametric Analysis	Energy Analysis	Economic Analysis	Environmental Analysis	Software
[26]	Yes	Yes	Yes	Yes	HOMER
[39]	No	Yes	Yes	No	REopt ®
[29]	Yes	Yes	Yes	Yes	/
[30]	Yes	Yes	Yes	Yes	HOMER
[33]	Yes	Yes	Yes	Yes	MATLAB R214a
[27]	Yes	Yes	Yes	Yes	TRNSYS, EnergyPlus, IDA ICE
[34]	Yes	Yes	Yes	Yes	EnergyPlus 8.0.0, MATLAB 7.10.0
[32]	Yes	No	Yes	No	/

Table 4. *Cont.*

Article	Parametric Analysis	Energy Analysis	Economic Analysis	Environmental Analysis	Software
[42]	Yes	Yes	Yes	No	Smart Energy
[41]	Yes	No	Yes	No	Excel
[28]	Yes	Yes	Yes	No	TRNSYS
[52]	Yes	No	Yes	No	/
[37]	Yes	Yes	No	No	/
[48]	Yes	Yes	Yes	Yes	Excel
[49]	Yes	Yes	No	No	Excel
[53]	Yes	No	Yes	No	Excel
[46]	Yes	No	Yes	No	Reopt Lite
[47]	No	No	No	Yes	/
[45]	Yes	Yes	No	No	Solar-GIS
[43]	No	Yes	No	No	/
[54]	No	No	Yes	Yes	Excel
[44]	Yes	Yes	Yes	Yes	Excel
[36]	Yes	Yes	Yes	Yes	HOMER Pro
[40]	Yes	Yes	Yes	No	IBM ILOG CPLEX v12.3
[31]	Yes	Yes	Yes	Yes	/
[35]	Yes	Yes	Yes	Yes	/
[50]	Yes	Yes	No	Yes	/
[51]	Yes	Yes	No	No	MATLAB
[38]	Yes	Yes	Yes	Yes	HOMER

The examined articles employed various research approaches, including numerical simulations, experiments on real systems, or a combination of both, comparing the outcomes of simulations with those of experiments, and vice versa. The publications have been categorized as “Experimental/Simulation”. The statistical analysis yielded the following results:

- An amount of 15 articles (52%) conducted studies based solely on simulations.
- An amount of 14 articles (48%) presented exclusively experimental studies.

These results show a balance between the preference for developing numerical simulations and the utilization of experimental investigations. Simulations require shorter execution times and fewer resources, whereas experimental studies present challenges related to costs and technical issues linked to system installation and operation. The articles have been categorized based on the type of analysis into the following groups:

- Parametric analysis, aimed at optimizing parameters through algorithms for system sizing;
- Non-parametric analysis, focusing on the examination of a specific system’s performance in terms of economic, energetic, or environmental aspects.

The analysis results show that:

- 25 articles (86.2%) proposed a parametric analysis;
- four articles (13.8%) developed a non-parametric analysis;
- 22 articles indicated the software used to conduct the study;
- And two of these articles utilized more than one software.

Most publications adopted a parametric analysis, focusing on optimal sizing, which depends on factors like the installation site, investment capital, and renewable resource availability. Parametric studies often include energetic, economic, and environmental analyses, though environmental aspects are less emphasized and considered in conjunction with other types of analyses. Additionally, the number of articles examining harmful emissions savings and the related environmental impact is surprisingly limited compared to other analysis types, making the environmental analysis a less-explored research topic to date.

The analysis also revealed the use of 12 different software applications in the articles examined. Homer, Matlab, and Excel, employed for simulation and data processing, make up 42% of the article samples. Less frequently used software, considered state-of-the-art for engineering simulations in the relevant sector, include Trnsys, REopt, EnergyPlus, Smart-energy, and Solargis. Lastly, 22% of the data represents studies that do not specify the software used.

3.5. Combined Data Analysis

The entries for each article have been combined, refining the information related to study types, system modes, and usage destinations. Table 5 shows an overview of analysis types.

Table 5. Overview of analysis types.

