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Thermodynamic Analysis of Hybrid Energy Systems: A Review of Modeling and Optimization Strategies

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***Abstract*—The rising demand of energy and the rising concerns of the environment have provided a great demand of efficient, reliable and sustainable hybrid energy solutions. Conventional single-source energy systems tend to be very difficult on intermittency, conversion loss, and sub-optimal performance. To gain insight into the role of energy and exergy techniques in enhancing the operation of multi-source arrangements, in this paper, an overview of thermodynamic analysis, optimization strategies and recent advances in Hybrid Energy Systems (HES) is provided. According to the review, the following factors play a role in increasing the reliability and operational efficiency because of energy flow modeling, subsystem interaction and load-matching strategies: Moreover, more intricate exergy-based assessment can be used to detect irreversibilities, which allows designing a better system. Recent works concerning the hybrid storage integration, dynamics of PV winds, fuel-cell assisted systems, and microgrid control structures are also reviewed. The results suggest the increased applicability of optimization techniques, such as multi-objective and intelligent control algorithms, to the issues of efficiency, cost, and environmental constraints. In general, the research paper offers a systematic insight into the thermodynamic-based enhancements that are imperative in the design of new, high-performance HES architectures.**

***Keywords*—Hybrid Energy Systems (HES), Energy Storage Systems (ESS), Thermodynamic Analysis, Energy Efficiency.**

I. Introduction

The rising energy consumption and the pressing need to respond to the problem of climate change have enhanced the emphasis on energy systems optimization to enhance efficiency and sustainability [1]. Traditional ways of dealing with energy management have relied on the principles of thermodynamics which give a primary insight into energy conversion and the thermodynamic limitations which the law of thermodynamics imposes [2]. A thermodynamic analysis of hybrid energy systems combines energy and exergy assessment techniques in order to appropriately evaluate the performance of systems. Through the First Law, energy analysis counts the inputs, useful products and waste and Second Law-based exergy analysis identifies the energy quality degradation and losses of irreversibility in components [3]. Combining hybrid energy systems (HESs) and energy storage systems (ESSs) has received a considerable amount of attention over the last few years due to the pressing necessity to find sustainable [4] and efficient energy options. HESs actively blend various sources of energy. The arrangement has the advantages of each technology but minimizes the limitations of each one. Here is one example: solar PV panels produce clean energy on sunny days, fuel cells are used as the backup energy source during the time when the sun is not available, and batteries are used to store the surplus energy, which can be utilized later.

The energy-efficient building design is based on thermodynamic principles, which are used to optimize energy circulation and temperature control in buildings. Of special interest in this regard are two important laws of thermodynamics the First and the Second Law. The first law of thermodynamics also known as the Law of energy conservation [5] states that energy is neither created nor destroyed, it only changes. In the design of buildings, this principle has been applied in efficient utilization and conservation of energy [6]. To illustrate the point, insulation materials and energy recovery systems can be used to reuse the energy that is absorbed by a building during the solar radiation process or even during the heat conduction process to reduce the wastage. Hybrid energy generating systems show enormous potential for delivering sustainable and effective power generation through the integration of diverse energy sources like solar wind [7]. To optimize the advantages of renewable energy sources, however, there are a number of obstacles that must be overcome during the integration process.

The optimization goals of renewable-based hybrid systems are to achieve optimal operating conditions and economic evaluation and optimize their performance to the point where all their physical and technical constraints are satisfied. Sizing a hybrid renewable energy [8] system is an attempt to remind that renewable energy sources are to be used effectively and cheaply. It is essential to maximize the power on sunny or windy days with the optimum designed design since the electricity provided by renewable energy sources like wind and solar is mostly dependent on meteorological conditions. The efficient use of renewable energy sources depends on the techno-economic [9] analysis of the hybrid system. The application of various optimal sizing techniques in the design of hybrid energy systems is becoming more and more popular[10]. Because the hybrid system's optimal configuration and control method are interconnected, it is more challenging to size, design, and evaluate hybrid systems.

A. *Structure of the Paper*

This paper is organized as follows: Section II is the description of the key configurations of Hybrid Energy Systems and the energy flow. Part III discusses thermodynamic assessment procedures of energy systems. Section IV provides a summary of important optimization methods. Section V gives a review of related studies done recently and Section VI is a conclusion to the future research directions.

