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REVIEWS

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A critical review on techno-economic analysis of hybrid renewable energy resources-based microgrids

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Abstract

Now that the population is growing, the expenditure on basic needs of life is also increasing due to a lack of or less availability of resources. The economy consumed electricity is reaching peaks as its main fuel, coal, is decreasing day by day. Due to this, 90% of the population who are in the middle class, lower middle class, or rural areas are economically poor and are unable to bear the prices. To overcome the financial problems, many researchers have prepared various types of microgrids that generate electricity from various types of flow resources, like hydro, solar, biogas, and air current power stations, whose system is called a compound flow power system. This paper gives a combined review of various research papers that discuss some case studies and some research on various models designed on software like HOMER Pro, how microgrids become economic barriers, optimal power supply solutions with CFPS, distributed and centralized microgrid components, the technical and economic feasibility of EV charging stations, and the analysis of various combinations of power systems at various locations like Bangladesh, Canada, the Republic of Djibouti, China, Indonesia, Sierra Leone, some rural sites in India, and some developing countries. This overview provides a glimpse into the various aspects of CFPS, including fusion approaches, techno-economic analysis, simulation platforms, storage technologies, design specifications, unit sizing methodologies, and control techniques. Further research and analysis in these areas are needed to explore their applications and advancements in CFPS development. The main reason for the study is to analyze and bring various ideas and models of various researchers together on a common platform and make a combined conceptual framework for further proceedings.

Keywords: Microgrid, Renewable energy, Compound flow power system, Software tools, Power storage system

Introduction

The increasing consumption of electrical power in various sectors has become crucial for the overall development of any nation. However, the reliance on non-flow resources such as fossil fuels, nuclear power, and hydrogen has led to problems like the depletion of fossil fuel reserves and land degradation. It is worth noting that currently, approximately 66% of the global power demand is fulfilled by fossil fuels. The combustion of fossil fuels releases carbon dioxide (CO2), carbon monoxide (CO), and other harmful pollutants, contributing significantly to global warming and adverse climate effects. Considering the escalating population growth and the rising electricity needs and lifestyle demands, it is essential to explore alternative power sources. Flow power resources, on the other hand, offer several advantages over non-flow resources. They can be harnessed without releasing harmful elements into the environment or water bodies. Moreover, flow resources replenish at a similar rate as their consumption, making them more sustainable in the long run. Recognizing the need for transitioning to alternative power sources, the Indian government has launched schemes to increase the percentage of flow energy. The goal is to make flow power account for approximately 40% of the total power by 2040. By embracing flow power resources, nations can reduce their dependence on fossil fuels, mitigate environmental pollution, and work towards a more sustainable and environmentally friendly energy future. The combustion of fossil fuels releases carbon dioxide (CO2), carbon monoxide (CO), and other pollutants into the atmosphere. These emissions contribute to the greenhouse effect and are considered the primary drivers of global warming and climate change. Carbon dioxide, in particular, is a major greenhouse gas responsible for trapping heat in the Earth's atmosphere, leading to rising global temperatures.

As the population increases and lifestyles evolve, the demand for electricity and energy-intensive activities also tends to rise. This growing demand puts additional pressure on energy production and consumption. Meeting this demand through traditional means, primarily reliant on fossil fuels, exacerbates the environmental challenges associated with climate change. Approximately 1.2 billion people still lack access to electricity. This lack of access hampers social and economic development in those regions. To address this issue and reduce reliance on fossil fuels, alternative power sources are being explored. Among these alternatives, flow power resources are gaining attention. Additionally, flow resources are renewable, meaning they can be replenished at a similar rate to consumption. For example, the water used for hydroelectric power can be naturally replenished through precipitation and the water cycle. This ensures a sustainable and continuous energy supply without depleting the resource over time. Countries like India recognize the potential of flow power resources and have taken initiatives to promote their usage. The Indian government has launched schemes and policies to increase the percentage of flow energy in its total power generation. As you mentioned, there is a plan to achieve a target of around 40% of total power generation from flow power by 2040. Such commitments and efforts contribute to the transition towards a more sustainable and environmentally friendly energy system.

The Compound Flow Power System (CFPS) is a power generation system that utilizes multiple flow power resources to meet diverse power requirements in a cost-effective and efficient manner, as shown in Fig. 1. When there are not enough flow power

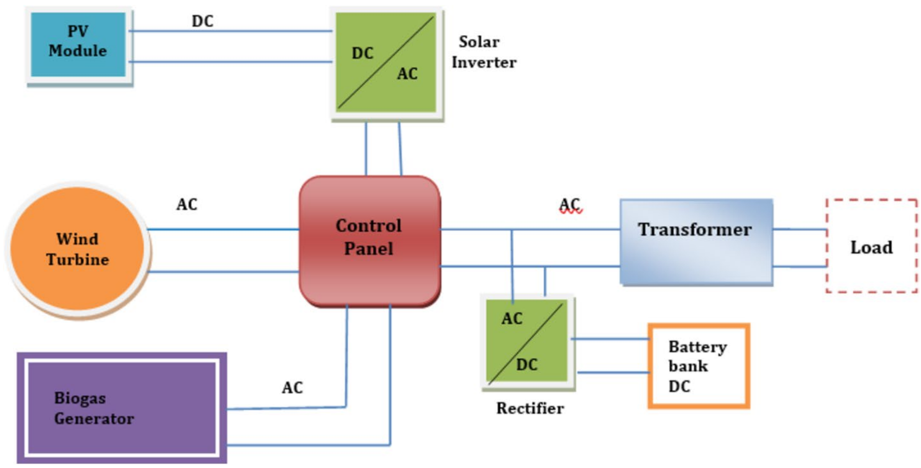

Fig. 1 Compound flow power system

resources available, two or more power resources are considered to provide power. In independent systems, supplementary power systems or drive systems are necessary to handle fluctuations in flow power resources. The incorporation of flow power resources into the CFPS aims to integrate various distributed generation equipment, storage equipment, thermal activation equipment, and power production management based on demand into the distribution or transmission network. This integration allows for better utilization of renewable energy sources, improved power reliability, and reduced greenhouse gas emissions. The CFPS is designed to cater to various power needs, including tasks such as food preparation, heating, refrigeration, and supporting mini-industries. By using a combination of flow resources, the system can ensure a continuous and reliable power supply for various applications.

The benefits of the CFPS include.

1. Power safety: by relying on multiple flow power resources, the system becomes more resilient and less susceptible to disruptions or shortages in a particular energy source.
2. Distributed power production: the CFPS promotes distributed generation, where power is produced closer to the point of consumption. This reduces transmission losses and increases overall system efficiency.
3. Decreasing greenhouse gas emissions: since flow power resources are renewable and emit little to no greenhouse gases during operation, the CFPS contributes to reducing the overall carbon footprint and mitigating climate change.
4. Cost-effectiveness: by optimizing the use of flow power resources and integrating various generation and storage equipment, the CFPS aims to provide power to end-users at the lowest possible cost.

Main text

"Compound flow power system monography" section describes the overview of the monography of compound flow power systems. "Regional scale techno-economic analysis" section describes the analysis of techno economic in a regional scale. "Building scale" section includes the building scale architectures using Renewable Sources.

"Storage technologies" section describes an overview of storage technology. "Design specifications" section includes the design specification of the compound flow power system. "Unit sizing methodologies" section describes a critical analysis of the sizing analysis of renewable sources. "Studies performed" section includes studies performed grid connected system and standalone system. "Control techniques for CFPS" section describes an overview of the control technique of compound flow power system. "Problems and solutions" section describes problem and solution of CFPS techno-economic analysis. "Discussion"and "Conclusions" sections include the discussion and conclusion of this research.

Compound flow power system monography

These systems are designed to include at least one flow power resource to ensure a balanced power supply for all required loads. Four applications are studied for each compound system, considering various geographical regions of Greece with various sun and air current profiles. Comparative Analysis of Compound Systems Producing Optimal Solutions Based on Minimum Total Cost Criteria. Several studies [1–6] have been conducted by various authors around the world on power generation by various compound systems. Designing such systems for India can be challenging due to the variability of input values from the power resources, which fluctuate randomly over time and are independent of the load requirements. Table 1 presents a compilation of different combinations of compound systems used by various researchers at various sites in India. This table may provide insights into the different approaches and configurations adopted in previous studies conducted in India. Panapakidis et al. investigated four combinations of compound systems (photovoltaic-diesel, photovoltaic-wind, wind-diesel, and wind-fuel cells) at various locations in Greece. The optimal system for power generation was found to be the photovoltaic-diesel system when the average wind speed was 3 m/s. The Phuangpornpitak et al. [7] study focused on a compound power system for Thailand and suggested that adding a diesel generator to a photovoltaic system improves the reliability of the power supply. Liu and Wang [8] applied wind-photovoltaic systems to sites in China, specifically for street lighting and pumping systems. The researchers developed guidelines for the government to promote the use of compound power systems in China. Omer Kaynakli investigated the optimal thickness of insulation in building envelopes and its impact on power consumption. The study presented results, development procedures, and economic analysis methods in comparative form. Practical applications for optimizing insulation thickness were performed, and effective specifications were explored using optimal values. Chaurey and Kandpal [9] conducted a review and analysis of the photovoltaic literature related to decentralized rural applications. It covered aspects such as techno-economic considerations, experience in rural electrification, and technology demonstrations. The trade-offs between capacity storage, load losses, and tiered power costs at various sites in India using HOMER software It considers design, operational aspects, and microgrid techno-economics to analyze these trade-offs. The HOMER software is utilized by governments, users, and power service companies for decision-making. Dihrab and Sopin [10] focus on the photovoltaic-wind compound system in three locations in Iraq: Basra, Mosul, and Baghdad. The study reveals that Basra has a higher potential for both photovoltaic and wind power generation. Mbaka et al.