Article	Experimental	Simulation	Heat	Electrical	Hydrogen
[26]	No	Yes	Yes	Yes	Yes
[39]	No	Yes	No	Yes	Yes
[29]	Yes	No	Yes	Yes	No
[30]	No	Yes	No	Yes	No
[33]	No	Yes	Yes	Yes	No
[27]	No	Yes	Yes	Yes	No
[34]	No	Yes	Yes	Yes	No
[32]	Yes	No	No	No	No
[42]	Yes	No	Yes	Yes	No
[41]	Yes	No	Yes	Yes	No
[28]	No	Yes	Yes	Yes	No
[52]	Yes	No	No	No	No
[37]	Yes	No	Yes	No	No
[48]	Yes	No	Yes	No	No
[49]	Yes	No	Yes	No	No
[53]	/	/	No	No	Yes
[46]	No	Yes	No	Yes	No
[47]	No	No	Yes	Yes	No
[45]	No	Yes	No	Yes	No
[43]	Yes	No	No	Yes	No
[54]	Yes	No	Yes	Yes	No
[44]	Yes	No	No	Yes	No
[36]	No	Yes	No	Yes	No
[40]	Yes	Yes	No	Yes	No
[31]	Yes	No	Yes	Yes	No
[35]	No	Yes	Yes	Yes	No
[50]	Yes	No	Yes	No	No
[51]	No	Yes	No	Yes	No
[38]	No	Yes	No	Yes	Yes

On closer examination, it is evident that while many articles delve into simulations, on-site or laboratory-based experimental validation for hydrogen applications in hospital settings remains conspicuously absent. This gap highlights a potential research area that may have been overlooked or possibly deemed too challenging or resource-intensive. Experimental studies provide invaluable real-world data and insights that simulations might miss. The lack of such data for hydrogen suggests that the adoption and understanding of hydrogen technologies in hospitals might still be in its nascent stages, or there could be prevailing concerns about safety, feasibility, or cost-effectiveness that deter hands-on exploration. Figure 5 shows an overview of the occurrences of simulation-based and experimental analyses.

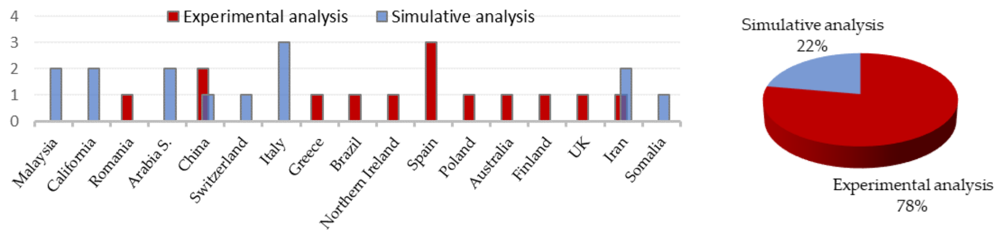

Figure 5. Number of occurrences of simulation and experimental analyses per country.

The research has shown that Italy holds the record as the European country with the most simulation studies conducted, while for the Asian continent, it is Iran. However, this is statistically irrelevant given the low number of simulation studies compared to experimental ones. Spain and China are the countries where, respectively, more investigations have been carried out with experimentation. The only study without simulation or experimentation comes from Poland.

Regarding the distribution of simulation studies only, there is a lower frequency of analysis compared to the country sample when contrasted with the experimental analysis conducted in 11 locations vs. eight for the simulation. Additionally, purely statistically, countries such as China and Iran share both analysis modes, confirming that these countries have a greater propensity towards research on these topics.

The geographical distribution and frequency percentage for each location on system installation modes are examined in Figure 6.

