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Review

Hybrid Energy Systems for Buildings: A Techno-Economic-Enviro Systematic Review

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Abstract: Hybrid energy systems physically or conceptually combine various energy generation, storage, and/or conversion technologies to reduce costs and improve capability, value, efficiency, or environmental performance in comparison with independent alternatives. Hybridization is an interesting energy sector solution for plants to expand their flexibility, optimize revenues, and/or develop other useful products. Integrated hybrid energy systems' improved flexibility can hasten the integration of more renewable energy into the grid and help become closer to the target of zero-carbon energy grids. This paper aims to provide an updated literature review of design and applications of hybrid energy systems in buildings, focusing on economic, environmental, and technical viewpoints. This current study will analyze current and future trends toward hybrid energy systems for buildings and their functions in electrical energy networks as potential research study topics for the future. This study aims to enhance sustainable building techniques and the creation of effective electrical energy networks by offering insights into the design and applications of hybrid energy systems. The methodology used in this study entails assessing present and potential trends, as well as looking at hybrid energy system uses and designs in buildings. The higher flexibility of integrated hybrid systems, which enables enhanced grid integration of renewables, is one of the key discoveries. The discussion of potential research study themes and conceivable applications resulting from this research forms the paper's conclusion.

Keywords: hybrid energy systems; energy conversion technology; buildings; energy system design; renewable energy sources

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1. Introduction

1.1. Motivations

According to the International Energy Agency (IEA), buildings account for around 40% of the world's energy consumption and 30% of global carbon dioxide emissions [1]. This highlights the urgent need to address energy consumption in buildings to reduce greenhouse gas emissions and to mitigate the negative impact on the environment. The adoption of hybrid energy systems in buildings has the potential to play a significant role in achieving this goal. The market for hybrid energy systems in buildings is expected to grow at a steady pace over the next decade. According to Ref. [2], the global hybrid energy market size is projected to reach USD 1.5 billion by 2025, growing at a compound annual growth rate (CAGR) of 9.6% from 2020 to 2025. The report also highlights that the increasing demand for renewable energy sources and government incentives and policies and the need for energy security and independence are the major drivers of this growth.

Recent attempts worldwide to reduce energy use and to investigate alternate energy sources have been sparked by the depletion of fossil fuels and the detrimental effects on the environment. Given that the building sector currently makes up 20–40% of all energy consumption in developed nations [3], renewable energy applications are viable replacements for fossil fuels to lessen the impact of the building industry's energy issues and environmental pollution. Solar and wind energy are two examples of renewable applications that have grown significantly in recent years [4]. Applications for wind energy, such as wind turbines, are often installed on a large scale [5] and widely used in distant and offshore places [6]. Solar energy is a better choice as a power supply source and is simpler to integrate with existing structures for buildings, with limited installation area, a need for vibration control, and unfavorable wind environments in urban contexts. However, to acquire a stable and dependable power supply, matching energy storage technologies are required, because solar energy and wind power are typically intermittent and unpredictable [7] and thus not continuously consistent with building demand. The integrated energy storage unit may control the utility grid frequency for on-grid renewable energy systems as well as adapt the solar power flow to match the building demand and increase energy autonomy [8]. Therefore, for efficient power delivery to buildings, it is important to research the integration of different electrical energy storage (EES) technologies with PV systems.

The adoption of hybrid energy systems in buildings is also being supported by advances in technology, such as improved battery storage and energy management systems. These technologies allow for better integration and optimization of renewable energy sources, which can further enhance the efficiency and reliability of these systems. The adoption of hybrid energy systems in buildings is gaining momentum due to the growing need for sustainable and efficient energy solutions. Technological advancements such as improved battery storage and energy management systems are playing a crucial role in supporting this trend. Hybrid energy systems combine multiple sources of energy, such as solar and wind power, with traditional grid electricity to meet the energy demands of buildings. Improved battery storage technology allows for the storage of excess energy generated by renewable sources for use during times of high demand. Additionally, energy management systems can optimize energy usage and reduce waste by monitoring and controlling energy consumption in real time. These advancements in technology are contributing to the wider adoption of hybrid energy systems in buildings, leading to a more sustainable and resilient future for the built environment [9].