Table 1 Overview of various fusion for compound electricity production systems

Compound system combination	Methodology	Location	Observation
Photovoltaic–air current	Power management technique	Bombay	Through the effective integration of converters, hybrid systems maximize the use of solar and wind resources
Photovoltaic–air current	Modified Particle Swarm Optimization	Jaipur	Compared to just a solo PV and wind system, the total cost of a hybrid system is lower
Wind-solar thermal-PV-DEG-biomass-fuel cell	Genetic technique	Wadgaon, Maharashtra	A genetic algorithm is utilized to optimize the controller's settling time, overshoot, and oscillations, and it produces better results than the traditional approach
Photovoltaic–Bio	Economic assessment framework	Pipariya Khurd, MP	Power generation utilizing biomass has a lower per unit cost (PUC) and is advantageous for Madhya Pradesh's rural communities. The lowest PUC ranges from Rs. 4.1 to 5.7/kW/h
Photovoltaic–Bio	Distributed generation technique	Wadgaon, Maharashtra	In contrast to grid extension, a hybrid system using gasifier systems, micro-hydro, dual fuel biomass, PV, and small wind electric generators is more advantageous for supplying power to remote areas with 20 families
Photovoltaic–air current	Iterative approach	Pipariya Khurd, MP	The manufacturer's specifications serve as a guide for choosing the best system configuration for the specific site
Air current–DC	Blade Element Momentum	Wadgaon, Maharashtra	Modeling of the load and wind speed uses predictable parameters. The load demand and windy zone affect energy prices
Air current–DC	Power center technique	Chhota Bainan, West Bengal	The issue is resolved using the cost per peak watt and system balance as they apply to the West Bengali village

[11] conducted a comparative analysis of photovoltaic compound systems, stand-alone photovoltaic systems, and stand-alone diesel generators for a village load demand in North Cameroon. The findings suggest that a compound solar power system is more economical compared to stand-alone systems, including diesel generators. In this study [12], a compound system, specifically a photovoltaic-diesel compound system with a storage battery, is proposed for power generation. An economic comparison is made between the compound system and a village diesel system. The study discusses the advantages of the compound system over diesel in terms of better results and analyzes its economic feasibility. The power demand in a village is currently met by a diesel

system, which is considered economical when the diesel price is $0.2/L. However, if fuel prices increase to $0.60/L or higher, diesel systems become uneconomical. Bakos [13] discussed the significant benefits and problems associated with the use of distributed microgeneration. The context is a small-scale photovoltaic installation in Greece, which increased photovoltaic penetration in the electricity market and reduced photovoltaic costs. EL-Shimy [14] emphasized that the percentage of power load and the number of battery replacements have a significant impact on selecting the optimal dimensions of a self-sufficient photovoltaic system for a 10-MW grid-connected power plant. Egypt is mentioned as a viable site for large-scale power generation. Kolhe [15] conducted a techno-economic analysis of an independent solar photovoltaic system. The selected system had the lowest total cost, with specific capital and net current costs mentioned. The system's average production and contribution from different sources (photovoltaic, diesel generator, and air current turbines) are also provided. A compound air current and photovoltaic system was developed in Jaipur, India, where the power is generated independently. The proposed algorithm, using the GA algorithm, aims to provide an optimal and cost-effective solution for variably supplying power to different loads [16, 17]. Yang et al. [18] proposed a model for optimizing the dimensions of compound solar air current systems using an iterative development method. The model considers power cost, loss of power supply probability, and power supply reliability. Specifications such as air current system power, photovoltaic, or battery bank capacity are taken into account. Diaf et al. [19] presented a methodology for automatically optimizing the size of compound systems. The aim is to achieve the desired system reliability and lowest power cost by selecting appropriate system components. Ashok [20] presented an iterative method for deploying compound photovoltaic power systems, combining various flow power resources such as air current and photovoltaic systems. The focus is on providing flow power generation to rural areas. Huneke et al. [21] proposed the use of linear programming to achieve optimal compound systems by combining solar and diesel cells. The goal is to find optimal results for the systems. Nogueira et al. [22] developed a compound system using linear programming and simulation tools to generate high reliability and minimal cost in rural areas. The LPSP (loss of power supply probability) concept is applied continuously for hours. Lee et al. [23, 24] developed a compound system based on linear programming to address various power loss cases. The emphasis is on minimizing power storage capacity and providing offload power rather than minimizing the overall system cost. The techno-economic requirements of diesel, photovoltaic, air current, and battery power generation systems for non-residential large power consumers in southern Iran were evaluated by Banesi et al. [25]. They discovered that an off-grid system, together with photovoltaic panels and air current turbines, could achieve a COE of 9.3–12.6₵/kWh and a flow fraction of 0–43.9%. The batteries utilized ranged in size from 0–1000 kW to 0–600 kW to 1300 kWh. The COE and flow fraction ranged from 5.7 to 8.4₵/kWh and 0 to 53%, respectively, in a grid-tied system without storage batteries when the same size solar modules and air current turbines were used.

This study focuses on solar and air-current technology to give an overview of the advantages of small island energy systems. According to Blechinger et al. [26], the cost reductions per kWh average out to 9 USDct when 14 gigawatts of air current power are paired with 5.8 gigawatts of battery storage. A methane recovery system that may generate methane for $0.37 per kg of CH_4 was suggested by Kimetto et al. [27]. According to Thomas et al.'s [28] analysis of a potential compound system of flow power resources, using renewable energy can cut the consumption of fossil fuels by up to 74%. Up to 74% of the energy use might be from highly efficient RES, with a near-present cost value of €2.25 million. Although a 100% flow power system is technically possible, it would require a sizable FPR plant, which would raise costs dramatically.

The potential of a compound flow power system (FPR) for a tiny island in Greece was investigated by Thomas et al. [28]. In the first and second scenarios, it was found that the traditional fossil power requirement was lowered by 52% and 74%, respectively, and by 17% and 26% when the complete system was included. Additionally, the first and second models' FPS coverage levels reached 68% and 74%, respectively, with NPC values of €1.84 million and €2.25 million as a result. While a nearly complete FPR system (third model) may be possible, it would require a larger FPS plant, which would be more expensive. Tudu et al. respond to this [29] suggested an improved particle swarm optimization strategy that might successfully simplify the challenging nonlinear optimization problem. Additionally, Day et al. [30] used the HOMER software to analyze and compare the compound FPR system. For a remote residential load in the Sundarbans of India, this model created the best, most affordable composite FPR system (see Table 1). Compound FPR designs have been investigated and applied by numerous research organizations all over the world, with varied degrees of success [31–34].

Based on the literature review, the following research gaps have been identified:

(i) Compound technology such as PSO + fuzzy logic controller compound system that can minimize cost and improve power generation by optimizing the DC/DC converter design MPPT algorithm provides improved efficiency and performance
(ii) A multi-input power system should be developed for the compound power system.
(iii) A survey of various combinations of compound systems for telecommunications applications worldwide.

Regional scale techno-economic analysis

Linking national energy plans to regional power plans can be accomplished with the use of a techno-economic study at the local and regional levels. Especially in areas with little research, optimized modeling of renewable energy sources like wind and solar could potentially offer fresh perspectives on RES-based power system analysis. In order to comprehend the many approaches and factors involved in evaluating power systems cost-effectively, research involving the South West region of Ireland has been done.

Evaluation on state/province level

A 2009 study by Hong et al. [35] examined the effects of different integration methodologies on Jiangsu, China's existing power system's 42% wind power, concentrated mostly on technical implications and ignored economic and managerial considerations. The next year, the same group, focused on long-term political objectives and taking into consideration economic successes, did an analysis of the integrated power network between social and economic development for Jiangsu by 2050. This effort largely ignored any potential socio-economic and management concerns in favor of concentrating on the technical aspects of integrating wind power into the electricity system. Hong et al. responded by presenting an integrated power path for Jiangsu Province throughout the economic transition by 2050, which takes into account economic success and starts a thorough and ambitious political strategy assessment [36]. Jiangsu's proposed energy transition has the potential to boost the local economy and offers a good example to the country of China in terms of its energy security system, resource conservation, and reduction in carbon emissions. In addition, McPherson et al. suggested using the new SILVER production cost model to assess their 100% renewable energy scenario for Ontario, Canada [37]. When it comes to using simulation techniques, taking into account related aspects, and creating macro policies, assessments of the energy sector at the province and state levels are comparable to those made at the national level.