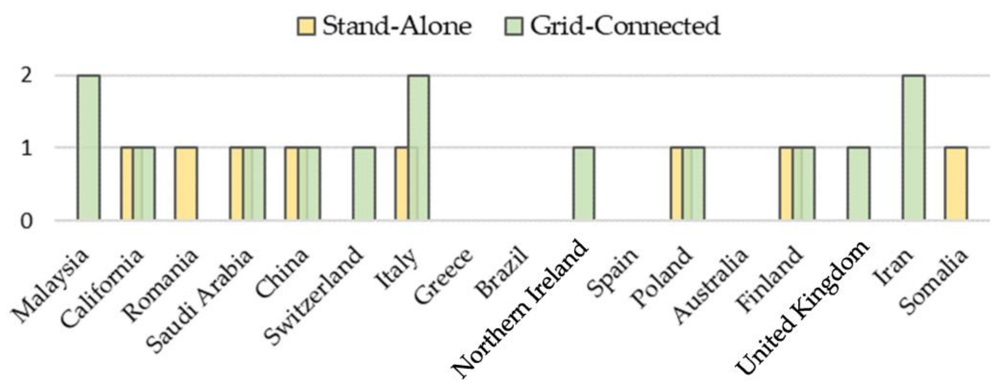

Figure 6. Occurrences of system installation modes in stand-alone and grid-connected modes.

The analysis revealed that Iran, Italy, and Malaysia have conducted the highest number of studies on grid-connected installations, including comparisons between stand-alone and grid-connected systems for the same installation. Meanwhile, Greece, Brazil, Australia, and Somalia do not analyze this configuration.

The distribution of grid-connected installation modes closely aligns with the research distribution. This is because grid-connected installations are more prevalent in the examined case studies. Stand-alone system installations are less common, typically found in healthcare facilities in technologically backward areas or locations lacking access to a homogeneous national grid supply. In advanced countries, stand-alone configurations are used in emergency cases or to manage load demand more efficiently, occasionally sharing supply between the national grid and an autonomous system to reduce costs. However, this is primarily observed when an optimized analysis supports such a decision.

Cross-referencing the data related to study types (simulation vs. experimental) with system modes (stand-alone and grid-connected) in Figure 7 reveals that articles conducting simulation studies are more prevalent in grid-connected systems.

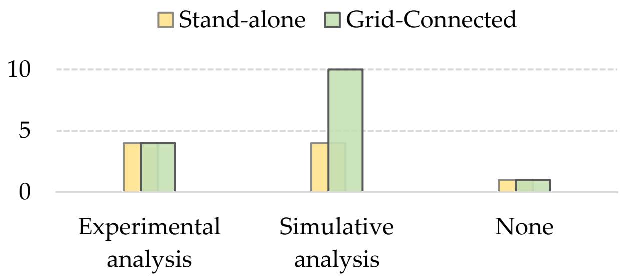

Figure 7. Distribution of study types in the modes of system installation.

This confirms that when studying the systems based on the installation mode, simulation is the predominant analysis method, with lower percentages for other methodologies. The simulation analysis is the most frequently used method when classifying the system based on the installation type.

To delve deeper into the analysis, a cross-sectional examination of system modes for different study types is conducted. In all study methodologies, the percentage distributions align with the overall trend of system modes.

Furthermore, information about the distribution of the three types of installations in the locations under examination is explored. Figure 8 presents the three different installation types: the cogeneration plant, plant based on renewable energy sources (RES), and hybrid plant.

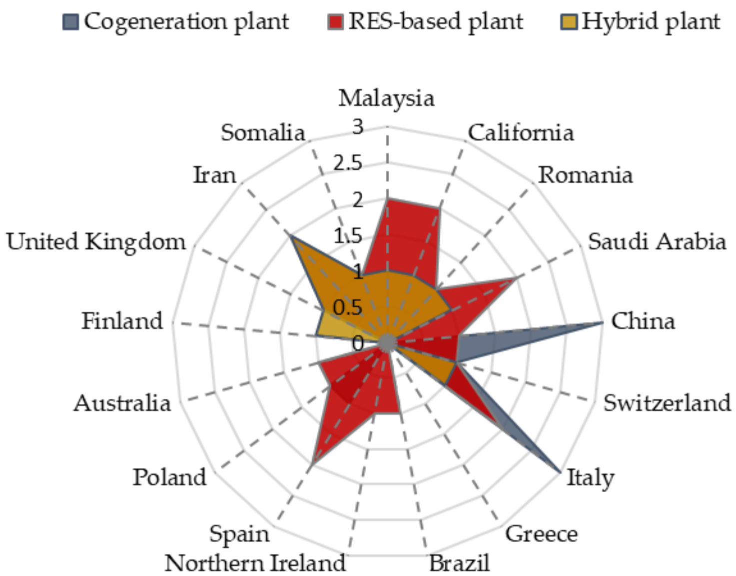

Figure 8. Number of occurrences of the three system configurations by location.