In addition to reducing greenhouse gas emissions and improving energy efficiency, hybrid energy systems in buildings can also lead to cost savings over the long term. A report by the Rocky Mountain Institute found that hybrid energy systems can provide a cost-effective alternative to traditional energy sources, with potential savings ranging from 10% to 60% on energy bills depending on the specific circumstances. Hybrid energy systems combine renewable energy sources, such as solar and wind power, with traditional energy sources, such as fossil fuels, to create an efficient and sustainable energy solution. This integration of energy sources allows for greater energy efficiency and reduced reliance on traditional energy sources, resulting in reduced greenhouse gas emissions and lower operating costs for building owners. As the benefits of hybrid energy systems become more widely recognized, they are increasingly being adopted in commercial and residential buildings to reduce energy costs and to promote sustainable practices [10].

1.2. Importance and Highlights of Previous Contributions

The authors in [11] reviewed optimal sizing, energy management, operating and control strategies for hybrid energy systems consisting of wind power, photovoltaic power, fuel cell, and micro-turbine generators. The use of such hybrid systems offers economic, environmental, and social benefits. Various controllers, such as micro-controller, proportional integral controller, hysteresis controller, and fuzzy controller, are analyzed for their feasibility in achieving zero steady-state error and producing the desired output response. A literature review on the optimization techniques used for designing and developing solar photovoltaic (PV)-wind-based hybrid energy systems is provided in [12]. The review analyzes different methods used by researchers and identifies new generation artificial intelligence algorithms as the most popular for optimization studies. The study suggests using hybridization of multiple algorithms to overcome limitations of a single algorithm and identifies additional techniques for further research in the design of PV-wind hybrid systems. The authors in [13] provide an overview of the functional integration of hybrid renewable energy systems (HRES) in multi-energy buildings, highlighting the potential benefits and challenges associated with their application in the residential building sector. The focus is on building-integrated HRESs, with at least two renewable energy sources, and their integration with thermal and electrical loads, as well as external multiple energy grids, to provide flexibility services. The paper describes new holistic approaches to management problems and more complex architectures for optimal control. The current status of solar hydrogen production methods and the energy and exergy efficiencies of a photovoltaic-hydrogen/fuel-cell hybrid energy system are reviewed in [14] for the case of Denizli, Turkey for stationary applications. The results indicate that the hydrogen path is the least efficient due to the addition of the electrolyzer, fuel cells, and second inverter for hydrogen production and utilization. The authors in [15] review recent developments in the classification, evaluation, and sizing methodologies of hybrid renewable energy systems, which are proposed to overcome the variability of a single renewable energy source. The authors suggest that decision makers should pay attention to environmental and social indicators when determining the system capacity and that hybrid methods with high accuracy and fast convergence are the most promising sizing method. In Ref. [16], the penetration of wind power into hybrid renewable energy systems is reviewed, which is a solution to current energy deficiencies in different countries around the world. The study considers economic and technical factors and finds that most countries have identified the potential for wind power generation using available wind energy resources, with Asian countries having the potential to penetrate wind energy into hybrid systems and European countries being ahead in terms of technical development.