Evaluation of municipalities/urban cities/countries

Assessment with the help of computer tools

CFPS analysis in addition to power planning in cities typically uses a large variety of tools and models as shown in Table 2. The latest research advances in seven simulation and development tools with much broader applications in cities are mentioned as follows:

(1) Energy PLAN

Numerous studies have used the Energy PLAN model to analyze both global and local power systems. It was used by Ma et al. [38] to assess Hong Kong's energy infrastructure and to suggest sustainable power plans that relied more on renewable resources than on nuclear power. It was determined that the renewable energy option showed a variety of advantages in terms of preserving the environment, reaping financial rewards, and ensuring long-term stability. Additionally, Østergaard et al. [39] utilized the model to investigate the feasibility of integrating geothermal, cold biomass, and wind energy to meet the energy requirements of the municipality of Aalborg and discovered that it had favorable socio-economic consequences in comparison to conventional energy sources. Østergaard et al. [40] created a scenario for converting Frederikshavn City to a 100% renewable power system, addressing the load-balancing challenges associated with CFPS and assessing the contribution of on-site renewable energy resources.

(2) Energy PRO

Energy PRO is modeling computer software that provides flexible development analysis of cogeneration by technoeconomic and multiple renewable energy-based projects. In a study conducted in Aalborg, Denmark, the software was utilized to simulate a 100% flow power scenario using air current, biological resources, and low-temperature geothermal power. The research focused on evaluating the impact of various storage options on the integration of air current power with different storage strategies and their associated costs [41, 42]. Kiss [43] employed Energy PRO to improve the flow of resources for heat, electricity, and transportation in a small town's energy system. Their study's findings suggested that employing renewable energy solutions could enhance environmental

Table 2 Overview of different RE simulation platforms

Tool	Developer	Accessibility	Objective functions
SAM	NREL	Free + paid	Evaluate the performance and economics for RES etc. (depends on the specific analysis)
CREST	NREL	Free	Minimizing production costs, maximizing production efficiency, etc. (based on the specific problem)
PVWatts	NREL	Free	estimation of energy production from solar
PVsyst	PVsyst SA	Paid	Maximizing energy production, minimizing LCOE, etc. (depends)
Windographer	AWS true power	Paid	Specific to the analysis performed using the processed wind data
Windpro	EMD international	Paid	Pursue various objectives based on the analysis of the wind energy project
RETScreen	CEDRL	Free	Estimating energy savings, assessing financial viability, evaluating greenhouse gas emissions reductions for RES
Helioscope	Folsom labs	Paid	Maximizing energy production, minimizing shading losses, optimizing system design and cost of solar PV system
REopt	NREL	Free	Is a techno-economic optimization tool for renewable energy and storage systems
HOMER	NREL	Paid	Minimizing net present cost, maximizing renewable fraction or self-sufficiency, maximizing system reliability (is a widely used tool for optimizing and analyzing hybrid renewable energy systems)
Gatecycle	GE	Paid	Allows users to model and simulate the behavior of power cycles, including gas turbines, steam turbines, and other components
ReEDS	NREL	Free	Provides flexibility to define and pursue different objectives while considering various factors, including generation capacity, electricity demand, grid constraints, environmental considerations, and economic factors
Energy PLAN	SEPRG, Aalborg university	Free	Analyze the energy, environmental, and economic impact of various energy strategies
Kom Mod	Fraunhofer IES, Germany	Unknown	Provides real-time estimates of demand side power requirements, as well as available sources producing power at optimal operation
EVST	NREL	Paid	Used to analyze the cost-effectiveness of energy storage. It does not fully incorporate renewable energy technology as an input, but can be very useful if you are also researching resiliency and storage of a solar PV system
LEAP	Stockholm environment institute	Paid	That can simulate and optimize energy consumption, production, and resource extraction in all sectors of an economy
DER-CAM	Micro grid team, Berkeley lab	Free	Purpose of this tool is to minimize the cost of operating on-site generation and combined heat and power (CHP) systems, either in residential or commercial sites
GridLAB-D	US.DOE, PNNL	Free	used to provide users with information about the design and operation of their distributed energy system

performance and sustainability. However, the use of air-source heat pumps, biogas plants, and geothermal installations is required in order to further optimize economic milestones. Please visit the software homepage [44] for additional details on Energy PRO projects and ongoing research.

(3) HOMER

HOMER, an effective tool developed by NREL, has been employed in numerous urban studies and is renowned for its user-friendly characteristics [45–49]. It has recently been used in a techno-economic assessment in Punjab, India, a modern photovoltaic-grid tie CFPS in Jos, Nigeria, and an evaluation of possible power supply from CFPS in Hargeisa, Somaliland. Additionally, this same tool has been used to carry out a feasibility analysis of establishing a PV-wind power plant in Hendijan, Iran.

(4) MARKAL/TIMES

The MARKAL/TIMES family of models is well-suited for in-depth analyses, so it is a great choice for constructing CFPS systems. It should be noted that great attention needs to be paid to precision when employing TIMES models in the testing of small-scale power systems. One example is the examination of Basel's, power system to identify the long-term outcomes of various energy regulations [50–58]. Additionally, it can also be utilized for assessing RE technologies for electricity and thermal power generation in urban areas.

(5) ETEM

ETEM is a model belonging to the MARKAL/TIMES family of models that is used to identify cost-effective technological solutions for providing energy services on a local and regional level. Revised versions of the model, such as ETEM-SC and ETEM-SG, have been adapted to incorporate policy alternatives for adapting to climate change, developing resilience, creating smart cities, and addressing uncertainty in the development of smart grids. These revised versions of ETEM have been used to develop sustainable power systems for Doha, Qatar, and evaluate CFPS models and energy distribution parameters in Arc Lemanique, Switzerland [59–61].

(6) MODEST

In order to comprehend and optimize the growth of power systems, the proven linear programming model MODEST is typically employed with Swedish power and district heating plants or the national grid. The model was created in 1994 by NUTEK and VARMEK to optimize local public utilities in Sweden. It generates a variety of cost-minimizing solutions, including the best use of engineering sizing, investment scenarios, annual cash flow, TAC, carbon emissions, and more. The original MODEST has undergone several upgrades, including MODEST-A (for adaptation of policy options) and MODEST-R (for robust development). The model has also been used to analyze the economic assessment of biogas CHPs and to assess how much biomass can be saved by district heating systems [62–67].

(7) Sifre

Researchers have discovered strategies to optimize power flows and electricity pricing as well as reduce operational costs in the system using the Sifre power system modeling tool. Sveinbjornsson et al. used Sifre to simulate the city of Snderborg's power system in 2029 and examined the effects of different flow patterns on operating expenses overall, power efficiency, net system carbon emissions, and biomass consumption [68]. As a means of achieving sustainability goals, this research showed how regional urban design might profit from technologies like biofuel generation, fuel cells, and electrolysis that might otherwise be disregarded. However, a large range of modeling and development technologies are accessible for carrying out techno-economic analyses of urban CFPS. Simulating the autonomous region of Catalonia in Spain has been done recently using the SimREN program [69], and a case study of the German city of Würzburg has employed the DEECO development model [70]. In addition, the analysis of flow power systems at the city level has been done using the MATLAB/Simulink tools published in [11, 71]. Finally, [48–50] contains more modeling frameworks and analysis tools.

Evaluation at the level of village/remote area

Due to the expense and complexity of connecting to the national grid, accessing power in many distant and rural settlements today presents both economic and political problems. Installing a stationary CFPS, a dependable and economical energy source with zero carbon emissions, is one possible solution [72]. In particular, for DER systems, the HOMER Calculator is a useful tool for assessing prospective design options for off-grid and on-grid electricity systems. The HOMER has been used in numerous studies and journal publications. Das et al.'s study of the technical and financial viability of a CFPS for a modest community of 254 families in Bangladesh serves as an illustration of this [73]. In order to offer dependable electrification and enhance the quality of life for rural communities, the authors built six off-grid compound systems integrating solar, air current, biogas, diesel, and battery modules. In India, Sri Lanka, Iran, and Colombia, comparable technologies have been utilized to successfully bring energy to remote villages, isolated homes, and endemic communities [74–79]. The Mathworks Incorporation software package MATLAB/Simulink is a common tool for creating research models. Researchers can easily create mathematical computations and system simulations with the aid of this program. A mathematical model of a distant stand-alone photovoltaic hydrogen system was developed by Jallouli et al. using the MATLAB/Simulink tool and varied load demand, power source, and weather data [80, 81]. This study recommends more precise power management systems to ensure system power sustainability as well as system sizing strategies to maximize component capabilities to meet economic needs.

Evaluation of islands

With the aid of HOMER software, it is possible to assess the advantages of achieving high-flow power performance levels while developing a system for an island or other distant location [81]. For a small tourist island in Greece, Thomas et al. examined three scenarios with progressively higher levels of renewable energy sources (RES), with the third scenario (a nearly 100% RES system) being technically viable but having a significantly higher cost due to the bigger RES plant size [82, 83]. Due to the high levels of summer tourism, seasonal variations should be considered when entering the demand data into the system prior to analysis. However, it is important to keep in mind that locals and authorities often approve of small-scale flow power projects. Future development of renewable energy projects and applications for islands must be done with the consent of the local communities because of the potential reduction in tourists and economics, the detrimental effects on landscapes and nature reserves, and conflicts with smaller islands. In order to prevent detrimental effects on currently occurring industrial, agricultural, and residential activities as well as the natural landscape, this entails taking into account a variety of assumptions and limiting factors. The HOMER software, RET Screen, HOMER and MATLAB, Mesap PlaNet and REMix, LEAP and RET Screen, and H2RES are some of the simulation tools for the techno-economic analysis of regional CFPS that are available for optimizing the EE system while simultaneously securing and minimizing system TAC to maximize energy [84–103].