Systems utilizing renewable energy sources are more prevalent compared to the other two categories and are featured in almost all case studies, except for Finland and Greece. Finland relies on fossil fuels for its energy production due to its climatic zone, while Greece does not provide data on the matter. Consequently, RES systems consistently garner significant research attention.

Hybrid and cogeneration systems are equally analyzed in the examined articles, each present in 11 out of the 29 cases. Italy and China extensively examine cogeneration systems, while Iran leads in the number of studies on hybrid systems.

Characteristic locations for RES systems include areas where the technology is applicable, such as Malaysia, California, Saudi Arabia, Spain, and Italy. These areas have favorable meteorological conditions for RES systems, evaluating the photovoltaic module installation as relevant. The average annual incident radiation on these modules remains constant throughout the year, justifying this choice. Countries contributing less to the data analysis are those where the field of study is still in its initial stages.

Regarding hydrogen-based storage systems, the analysis revealed that hydrogen is coupled with photovoltaic panels and/or flat solar collectors in 100% of the cases. Electrolysis systems are integrated into 50% of the studies, while fuel cells and wind energy are incorporated in 25% of the cases. Despite the technology's potential, this study highlights its limited analysis in the hospital sector, with only four out of 29 papers taking advantage of this technology.

4. Conclusions

In this study, data from leading scientific journals published between 2012 and 2022 were analyzed. The focus was on systems for producing energy and medicinal gases to meet the needs of healthcare facilities, including hospitals, private clinics, and medical university campuses in various continents and countries.

The statistical analysis of the collected data revealed research trends related to the investigated systems, whether they were hybrid, based on renewable sources (RES), or single or multiple cogeneration systems. The results include the following observations:

- Iran and China have the highest number of publications in Asia, while Italy and Spain are notable in Europe.
- The experimental analysis is the predominant study methodology.
- Batteries are the most frequently used auxiliary components for both stand-alone and grid-connected systems. Diesel generators are mainly employed in stand-alone systems, while grid-connected systems use biomass, fuel cells, and geothermal probes.
- Grid-connected systems are more extensively studied due to their applicability in medium and large-sized healthcare facilities, especially in densely populated urban areas. Stand-alone systems are prevalent in remote climatic zones and developing countries where a continuous energy supply from the national grid is unreliable.
- Some systems combine grid connections with autonomous operations to reduce overall costs and ensure efficient operation and service delivery.
- Hospital-use is the primary context, focusing on public structures. The parametric analysis is the most developed methodology, emphasizing the optimal sizing of systems based on energy, economic, and environmental criteria.
- Photovoltaic systems are preferred for low and medium power, while wind systems are more important for larger systems, often in combination with other auxiliary components and hybrid or cogeneration systems. Photovoltaic systems are used to cover load variations/interruptions where needed.

The overall statistical analysis has identified the most important themes regarding the production systems examined, previously classified into three categories: systems based on renewable sources (RES), hybrid systems, and single or multiple cogeneration systems. Thanks to this analysis, it was possible to recognize the advantages and limitations of each system, using specific energy, economic, and environmental indicators for each case. Furthermore, concerning hydrogen storage systems and configurations, the study shows that they consistently pair with photovoltaic panels or flat solar collectors. Despite its potential, only 14% of papers explore this technology in hospitals, highlighting its underutilization.

The transition to renewable energy in healthcare is not just a technological shift but also requires robust policy frameworks and support from global initiatives. Governments worldwide can accelerate this transition by providing subsidies, tax breaks, and grants to hospitals transitioning to renewable energy sources. Furthermore, global initiatives like the United Nations' Sustainable Development Goals can play a pivotal role in emphasizing the importance of sustainable energy in healthcare, thereby influencing national policies. Hospitals, being significant energy consumers, can serve as role models in adopting renewable energy, thereby influencing other sectors to follow suit.

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