1.3. Novelty of the Research and Contributions

The adoption of hybrid energy systems in buildings has the potential to significantly reduce the environmental impact of building energy use while providing a reliable and cost-effective source of energy. As such, the development and implementation of these systems is likely to continue to grow in the coming years, driven by advances in technology, government policies, and increasing concerns about climate change. Accordingly, this paper aims to provide a technical systematic review on hybrid energy systems for buildings. This study provides various breakthroughs in hybrid energy system applications and design. This paper provides a thorough understanding of the advantages and difficulties related to hybrid energy systems in buildings by considering the economic, environmental, and technical aspects. It examines past, present, and projected trends to find potential research study subjects that could develop these systems. Additionally, this article seeks to advance hybrid energy system design and implementation in sustainable construction practices. By analyzing these systems' functions and how they fit into the larger grid, it highlights the importance of building efficient electrical energy networks. The better flexibility of integrated hybrid systems, which enables improved grid integration of renewables, is one significant finding noted in this paper. This report ends with a discussion regarding potential research subject themes, offering direction for additional investigations in this area. Overall, these developments support the creation of cost-effective and environmentally friendly hybrid energy systems for buildings. The main contributions of this study can be summarized as follows:

- By studying the literature around the economic aspect of hybrid energy systems in buildings, the authors aim to provide insights into the cost-effectiveness of implementing such systems. Additionally, the key factors that influence the economic viability of these systems will be identified, which can guide decision making for building owners, policymakers, and other stakeholders.

- The literature review provides a comprehensive analysis of the environmental impact of hybrid energy systems in buildings, highlighting their potential to reduce greenhouse gas emissions and to promote sustainable energy practices. It contributes to the existing body of knowledge by synthesizing current research findings and identifying knowledge gaps for future research in this field.
- The literature review on the technical aspect of hybrid energy systems in buildings will be given to provide a comprehensive understanding of the current state of research in this field, including the challenges, opportunities, and best practices. It will also highlight the potential of hybrid energy systems to improve energy efficiency, reduce carbon emissions, and enhance the resilience of buildings.

1.4. Organization

The remainder of this paper is organized as follows: Section 2 focuses on the economic aspect of hybrid energy systems in buildings, a review of recent papers, and some tables and graphs. Section 3 discusses the environmental aspect of hybrid energy systems in buildings, a review of recent papers, and some tables and graphs. Section 4 focuses on the technical aspects of hybrid energy systems in buildings, a review of recent papers, and some tables and graphs. Finally, Section 5 provides the conclusions and future work.

2. Economic Aspect of Hybrid Energy Systems in Buildings

Significant energy consumption has a considerable implication on building energy economics. With growing concerns about climate change, many scientists and researchers have tried to decline the damaging effect of using fossil fuels. However, sustainable development can be achieved if the produced energy is economically affordable, technically reliable, and environmentally sustainable [17]. Fossil fuels directly contribute to global warming by unbalancing carbon equilibriums; furthermore, their steady supply is vulnerable to global wars and pandemics. In contrast, renewable energy resources have been introduced as one of the promising substitutes for fuel-based energy carriers for years. Solar, wind, geothermal, biomass, and other renewable energies are abundant in nature, so they can meet the energy demand with the most negligible environmental hazards [18]. Many technologies have been developed to exploit these energy sources efficiently, but they have yet to be able to compete with cost-effective fossil fuels to date. Considering the political and environmental disadvantages of conventional fossil fuels and nonprofitable renewable energies, hybrid energy systems are essential if it is planned to employ renewable energies in the current market [19]. Hybrid energy systems can balance the energy market by concurrently producing electricity, heating, cooling, and other energy carriers in need [20]. Thus, hybrid systems are promising tools in buildings if sustainable development is leveraged by prioritizing economics. In this way, profound analytics can justify changes in energy policies in favor of hybrid systems. Despite their scientific legislation in the scientific community, hybrid renewable energy systems are not supported by federal incentives in most of the developing and developed countries.