Building scale

Instead of doing extensive techno-economic analyses, the CFPS design for this building complex focused on the specifics, such as building attributes, load details, and user needs. To accommodate the needs of the various users, the complex was separated into buildings for manufacturing and buildings for civil use. In particular, user comfort and ease of use should be given top priority when designing CFPS for civil buildings, in addition to the stability of the power supply. Based on pertinent case studies and the particular factors that apply to this scale, this section outlines the assessment methods and models used in this situation.

Buildings for production purposes

Industrial architectures

Industrial systems, which frequently ask for an autonomous power system, require the HOMER software, which is crucial to the development process. A stand-alone photovoltaic compound system at Kavala, Greece, as well as a number of power systems for remote communications, have all been examined using this technology. Furthermore, Genetic Algorithms (GA) are a powerful technique for locating the best system designs with the lowest cost and power loss likelihood [104–106].

This study illustrates that when assessing solar and wind energy resources on a building-by-building basis, taking into consideration local conditions and space limits, a more thorough assessment of techno-economic feasibility must be made. For instance, the space for solar modules may be constrained due to the tiny roof areas of some buildings, and the influence of typhoons may cause the actual installation altitude of wind turbines to be lower than the ideal level. Despite this, adding more wind turbines may be able to overcome these restrictions.

Agricultural architectures

Greenhouses, facilities for processing animal feed, ranches for raising livestock, and repair shops for farm equipment are all examples of structures used in agriculture. Biogas-photovoltaic ground source heat pump compound systems were constructed, analyzed using the uncertainty analysis method and net present value, and tested in greenhouses with a high demand for livestock production in order to gauge the effectiveness and potential cost savings of these structures. The findings demonstrated that despite the system's initially high acquisition cost, it offered a cost-effective solution. These systems' implications on system performance as it relates to operating requirements and regional climate were also investigated.

Civil architectures

In recent years, with the growth of renewable energy sources and the push for sustainable development, civil engineering buildings have advanced significantly. In order to efficiently control electricity demand and cut CO2 emissions, this has led to the integration of both residential and public buildings adjacent to one another. To evaluate and contrast the various approaches and factors taken into account by the three different types of clusters—residential, public, and mixed—techno-economic assessments of CFPS have been done.

Residential building complexes

The Monte Carlo analysis (MCA) is a widely used approach for simulating the financial implications of installing a photovoltaic-wind-battery system in a home setting, as seen in one study done in Urumqi, China [107]. This approach can be used to calculate various financial factors associated with photovoltaic installation, such as Npv (net present value), IRR (internal rate of return), PBP (payback period), and BCR (benefit cost ratio). Additionally, MCA is also used in various studies, such as examining the use of solar systems in the Greek residential sector [108] and energy-saving scenarios in the Iranian housing sector [109, 110], as well as in the Swedish real estate market [111–113]. HOMER and RET Screen's 'Clean Power Project Analysis Software' are also popular tools for residential CFPS analysis and are free computerized tools for evaluating the economic feasibility of installing a photovoltaic system [114–118].

This research investigated the economic performance of various combined heat and power systems for residential applications by using iterative approaches, such as a mixed-integer linear programming model and heuristic techniques such as the genetic algorithm (GA) and particle swarm optimization (PSO) as shown in Fig. 2. The results suggested that the PSO algorithm was quicker in producing cost-effective solutions, while GA offered the most promising results. Cost-effectiveness was determined through an evaluation of the system solutions [119, 120].

Public building complexes

In the early 1990s, numerous studies were conducted to investigate the potential of public architecture using renewable energy (RE) systems. In 1997, Protogeropoulos et al. developed a general methodology for the design of an autonomous CFPS

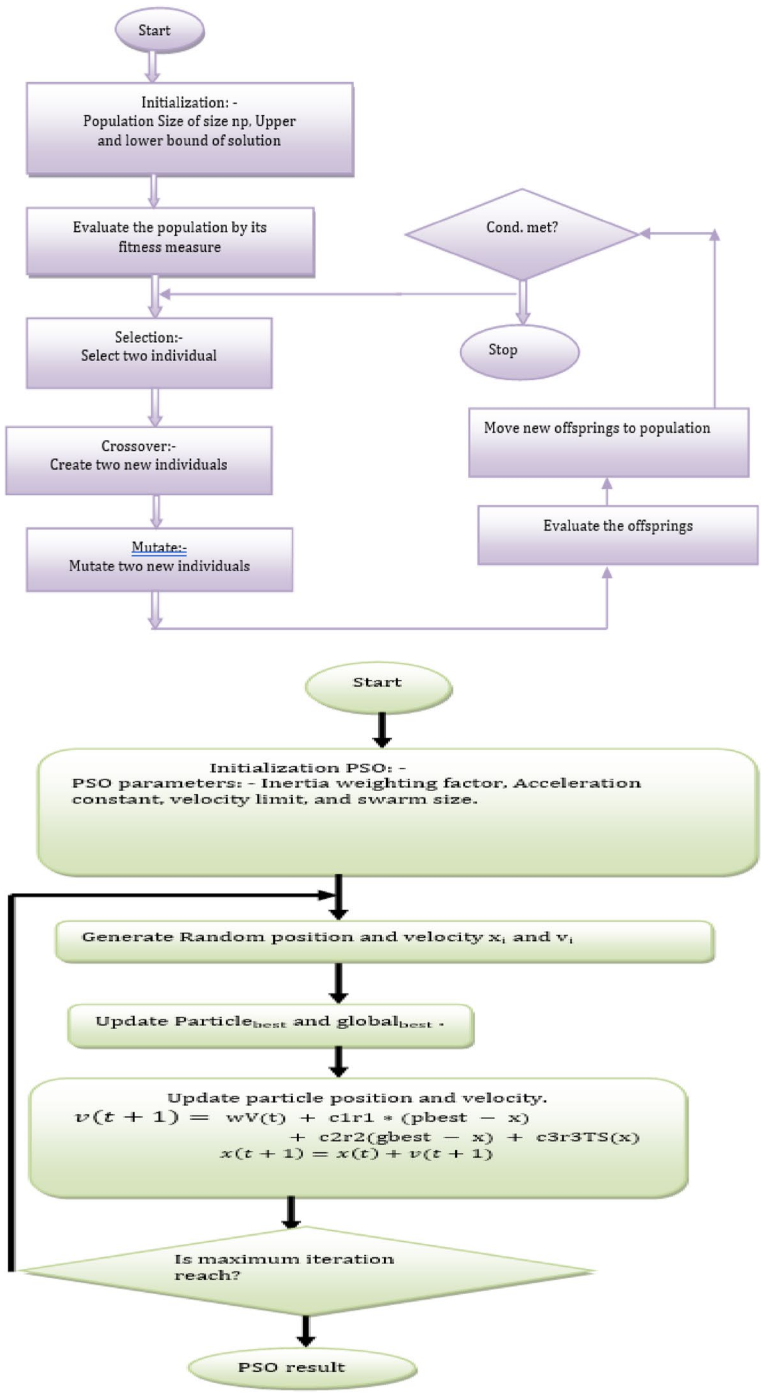

Fig. 2 Comparison of flowchart GA and PSO

(Concentrating Solar Power Plant) installed in the Klepa Park near Cardiff, UK. This required an evaluation of different RE components of varying sizes and an assessment of economic benefits and technological advances. Subsequently, Blok and ter Horst (1988) applied a time-scaled simulation method, SOMES, to optimize the CFPS design [121, 122]. Ajan's (2003) research endeavored to understand the feasibility and economics of her photovoltaic system connected to an off-grid utility system in rural East Malaysia [123]. This was done by employing an algorithm to conduct a techno-economic study. In 2005, a technical feasibility and financial analysis of a photovoltaic air-current system was conducted for the Cooma's Education and Interpretation Center using the TRNSYS (Transient Simulation System) [124, 125]. Finally, Singh et al. (2015) performed a technical and economic feasibility assessment of a solar power-hydrogen fuel cell hybrid CFPS for academic research building in India [126]. This was performed utilizing HOMER software, along with the FL (Fuzzy Logic) program, to calculate capital cost and replacement cost, respectively.

Mixed building complexes

The techno-economic analysis of automated photovoltaic-diesel compound systems was investigated in 2002 by Bacos et al. for a bungalow complex composed of 12 individual villas and a restaurant in Elounda, Crete. This study utilized RET Screen software to determine the Internal Rate of Return (IRR), Net Photovoltaic (Nphotovoltaic), Payback period (PBP), and annual positive cash flow. In 2017, this system was proposed to be used to power a smart grid community of 30 homes and 4 stores in the coastal area, Brisbane on account of its reliability and cost-effectiveness. HOMER software was employed to analyze the simulation results, which demonstrated the economic and environmental viability of this system when compared to the previous generation system. Table 3 summarizes the techno-economic analysis software for various building clusters and offers a comparison.