The economic aspect is a critical criterion for selecting an efficient hybrid energy system in a building [21,22]. In almost all cases, a mature challenge with renewable energy applications is the considerable amount of capital investment. However, renewable energies can become long-term alternatives in buildings by justifying their benefits in environment protection, social promotion, and fuel independence [23]. This can be addressed either by applying green plans in public platforms or short- and medium-term incentives to feed-in-tariffs. The allocation of greater weights to decision-making coefficients in management strategies and development plans could pave the way to an extensive application of hybrid renewable systems in the near future. Several indices have been proposed to evaluate the costs and to conduct economic appraisals of hybrid energy systems in buildings. Cost of energy (COE) is a mature metric to present the costs while generating energy by a given system [24,25]. It can be obtained in total or levelized forms. The levelized cost of energy (LCOE) is a conventional index for employing renewable energies in hybrid systems because of its better consistency with long-term construction projects [26]. On the other hand, the total costs are used in comprehensive reports of a project. These indices include sufficient details of the probable costs [27]. The initial investment costs are calculated, regardless of future political and economic fluctuations such as volatile inflation, recession, or incentives [28]. The indices of this category are used to provide the stakeholders, investors, and beneficiaries of a project with sufficient information about the requirements of a project. In contrast, total revenue represents all the economic benefits of a hybrid energy system in a building. Counting carbon reduction or other economic-environmental benefits can be improved while shifting from conventional to hybrid systems [29]; hence, they are usually preferred in macro-economic studies and national policies.

In contrast to costs, total revenue represents all the economic benefits of a hybrid energy system in a building. Counting carbon reduction or other economic environmental benefits can be improved while shifting from conventional to hybrid systems [29]. The latter term includes the project's running, maintenance, and contingency costs. Finally, the system's net present cost (NPC) is a mature term to present all these costs, regardless of annual economic changes. In other words, all costs are agglomerated, but the computational economic parameters are assumed to equal the present values in obtaining this cost [30]. The payback is usually calculated according to the NPC. It represents a period of time required to earn all the investment by selling the products of a system [31]. Considering the dynamic social and environmental costs and benefits of a hybrid system, the payback can be obtained from stochastic models with several scenarios [32]. The cost ratio would replace the above-mentioned metrics to obtain a fraction of costs in a comparative economic model [26]. The internal rate of return follows a similar formulation to the net present value and represents the profitability of a project with respect to the cash flows [33], despite the significance of the number and duration of failure in operation and maintenance models of the renewable energy systems, which is usually calculated with lifecycle costs of a project [34]. The total annualized cost (TAC) is the most reliable index encompassing prominent economic parameters of hybrid energy systems. It is a function of the total capital costs of an engineering system and a capital recovery factor of the economic system [35]. TAC is used in both the theoretical engineering literature and management reports.

The applications of hybrid energy systems in buildings have been economically evaluated using the metrics mentioned above and some other indices. Some of the recent articles and their highlighted economic constraints are summarized in Table 1. The systems have been proposed for different purposes in various climates and built environments, hence they are composed of different equipment. The correlation between the climate and system configuration significantly controls the economics of hybrid renewable energy systems in the built environment. Following a global trend, BAT-assisted solar PVs have been applied in most systems. WTs are the second most abundant weather-driven renewable component used to increase the reliability of hybrid systems in appropriate conditions. The hybrid renewable energy systems can accommodate mini-WTs in building applications. The systems have usually been modeled with their utilities, but the costs of the resources have been addressed when necessary [36]. The economic constraints mainly depend on the objectives of the studies. For instance, comparative analyses could be easily completed by hiring NPC as the economic criterion. However, the COE and LCO are used when the aim is to supply the market with the produced energy; the total costs are employed for complicated systems. Among various economic constraints, TAC is the most flexible one to be updated by environmental and social life-cycle parameters in advanced appraisals. Even though economic analyses aid quantitative estimations over applications of hybrid systems, final decisions should be made considering the social, environmental, and technical aspects of the projects. This is attributed to the erratic behavior of the natural resources as well as the unpredictable consumption patterns in the buildings.

Table 1. A summary of the literature around hybrid energy systems for buildings considering economical viewpoints.