Frequently used evaluation indicators

Table 4 provides an overview of commonly used metrics for evaluating the performance of CFPSs. These metrics can be applied to both small and large systems, but depending on the specific context of the project, the selection of metrics should be adjusted accordingly. In particular, small CFPS assessments often incorporate cost-related information in their evaluation, whereas large CFPS appraisals tend to prioritize social indicators.

Table 3 Overview of flow power emulation platform for facility construction projects

Title	Designed by	Procedure	Time division	Methodology	Accessibility
Hybrid Optimization Mode	National RE Lab	Interdependency model	Mins	Emulation development platform	License is free for 30 days
Clean Energy Project Analysis Too	Canadian ED and RM Centre	Interdependency model	months	Development platform	Freely downloadable
Energy System Simulation Too	Utrecht University	Particularly for independent flow structure	Uncertain	Emulation development platform	Enigmatic
Transient System Simulation Too	UW-Madison	Temporarily structured emulation program	Heartbeat instants	Emulation development platform	Pay and use

Table 4 Summary of the standard analyzing metric of HRES

Class	Title	Elucidation
Financial metrics	Profit price ratio	The goal is to determine the relationship between a prospective venture's benefits and associated costs
	Price	A variety of measures, including but not limited to net present value (NPV), cost of energy (COE), cost of energy/renewable energy (RE), anticipated cost per unit of consumed power, and other pertinent indicators, are frequently used to assess the costs related to systems
	Yield	The yield is the discount rate at which the analyzed project's net present value (NPV) decreases to zero
	Cost of load balancing	It includes all costs related to the capital and operational aspects of every element required for effectively using renewable energy (RE)
	Recoupment period	It assesses the rate at which the system's cash flows may recoup the initial investment, taking into account indicators like the simple payback period (SPBP) and the dynamic payback period (DPBP)
Technological metrics	Energy conservation	the efficiency with which the system uses power from renewable (RE) sources
	Irreversibility	It represents the unstoppable loss of energy
	Useful energy production	the process of producing energy that is useful and suitable for use in industry
	Deployed renewable energy share	It stands for the electricity/heat generated throughout the system from renewable energy (RE) sources
	Renewable share	The percentage of renewable sources that have been incorporated and installed in renewable energy (RE) systems is referred to as the renewable fraction
Climate metrics	Carbon footprint	This statistic constantly takes into account both current carbon emissions and carbon emission decreases
Societal metrics	Employment generation	It emphasizes the quantity of brand-new work that each system is expected to produce
	Affected population	It measures how much the locals can gain from the renewable energy (RE) grid [117]. It can also be calculated by taking into account the areas that benefited, which gives the number of square meters (m2) per unit of power [118]

Storage technologies

For CFPS to control the fluctuating energy output of flow power resources, a storage system is necessary as shown in Fig. 3. The storage system is utilized to provide consistent levels of power to charge the system during peak periods because the flow power resources have been disconnected. Additionally, this storage technology corrects any inconsistencies between load and demand. The region's power generation and load distribution patterns determine how the power storage component is charged and discharged. Presently, there are several storage solutions, including battery banks, supercapacitor power storage, hydroelectric pumped storage, hydrogen power storage, compressed air power storage, flywheel power storage, liquid air power storage, stack blocks, and more [127–138]. Battery selection criteria as shown in Fig. 4. The following is a list of different types of power storage methods as shown in Table 5:

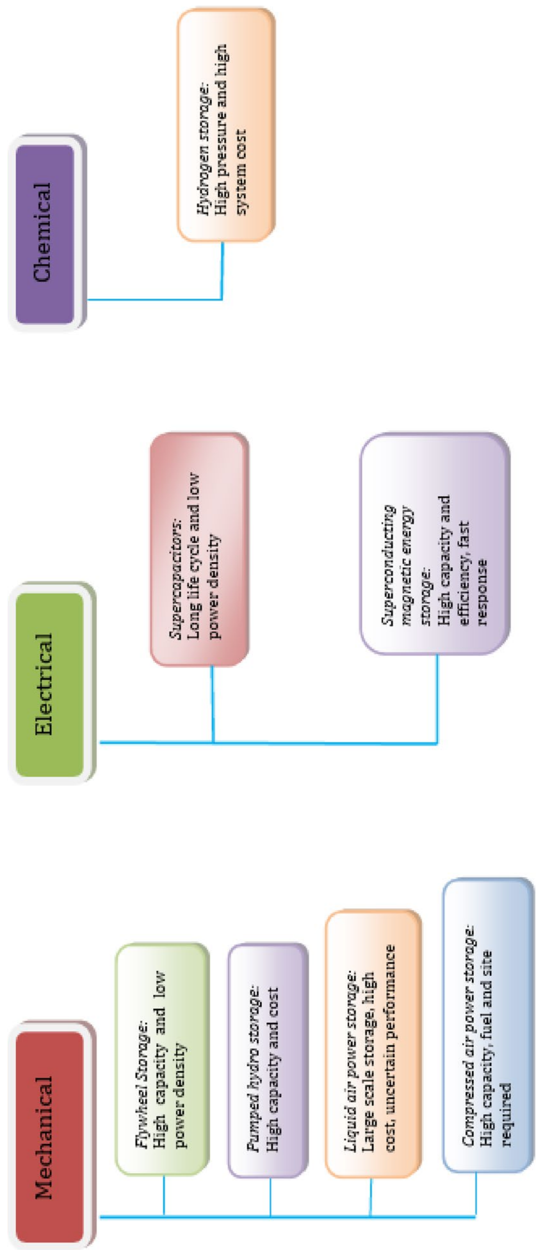

Fig. 3 Energy storage technology

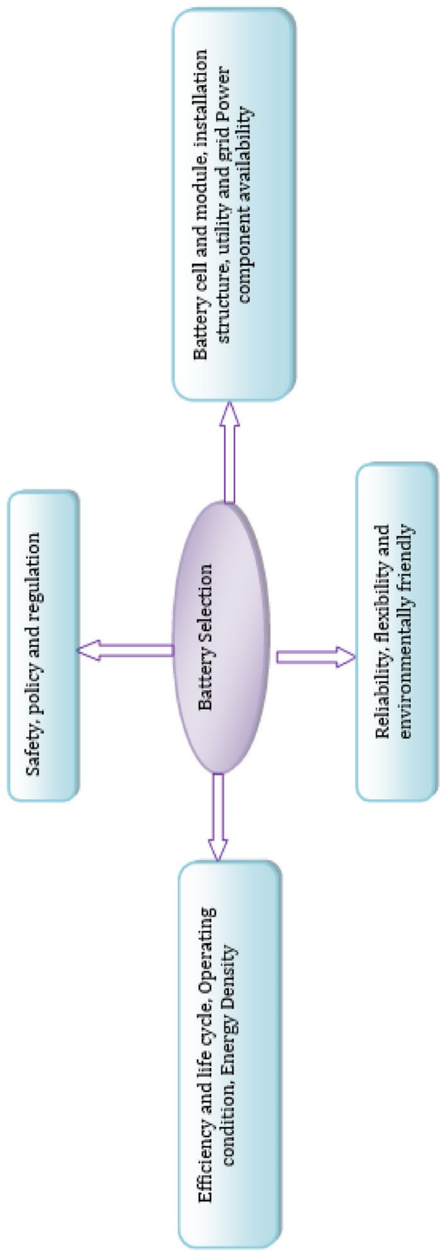

Fig. 4 Battery selection criteria

Table 5 Different types of power storage and their comparison

Storing type	Storing method	Storing time	Pro's	Cons	Expenses
Rotary depositor	Automatic	Short time	Max power can be deposited	Tenuity of power takes place	-
Ultra capacitor	Electric	Short time	Lengthy cycle of life	Tenuity of power takes place	-
Pumped depositor hydropower	Automatic	Much time	Max power can be deposited	Need particular area	Too much
H2 depositary	Enzymatic	Medium	–	Peak force is needed for H2 depositary	More
Cryogenic Energy Storage	Automatic	Much time	Max power can be deposited	Unexpected behavior in transitory and changing cases	More
Warehouse concrete depositary	Automatic	Medium	Max power can be deposited	Tenuity of power takes place	-
Pressurized air energy depositary	Automatic	Medium	Max power can be deposited	Fixed propellant and area are needed	Low

Battery bank and supercapacitor power storage

A battery bank pack is the best option for a combined frequency power system (CFPS) that needs constant power. It is not only more dependable and adaptable than alternative options, but it is also a greener choice. There have been studies and comparisons of various battery material types, including Nickel Iron, Lithium Iron Phosphate, Nickel–Cadmium, Vanadium Redox Batteries, and Lead-Acid. The Lithium Iron Phosphate battery has the highest power density and cycle life, measuring 19–160 W–h/kg and 2500–12,000, respectively. Lead-Acid batteries, for example, with a cycle life of 50–100 cycles and a power density of 30–40 W–h/kg. The cycle life of nickel–iron batteries is 5000 cycles, and they have a power density of 19–25 W–h/kg.

Supercapacitors are an energy storage technology that sits between electrolytic capacitors and regular rechargeable batteries. Compared to conventional electrolytic capacitors, it has a much larger power storage capacity in a smaller volume or mass, enabling 10 to 100 times more power to be stored per unit of volume or mass. At 2.5 to 2.7 V, each supercapacitor cell is in operation. During times of off-peak loads, water is pushed from a lower dam to an upper dam to produce electricity. Water is returned from the top dam to the lower dam at peak loads, spinning the turbines and generating energy.

The night load of the flowing resources provides the necessary energy for electrolysis. Both gaseous and liquid forms of hydrogen can be stored; however, liquid hydrogen must be kept at cryogenic temperatures. Since hydrogen's high density presents the biggest storage problem, the Fuel Cell Technology Office (HFTO) is focusing on two different strategies: short-term techniques that concentrate on gas compression up to 700 bar and long-term procedures that rely on cryogenic compression storage of hydrogen.

Compressed air and liquid air power storage

Compressed air power storage (CAES), liquid air power storage (LAES), flywheel power storage, and stacked blocks are just a few of the storage systems that are compared in Table 5. Large amounts of power can be stored using CAES, which has a shelf life of around a year. Flywheel Power Storage uses a rapidly spinning rotor to store energy, while LAES cools and stores air in liquid form. Last but not least, Stacked Blocks store energy by using brick movement and gravity. These technologies' power output ranges, storage capacity, and continuous power outputs are also contrasted.

Design specifications

Researchers have considered many types of specifications when designing and developing the CFPS. During the development process, the system ought to be assessed in terms of fiscal specifications, performance 4464 reliability specifications, environmental specifications, and social specifications [4].

Economic specifications

In order to help determine system size, researchers have taken into account a number of economic criteria, including the levelized cost of energy (LCOE), annual system cost (ASC), current net cost, payback period, and internal rate of return. The annual system cost, which is the sum of the annual capital cost, annual replacement cost, and annual maintenance cost for each system component, and the annual power yield are used to calculate the stratified power cost. Additionally, the economic viability of various systems has been examined using the net present cost, payback period, and internal rate of return. This is crucial when considering the total annual cost and return on capital, where the internal rate of return is the return on investment over the course of operations and the payback duration is the duration of time required for the initial investment to be fully recovered [139–144].

Technical specifications

Technical parameters like expected power unsupplied (EENS) and power supply loss probability (LPSP) have been looked at in numerous prior studies. Calculating EENS determines how much power demand exceeds the capacity of the generating equipment, while LPSP refers to the loss of power supply at the user's location as a result of load demand exceeding output [145–149]. By dividing the time segments into the total number of hours where the load is not filled (HLNF) and the total number (HTOT), the degree of autonomy is demonstrated.

Environmental specifications

The use of fossil fuel-based power causes emissions such as carbon dioxide, carbon monoxide, and sulfur dioxide. Therefore, environmental specifications should be considered when optimizing CFPS. Many researchers considered power carbon footprint (CFOE), carbon emissions (CE), embodied power (EE), and life cycle analysis (LCA) as environmental specifications [150], with the following explained as follows:

Carbon footprint of energy

CFOE is simply the total CO2 emissions of a given system. It is used to measure greenhouse gas emissions per kilowatt-hour of electricity generated over the life cycle of a facility.

Carbon emission and embodied energy

As a way to quantify environmental impact, prior research has frequently focused on quantifying carbon emissions. Assessing CO2 emissions over time is a common step in calculations [151–153]. Additionally, embodied power (EE) is utilized to estimate how much energy is required by the CFPS while it is in use, which requires energy to be extracted from primary power sources that are not in flow [154, 155].

Life cycle assessment

In order to assess the greenhouse gas emissions caused by the design, production, and transportation of CFPS system components, life cycle assessment (LCA) is used. Because of the energy needed for these processes, contaminants are released into the environment.

Social specifications

CFPS development that considers societal requirements can aid in lowering pollution while promoting industrial development. The Human Development Index (HDI), Portfolio Risk (PR), Job Creation (JC), and other metrics are among these social criteria [156]. These social requirements are regarded as markers of employment growth and human progress. For instance, HDI considers a nation's financial and social success, future prospects, lengthy educational programs, and per capita public wages [157]. This information is accessible and useful for a variety of organizations. As a result, a network of opportunities for manufacturing, transmission, transportation, construction, dispatch, operation, and maintenance of power components is established, and the creation of jobs is assessed in accordance with the CFPS [158].

Portfolio risk and flow power consumption

The relationship between the risk of a portfolio and the factors influencing electricity consumption, such as Gross Domestic Product per capita (GDPpc), Foreign Direct Investment (FDI), Trade Openness, Life Expectancy Index (LEI), Education Index (EI), and Governance Index (GI), can be expressed as [159]:

$$A = \beta 0 + \beta 1\text{InGDPpcit} + \beta 2\text{InFDIit} + \beta 3\text{TOit} + \beta 4\text{EIit} + \beta 5\text{LEIit} + \beta 6\text{GIit} + \text{eit}$$

where:

- A represents the risk of the portfolio.
- β0 is the intercept, representing the base level of risk when all other factors are zero.
- β1, β2, β3, β4, β5, and β6 are the coefficients or elasticities of the respective factors (GDPpc, FDI, TO, EI, LEI, GI) indicating how much the risk of the portfolio changes for a one-unit change in each factor while holding other factors constant.
- InGDPpcit, InFDIit, TOit, EIit, LEIit, and GIit are the values of the factors (GDP per capita, Foreign Direct Investment, Trade Openness, Education Index, Life Expectancy Index, and Governance Index) for a specific country i and year t.
- eit represents the error term, which accounts for unexplained variation in portfolio risk.

This model is a multiple linear regression model used in finance or economics to understand how changes in these factors can affect the risk of a portfolio. The coefficients (β values) tell you the direction and magnitude of the effect each factor has on portfolio risk. For example, if β1 is positive, it means that an increase in GDP per capita is associated with an increase in portfolio risk, all else being equal.

Miscellaneous factors

Systems that run on air currents can cause a variety of problems, including noise pollution, visual alterations, local climate change, electromagnetic interference, wildlife disturbance, and disruption of marine life. On the other hand, they lessen carbon dioxide emissions and other toxins that might cause asthma, like SOx, NOx, and PM. With downstream consequences on water quality, creatures, and human resettling, it can result in increases in salinity, heavy metal toxicity, and temperature of the water bodies for hydro power. Depending on the fuel source, biomass-based power plants produce gases that alter the regional vegetation. High nutrient requirements for power plant growth also cause soil erosion and nitrogen depletion. Despite requiring large amounts of space, solar power generation has less of an impact on the environment than conventional power systems, such as soil erosion. Additionally, there are environmental issues associated with the development, exploration, extraction, and disposal of solar components.

Unit sizing methodologies

To ensure optimal operation, cost-effectiveness, and compliance with all operational criteria, a CFPS's design must be optimized. Finding the ideal sizes for various components, such as the battery bank's capacity, the number of solar modules, and the number of air current turbines, is necessary for accurately designing this system [132] as shown in Fig. 5.

Software tools

For the development and deployment of CFPS, a number of software tools are available, including HOMER, COMPOUND 2, HOGA, RET Screen, TRNSYS, Photovoltaic System, and others. These tools' descriptions are as follows:

HOMER and compound 2

This program was created for the analysis and optimization of grid-connected and freestanding CFPSs by Homer Power, the National Flow Power Laboratory (NREL), and the Flow Power Laboratory (RERL). To choose the most economical and effective system configuration, the software can be used to input load requirements, resource information, and emission statistics. Power expenses, fuel usage, capital expenditures, and a financial assessment of the system are among the outputs of this software. It is ineffective for multi-objective optimization, though.

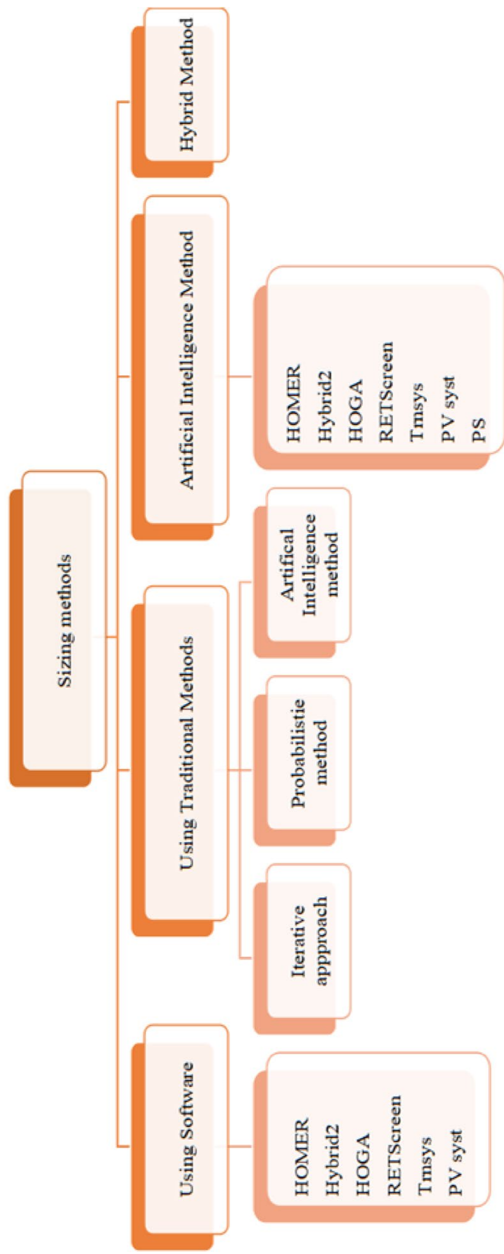

Fig. 5 Sizing method of CFPS

HOGA and RET screen

The Zaragoza University in Spain created the Compound Development of Genetic Algorithm, a development tool that makes use of the strength of genetic algorithms to enhance system output. Users of Natural Resource Canada's RET Screen, an Excel-based power management program, can conduct a feasibility study to evaluate system power, life cycle costs, and greenhouse gas emissions. The project database and the climate database serve as the software's inputs, and its outputs are sensitivity and environmental studies.