Ref.	Main Objective	Hybrid System Equipment	Economical Constraints	Published Year
[37]	A new system was proposed; multi-objective optimization was carried out	PV, BT	Total annual cost (TAC)	2023
[38]	The best optimum hybrid renewable energy system was proposed in school	PV, WT, DG	Net present cost (NPC)	2022
[36]	A novel dispatch strategy was developed	PV, WT, BAT, DG	Total net present cost (NNPC), initial cost (IC), replacement cost (RC), operation and maintenance cost (O&M), resource-related costs	2020
[39]	A hybrid energy system was proposed that used surplus electricity to make hydrogen	PV	Energy cost, the annual total cost	2021
[40]	A methodology for the optimal design of hybrid systems was analyzed and proposed	PV, WT, BAT, DG	COE	2021
[41]	A sufficient optimization method for optimal sizing was introduced	PV, DG, FC	TNPC	2019
[42]	Energy management optimization and also the optimal sizing were investigated	PV, WT, BAT	Cost of electricity (COE)	2019
[43]	The viability of developing a stand-alone hybrid RES system was assessed using solar and wind	PV, WT, BAT, DG	NPC, COE	2019
[44]	Techno-economic feasibility of PV-Wind hybrid energy systems was performed	PV, WT	COE	2017
[45]	The size of the optimal hybrid energy system was analyzed	PV, WT, BAT	Total cost of electricity (COE)	2018

3. Environmental Aspect of Hybrid Energy Systems in Buildings

In terms of environmental sustainability, hybrid energy systems have a number of advantages over conventional energy systems [46]. Hybrid systems can offer a dependable and cost-effective energy supply while lowering greenhouse gas emissions and supporting environmental sustainability by mixing various energy sources, such as renewable and non-renewable sources. Buildings' greenhouse gas emissions can be greatly reduced and environmental sustainability can be improved by integrating renewable and conventional energy sources [47]. The utilization of renewable energy sources in hybrid energy systems is beneficial because they have little negative environmental impact and can greatly cut carbon emissions [48]. However, the layout and optimization of a system's individual parts determine how well hybrid energy systems support environmental sustainability. To maintain the overall sustainability of a hybrid energy system, the environmental impact of each component must be taken into account [49,50].

To increase energy system efficiency, reduce energy consumption and waste, and maximize the use of renewable energy sources, building design and energy management are crucial [51]. Hybrid energy systems can further improve environmental sustainability and lower carbon emissions when they are combined with energy-efficient building design and energy management strategies [52]. For instance, building-integrated photovoltaic systems can be incorporated into the building envelope to generate renewable energy and to lower the energy requirements of the structure [53], which is similar to how energy-efficient building designs that include passive solar heating, natural ventilation, and energy-efficient lighting and appliances may considerably lower a building's energy consumption and improve the effectiveness of hybrid energy systems.

The life-cycle environmental effects of power produced by a home hybrid system that combines solar PV and lithium-ion batteries are presented in [54]. Seven regions of Turkey are taken into consideration, together with the variations in insolation and other climatic factors; the implications are evaluated for both individual installations and at the national level. The system can provide between 12.5% and 18.4% of a household's annual electricity demands, according to the results. It produces 4.7–8 times more energy than it uses throughout the course of its lifetime. Except for human toxicity, which is mostly caused by the battery, the production of system components and raw materials, both of which are heavily associated with solar photovoltaics, are shown to be the major environmental hotspots. Based on the research conducted in [55], it is possible to build a community that uses almost little-to-no energy by using a distributed energy system (DES), which combines hybrid energy storage with fully utilized renewable energies. The DES configuration is optimized in connection to its environment, economy, and net interaction based on practically zero-energy communities and buildings. The price of equipment, the price of power, and the carbon tax are all the subject of a sensitivity analysis. The findings indicate that the new DES's annual carbon emissions and net interaction are decreased by, respectively, 51.7–73.2% and 33.5–63.6%, when compared with the reference system.

Table 2 summarizes some of the newly published papers around hybrid energy systems for buildings with environmental standpoints.

Table 2. A summary of the literature around hybrid energy systems for buildings considering environmental viewpoints.