TRNSYS and photovoltaic system

The Solar Power Laboratory at the University of Wisconsin created TRNSYS, a computer software simulator that allows users to adjust the time step from 0.01 s to 1 h. It is frequently employed in the examination of conventional structures and biological procedures. The tool accepts weather data as input, and its generated outputs offer a dynamic simulation. Swiss physicists Andre Mermoud and Michel Villoz created the photovoltaic system software, which includes elements including primary design, database gathering, project design, and tools. Plane orientation, photovoltaic array, inverter model, battery pack, and other elements of the system are among them. Its economic analysis capability also aids in determining the precise component pricing, additional expenses, and investment status.

Studies performed

Grid-connected system

The grid-connected system integrates the flow power model into the National Grid. In grid-tied mode we see his two modes of.

i)Matched output mode
ii)Unmatched output mode

Numerous investigations on grid-connected compound power systems (CFPS) have been done by researchers in an effort to lessen dependency on traditional resources and assure sustainable emissions. Using mini-grids and micro-hydropower compounds based on the capacity factor and the ultimate yield factor, Khatib [160, 161] suggested the design of a grid-connected compound photovoltaic/wind system using linear programming. Lawal and Tafawa [162] have created a dependable and green source of electricity. Mamma Darao et al. [163] were able to show that an on-grid system uses solar, grid, and other energy sources to produce better outcomes than an off-grid system. Gopi and Reddy [164] created a decision support system (DSS) model to control power in real-time. When analyzing a compound system made up of solar photovoltaic, wind turbine, utility grid, and battery storage system, maximized reliability and minimized cost and found that the optimum solution was most affordable and had the lowest CO2 emissions. By comparing the outcomes with the grid, Dalton et al. [165] sought to minimize existing net costs for wind turbines and photovoltaic/wind turbine compound systems. For a grid-connected CFPS environment, Tumara et al. [166] developed a new sliding-mode controller with a disturbance observer to account for disturbances such as variations in load, design specifications, and flow energy. A methodology for analyzing wind power uncertainty in a grid-connected system, where overloads can result in cascading events if the wind turbine is unable to handle the load, was proposed by Sansavini et al. [167]. A Nuvula et al. [168] suggested a thorough analysis of large-scale integrated flow battery systems, employing a mutation-activated QPSO to reduce LCOE, LPSP, and LCE, to increase the sustainability of smart cities. It was also determined how the tech economy had changed.

Stand-alone system

Off-grid technologies are frequently utilized to generate electricity in places without connection to the grid. These systems create power using many technologies, including solar, wind, and biomass. These resources, however, can be geographically restricted and have physical limits. As a result, if electricity consumption rises, a single technology system is not economically viable. As shown in studies using the HOMER software by Khan et al. and Rafi et al. [165], which used high-temperature superconducting (HTS) generators and HTS wind turbines, the integrated flow power system is the most cost-effective way to combat this. These studies reduced power losses, COE, and CO2 emissions.

In Xiaojin, Sichuan, China, Xu et al. [132] used optimization approaches to identify the optimal photovoltaic-Air current farm working in independent mode with pumped storage. They noticed that the two systems reduced electricity costs by 32.8% and 45.0%, respectively, with a 5% LPSP model having the lowest power cost at $0.091/kWh. PSO and GA experiments were carried out for a photovoltaic/biomass/air current-based compound power system by Salwe et al. [169]. So, for GA and PSO, the cost of power using the continuous charging technique was $0.2625/kWh and $0.2617/kWh, respectively; for GA and PSO, the cost of electricity using the cycle charging method was $0.2396/kWh and $0.2393/kWh.

For the sizing and setup of a stand-alone solar photovoltaic system in Yemen, Saruhan et al. [170] employed an upgraded His numerical analysis technique. A net present value and COE of $22,224 and $0.403/kWh, respectively, were the results. Belmili et al. [171] created a fuzzy logic-based control and sizing method for a photovoltaic-to-air current power conversion system. A microgrid model for two coastal Bangladeshi communities was studied by Rafi et al. [172] and featured solar, wind, and natural gas power generation systems, and storage and charging stations for electric vehicles. HOMER was used to analyze independent CFPS while MATLAB was utilized to create a standalone CFPS; summaries of their findings are presented in Appendices 1 and 2, respectively [1, 173–190].

Control techniques for CFPS

Flow resources are highly intermittent, so control technology is essential for CFPS. Under various input conditions, the output of each flow power source should be adjusted [191–198].

Critical specifications that need to be controlled. H. Stable voltage, stable frequency, equipment protection, power balance.

- *Stability*: controlling the voltage and frequency of the system can improve CFPS stability.
- *Power balance*: maintaining a balance between the supply and demand of energy can be achieved through optimal load distribution to ensure continual power flow.

CFPS are typically controlled by three various power flow schemes, i.e., distributed, centralized, and compound methods.

Centralized control arrangement

A full system with a centralized control setup can be used to better manage and optimize the use of electricity in a storage system as shown in Fig. 6. To deliver power, this system would include several slave controllers coupled to a master controller (power management). Based on the objectives and constraints established, the main controller then decides how much power to send. Even though this kind of control setup has some drawbacks, like longer computation times and component failures, it is still thought to be a good technique to control power.

Distributed control scheme

In Fig. 7, a schematic representation of a typical control strategy is shown. It has been discovered that every flow source in the distributed control system produces a measurement signal for the local controller that corresponds to it. To make the best choices for overall advancement, local controllers collaborate. This design eliminates the possibility of a single point of failure and reduces the effort placed on each local controller [186]. The requirement to build complicated communication protocols amongst numerous local controllers hinders this control system. Deep learning networks, fuzzy logic, and evolutionary algorithms are examples of AI technologies that can be used to build more efficient decentralized systems to address this issue.

This control system may encounter issues if complex communication protocols among numerous local controllers emerge. Deep learning networks, fuzzy logic, and evolutionary algorithms are examples of Artificial Intelligence (AI) technologies that can be used to build more effective distributed systems to address this issue. The multi-agent system (MAS), which is frequently employed in the areas of power consolidation, recovery and reconstruction, and integrated system power management, is one of the best possibilities for a distributed control system.

Compound centralized and distributed control scheme

The CFPS uses a variety of different generational equipment, and the Compound Control Architecture mixes centralized and distributed control technology. The design employs a two-level control system; local control is carried out via centralized control inside each group, whilst distributed control is carried out across many groups of power resources to execute global control. This helps to resolve the particular hotspot problems by cutting down on processing time for both the master controller and the connected local controllers. The compound control architecture is made to maximize both centralized and dispersed control, as shown in Fig. 8.

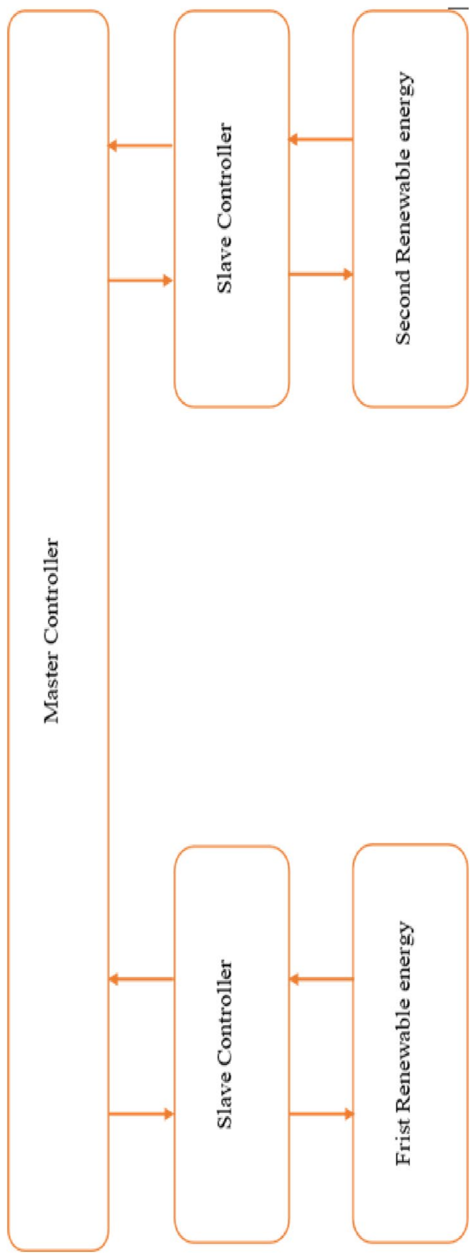

Fig. 6 Centralized control arrangements

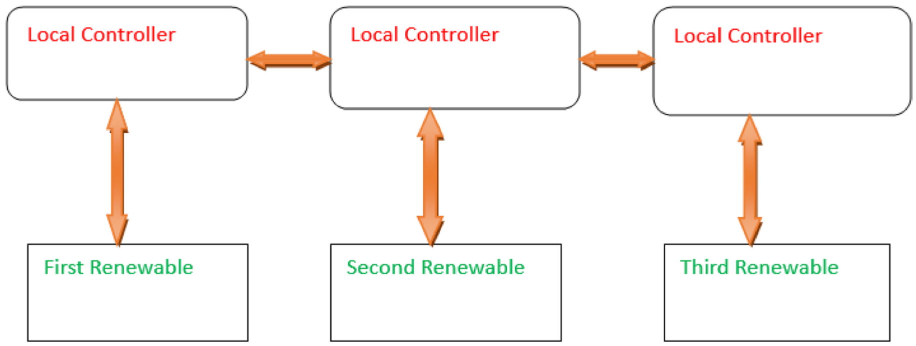

Fig. 7 Distributed control scheme

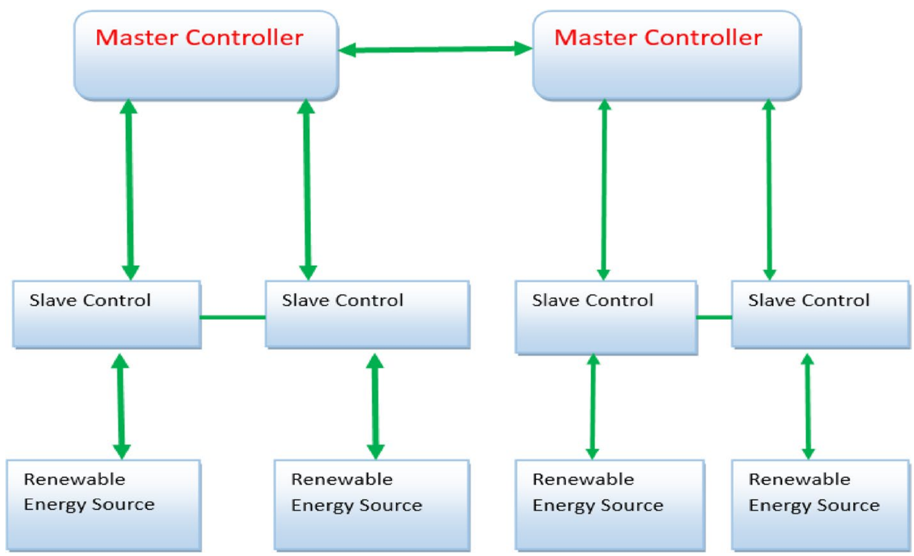

Fig. 8 Compound centralized and distributed control scheme

Problems and solutions

Problem

The discussion led to the conclusion that HOMER was used in the majority of CFPS research and techno-economic models. The researcher used MATLAB and an algorithmic technique to first construct the system. Each system component's design requirements were taken into account during this procedure. The various batteries' performance with varying depths of discharge and mixtures of solar and biomass energies might also be evaluated techno-economically. In addition, a battery life cycle study is necessary to finish the system's design phase. It has been suggested to utilize active shunt power filters in series to handle voltage swings. Additionally, the amount of harmonic distortion brought on by flow resources can be lessened by using pulses width modulation (PWM).

In order to decrease current irregularities and safeguard system relays, flow power integration into the grid is crucial. In order to run solar and air current farms, as well as to offer load tracking, pre-load sharing, power trading, maintenance, repair, and reserve management services, accurate and regular load forecasting is required. In order to protect and deliver power as needed, it is crucial to integrate an anti-islanding device and a zero-crossing detector synchronized with the grid in order to properly utilize the flow power resources.

Solution

A combination of two or more dependable flow power supplies may be used to lower system costs for integrated systems while addressing the unresolved problems during CFPS design and development. By allocating resources properly and efficiently, power storage technology can help with the intermittent nature of flow resources while reducing the size and expense of the storage system. The precise output of these power sources can be calculated using predictive models for flow power resources like air current speed and solar irradiation. Power electronics-based converters may also be used to keep the voltage and frequency constant in a separate system. When existing resources are insufficient to fulfill demand, flow power can be added to diesel generators as a backup. The integration of flow power with fuel cells and hydrogen storage offers a practical option for long-term power storage, and protective equipment must be implemented to provide adaptive protection across multiple operating modes in an active distributed network.

Discussion

Compound flow power system (CFPS) is a concept that combines different energy conversion technologies, such as solar, wind, and hydropower, to create a more efficient and reliable power system. It integrates multiple energy sources and storage technologies to ensure continuous power supply.

fusion approaches in CFPS:

1. Solar-wind fusion: integrating solar photovoltaic (PV) systems and wind turbines to balance power generation throughout the day and optimize resource utilization.
2. Wind-hydro fusion: combining wind turbines and hydropower systems to smooth out intermittent wind power and provide constant power supply.
3. Solar-hydro fusion: integrating solar PV systems and hydropower plants to utilize solar energy during the day and hydropower during periods of low solar generation.

Regional-scale techno-economic analysis: a techno-economic analysis at the regional scale involves assessing the potential of CFPS implementation, evaluating costs and benefits, and considering regional energy demand and resource availability. Computer tools like energy system modeling software can aid in simulating and analyzing different CFPS configurations and optimizing system performance. Several simulation platforms exist for assessing and simulating renewable energy (RE) systems, including CFPS. Some popular platforms include:

1. PLEXOS: a comprehensive energy market simulation software that can model and analyze CFPS configurations.

2. HOMER energy: a tool for optimizing hybrid power systems that combine multiple RE sources, storage, and conventional generators.
3. SAM (system advisor model): developed by the National Renewable Energy Laboratory (NREL), SAM can simulate the performance and financial viability of various renewable energy projects, including CFPS.

Buildings for production purposes:

4. CFPS can also be implemented in building structures for production purposes, such as industrial facilities or manufacturing plants. These buildings can integrate renewable energy sources and storage technologies to meet their power demands while minimizing their environmental impact.

A flow power emulation platform can be used for designing and simulating CFPS for facility construction projects. This platform enables engineers and planners to assess the optimal sizing of CFPS components, evaluate system performance, and estimate project costs.

CFPS relies on storage technologies to store excess energy during periods of high generation and discharge it during periods of low generation. Various storage technologies suitable for CFPS include batteries (e.g., lithium-ion, flow batteries), pumped hydro storage, compressed air energy storage, and thermal energy storage.

Designing a CFPS requires determining the appropriate size of individual components, such as solar panels, wind turbines, and storage systems. Unit sizing methodologies involve considering factors like energy demand, resource availability, system reliability, and cost optimization to achieve an optimal CFPS configuration.

Effective control techniques are essential for optimizing CFPS operation and maintaining system stability. Control strategies for CFPS may include power dispatch and scheduling algorithms, energy management systems, load balancing and frequency control mechanisms, and adaptive control algorithms to accommodate changing conditions and optimize energy flow within the system.

Conclusions

The integration of flow power systems has emerged as the most promising approach for supplying power to standalone applications, offering a path toward sustainable and renewable energy generation. Research in this field has made significant strides in understanding the characteristics of various flow power sources, comparing storage technologies, establishing methodologies for sizing integrated systems, and designing effective power flow control architectures. Prolonging the lifespan of energy storage systems, particularly batteries remains a priority. Advances in battery technology and management systems are necessary to ensure reliability and reduce replacement costs. Research in resource forecasting focuses on improving forecasting models using advanced meteorological data, machine learning, and artificial intelligence techniques. Reducing the cost of photovoltaic panels, wind turbines, and other renewable energy components is critical for making flow power systems more economically viable. Ensuring the stability of power systems with intermittent renewable energy sources is a challenge. Research is needed to develop advanced control algorithms, energy management systems (EMS), and grid-forming technologies to maintain stability during transient conditions. Combining multiple renewable energy sources (e.g., solar, wind, biomass) and energy storage technologies in hybrid systems can improve reliability and efficiency. Developing efficient energy management strategies and integrating flow power systems with existing grids or microgrids is a complex task. Research focuses on smart grid technologies, grid integration standards, and demand-side management. Assessing the environmental impact of flow power systems is crucial for their long-term sustainability. Researchers are working on life cycle assessments and environmental impact studies to minimize the ecological footprint of these systems.

Abbreviations

CFPS	Compound flow power system
MPPT	Maximum power point tracking
RES	Renewable energy sources
TAC	Total annual cost
IRR	Internal rate of return
PBP	Payback period
BCR	Benefit on profit
ROI	Return on investment
NPC	Net present cost
LPSP	Power supply loss probability
DSS	Decision support system

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Declarations

Competing interests
The authors declare that they have no competing interests.

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