Ref.	Main Objective	Hybrid System Equipment	Environmental Constraints	Published Year
[49]	Assesing the environmental effects of the total life-cycle of hybrid energy systems for buidlings	PV, BAT	Life-cycle inventory (LCI)	2019
[56]	Examining the effects of H2NG on the technical, financial, and environmental aspects of hybrid energy systems for the renovation of buildings	PV, HP, CHP, absorption chiller	CO_2 emissions	2022
[57]	Environmental evaluation of hybrid energy systems designed for supplying electric power and heating and cooling demands of office buildings	PV, BAT, WT, PEM electrolyzer, trigeneration CHP	Life-cycle assessment (LCA)	2021
[58]	Achieving the most usable energy with the least amount of pollution and expense by applying a two-step optimization combined with a multiple criteria decision-making technique.	Biomass–geothermal	CO_2 emissions	2021

Table 2. *Cont.*

Ref.	Main Objective	Hybrid System Equipment	Environmental Constraints	Published Year
[59]	Optimal design of hybrid energy systems for improving economic and environmental advantages	PV, BAT, WT, DG	CO_2 emissions	2021
[60]	Optimizing configuration of a stand-alone hybrid energy system for villiage buildings	PV, BAT, WT, DG	CO_2 emissions	2021
[30]	Evaluation of a hybrid energy system for a complex of buildings with power and heat loads considering technical, economical, and environmental optimization	PV, WT, micro-gas turbine (MGT) and fuel cell (FC), electrolyzer, hydrogen tank (Htank), BAT	CO_2 emissions	2023
[61]	Evaluation of renewable-based hybrid energy systems for buildings considering energy–exergy analysis	PV-thermal collectors, fuel-fired micro-cogeneration plants	Natural surroundings with constant properties of pressure, temperature, and chemical composition	2023
[62]	Proposing a bi-level optimization framework for sizing hybrid energy systems	Distributed solar hybrid CCHP, PV/thermal panels	Annual total emission saving rate (ATESR)	2023
[63]	Asssesing hybrid energy systems for zero-energy buildings considering reliability indices	PV, DG, BAT	DG emissions of CO_2, CO, SO_x, and NO_x	2023
[64]	Assessing hybrid renewable-based energy systems for urban buildings	Geothermal, biomass, PV	Carbon emissions	2023
[65]	Multi-objective design framework for home-scale systems based on the technical modeling of various common components	PV, WT, solar heat collector, HP, heat storage, BAT, heat insulation thickness	LCA	2021

4. Technical Aspect of Hybrid Energy Systems in Buildings

Population growth and urbanization have been stated to be the main reasons of increasing building energy consumption in the last decades [23]. Technical responses to these factors have not been environmentally friendly, so the increasing energy demand has resulted in many global warming-related issues. In addition to environmental concerns, fossil fuel depletion encourages us to amend technical issues in buildings to minimize losses and maximize renewable energy conservation [66,67]. Considerable attempts have been addressed to employ hybrid renewable energy systems in buildings because of their reliability, resilience, and cost-effectiveness in comparison with the other systems. They have the potential to meet the energy needs in buildings in both stand-alone and grid-connected modes. The off-grid systems are usually employed in remote areas, special locations, and naturally protected areas, whereas the on-grid system benefits from perennial electricity trade with the electrical network. However, the selection of appropriate control dispatch strategies, suitable size and configuration, and efficient optimization methods are the main problems to guarantee efficiency and reliability of the systems [68]. Reconfigurability of the systems leads to the consideration of minimum external energy consumption while designing integrated hybrid systems and buildings. These studies usually address a single type of resource or an extremely limited load type [18]. However, recent studies have employed several green sources of energy to increase the reliability of energy conversion systems. Since the main technical parameters in energy systems are sufficient performance, the life-cycle of components, and the system's stability, hybrid energy systems would retain their unique role in providing energy for buildings [69].

Hybrid energy systems are generally assessed, designed, and optimized according to their techno-economic concerns. Indeed, the optimal sizing elucidates the ideal hybrid energy system configuration(s) and requires costs for both operation and technical performance [70]. Not only the economic models but the social and environmental performance of the systems are usually assessed based on their technical models. Independent environmental or social analyses can be performed following a technical model [71] or various aspects of a system can be integrated into techno-economic-enviro-social models [72]; in any case, a technical model is an indispensable part of a comprehensive evaluation. Various technical indices have been used as optimization constraints, objective functions, and parameters. Technical indices such as power supply probability (PSP), loss of power supply probability (LPSP), and loss of load probability (LLP) are introduced as reliability constraints. These parameters are associated with the probability of failing to supply the demand power load over time. Electricity production over the entire life-cycle of a hybrid energy system is represented by EP. The EP is a function of the availability of resources, as well as the capacity factor of the systems. However, the systems rarely operate at their full capacity. The efficient operation of a conversion system is usually represented by energy efficiency. Taking the quality of energy in addition to its quantity into account, exergy efficiency best serves performance evaluation purposes. Power production, loss factor, voltage availability, and profile are the factors used to put more emphasis on the electrical performance of the systems. However, level of autonomy, load margin, renewable penetration, and fraction are parameters that deal mainly with technical aspects of the hybrid renewable energy systems.

Some of the recent papers regarding the technical aspects of hybrid energy systems in buildings are summarized in Table 3. According to the table, solar PVs and WTs are the popular components with an increasing application rate in the buildings. The geographical location of the built environment determines the type of resources. However, growing interest in weather-driven renewable energies has motivated many researchers to focus their designs on solar and wind facilities. Otherwise, useless rooftop and façade areas of buildings and free spaces in built environments turn them to technically viable alternatives for solar and wind systems installation, respectively. Reliability and loss constraints have a crucial role in hybrid systems equipped with batteries. They can readily affect the economic performance of a system. Considering the trade-off between these metrics, a reliable system is often noneconomic in a long-term operation. The systems with a high upper bound of battery sizes are less sensitive than the systems with big storage to the variations of the demand load and uncertainties of the natural variables. In contrast, the systems retrofitted by short- and long-term storage facilities are expected to be reliable in meeting dynamic demand. The technical constraints can provide the evaluation models with a chance of including social and environmental aspects. Simpler technical models are preferred for future extensions. Special attention is devoted to production and consumption variables in management studies, whereas the capacities of the components and their efficiencies are the major technical constraints for design purposes. Recent research shows an interest in substituting hydrogen facilities with traditional storage equipment. Although technical constraints can constitute a full model of the energy systems in buildings, they are usually complemented by economic, environmental, and social models to present comprehensive analyses. In these combined models, technical models provide analytical bases.

Table 3. A summary of the literature around hybrid energy systems for buildings considering technical viewpoints.

Ref.	Main Objective	Hybrid System Equipment	Technical Constraints	Published Year
[73]	Different dispatch strategies were investigated to find a suitable one for the desired location	PV, WT, BAT, DG	Unmet load, excess energy factor, the renewable energy portion	2022
[74]	Various analyses were conducted with specific models in the target location to conclude the optimal solution for continuous power supply	PV, WT, DG	Energy consumption, energy production, excess energy, unmet load, capacity shortage, and renewable fraction	2022
[75]	Natural gas-fired boilers were replaced by solar borehole thermal energy storage (BTES) and sewage heat recovery (SHR) systems in Canadian buildings	BTES, SHR	Net annual direct energy consumption, net annual primary energy consumption	2022
[76]	The potential of solar and wind power units was studied to propose effective short-, mid-, and long-term solutions to power crises	PV, WT	Energy production and energy consumption	2019
[77]	Sensitivity of prime and deferrable loads of hospitals were evaluated employing hybrid systems	PV, WT, BAT	System performance	2021
[78]	The feasibility of retrofitting university buildings with hybrid renewable energy systems was studied in Saudi Arabia	BAT, PV, WT	Components' sizes, power loss probabilities	2021
[79]	A whale optimization algorithm (WOA) was applied to optimally design a hybrid system	PV-Biowaste-FC system	Reliability	2022
[80]	An optimal configuration was obtained with minimum loss of power supply, net present cost, cost of energy, and hydrogen production costs	PV, WT	Primary energy input	2019
[23]	A techno-economic analysis was performed on a hybrid energy system and its on-grid and off-grid operations were investigated	PV, WT, BAT	Energy demand	2021
[81]	An optimization method was proposed based on technical, economic, environmental, and socio-political objectives.	PV, WT, BAT	Efficiency of the hydrogen tank	2019

5. Conclusions

This study reviews existing research on hybrid energy systems for buildings and assesses emerging issues. Energy technologies are combined in hybrid energy systems to save costs and boost effectiveness, adaptability, and environmental performance. They provide a viable option for facilities looking to maximize profits and create other beneficial items. Significant reductions in greenhouse gas emissions can be achieved by using hybrid systems to target difficult-to-decarbonize applications and integrate additional renewable energy. Policymakers, building owners, and stakeholders can be directed toward making effective policy decisions that encourage the widespread adoption of these systems by building on the technical, economic, and environmental research offered in this paper. Implementing strong government incentives and subsidies to promote the integration of hybrid energy systems is a crucial recommendation for policy. Governments can speed up the adoption of these systems and shorten the payback period by providing financial assistance in the form of tax credits or grants to building owners. In addition, regulatory frameworks that mandate or reward the inclusion of hybrid energy systems in building regulations and standards should be considered by politicians. The building industry would be pushed toward more eco-friendly and energy-efficient solutions because of this explicit demand for sustainable energy practices. In addition, supporting R&D projects through collaborations between government, business, and university can result in technological improvements and innovation in hybrid energy systems. This would support ongoing system efficiency, cost-effectiveness, and grid integration improvements, supporting the sustainability and scalability of these solutions over the long term. Policymakers may successfully harness the potential of hybrid energy systems, lower greenhouse gas emissions, improve energy resilience, and promote sustainable growth in the construction industry by putting these policy proposals into practice.

There are several potential directions for further research in hybrid energy systems for buildings, in addition to examining present and anticipated trends. These consist of:

- The process of tailoring hybrid energy systems to a certain building type and location while considering the local climate, energy demand profiles, and resource availability considering social equity access to energy sources.
- The creation of novel energy storage technologies that can be included into hybrid energy systems of buildings.
- The real-time optimization of energy production and consumption through the integration of cutting-edge control systems and artificial intelligence into hybrid energy systems of buildings.
- The examination of hybrid energy systems' economic viability and scalability, especially considering developing nations and off-grid or isolated locations.
- The investigation of cutting-edge business strategies and funding options, including community ownership models, energy as a service (EAAS) model, and green bond, to promote the adoption of hybrid energy systems.
- Future lines of action can be expanded for buildings in cities that allow governments to align their development objectives sustainable development goals (SDGs).

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Abbreviations

BAT	Battery system
BTES	Borehole thermal energy storage
CCHP	Combined cooling, heating, and power
CHP	Combined heat and power
CAGR	Compound annual growth rate
COE	Cost of energy
DG	Diesel generator
DES	Distributed energy system
EES	Electrical energy storage
EAAS	Energy as a service
HP	Heat pump

HRES	Hybrid renewable energy systems
IEA	International energy agency
LCOE	Levelized cost of energy
LCA	Life-cycle assessment
LCI	Life-cycle inventory
LLP	Loss of load probability
LPSP	Loss of power supply probability
NPC	Net present cost
PV	Photovoltaic
PSP	Power supply probability
SHR	Sewage heat recovery
SDGs	Sustainable development goals
TAC	Total annualized cost
WOA	Whale optimization algorithm
WT	Wind turbine

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