II. Insights of Hybrid Energy Systems

Hybrid energy system is the combination of conventional and renewable energy sources like wind, solar, hydro etc. These provide a clean and eco-friendly energy[11]. These hybrid systems can be standalone or can be grid connected. The grid connected hybrid system are more reliable to deliver continuous power to the grid because if there is any shortage of power or fault in the renewable energy [12] sources then the loads are directly connected to the grid. Since the wind and sunlight are not constant at all the time in a day these causes stability problem of hybrid system [13]. Another example of a hybrid system combines solar and hydro energies. The solar panels produce electricity during the day which is pumped to a dam to pump the water in a river or a lake. During the dark hours when the sun is not shining, the water accumulated in the dam is discharged through a hydro turbine to produce more electricity. The schematic diagram of hybrid Energy System is shown in Figure 1.

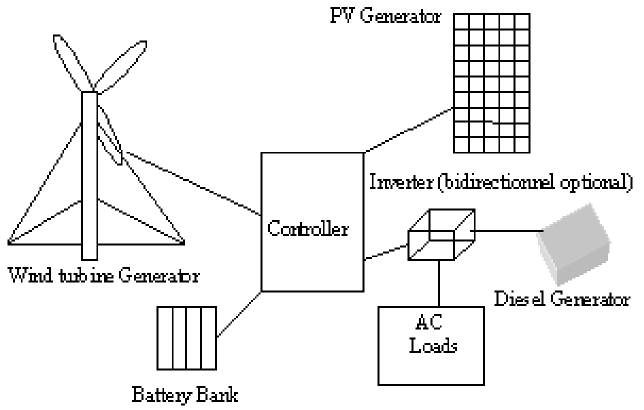

Fig. 1. Schematic diagram of hybrid energy system.

A. Advantages Of Hybrid Systems

There are various advantages of hybrid energy systems and use of renewable hybrid energy systems some are discussed below:

- **Complementary Nature:** A hybrid energy system can make use of the complementary nature of various sources, which increases the overall efficiency of the system and improve its performance (power quality and reliability) [14]. For instance, combined heat and power operation, e.g. MT and FC, increases their overall efficiency & or the response of an energy source with slower dynamic response (e.g. wind or FC) can be enhanced by the addition of a storage device with faster dynamics to meet different types of load requirements.
- **Lower emissions:** hybrid energy systems can be developed to utilize the renewable resources to the maximum thus giving rise to a system that has reduced emissions.
- **Acceptable cost:** The hybrid energy systems can be designed to attain desired attributes at the lowest acceptable cost which forms the key to acceptance in the market.
- **Flexibility:** They provide flexibility in terms of the effective utilization of the renewable sources.

B. Energy Flow of Hybrid Energy Systems

The Hybrid Energy Systems (HES) are those that are engineered to manage and allocate energy sources of various sources in an intelligent manner to provide demand efficiently. Their operational architecture determines the relationship between energy generation, storage, and consumption and analysis of energy flow shows how power is redirected, transformed, and wasted in the system. This flow is important to thermodynamic analysis, as well as optimization of a system. Energy flow diagram of hybrid energy systems is shown in Figure 2.

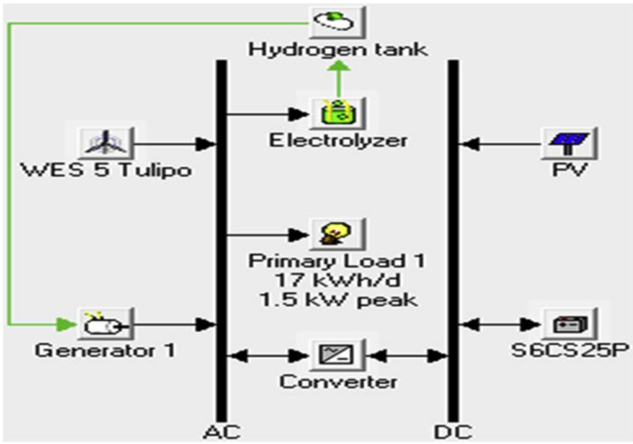

Fig. 2. Energy flow diagram for the hybrid energy system.

1) Subsystem Interactions and Control Strategy

HRES control strategy is necessary, to enhance productivity and reliable operation in uncertainties of renewable energy resources and to meet the variation of load demand. Maximum power point tracking (MPPT) control is employed in such systems to maximize the efficiency of solar and wind energy sources [15]. And an energy management system (EMS) is a controller that ensures power flow among various components is maintained stable. Conventional control strategies are based on clear mathematical descriptions of both the system and its surroundings, necessitating specific control information, precise data and familiarity of the domain.

2) Energy Flow Dynamics and Load Matching

Dynamics of energy flow and load correspondence are important features of hybrid energy systems (HES) and define the level of efficiency and reliability. These systems have to maintain a consistent trade-off between the changing power generation of renewable sources such as solar [16] and wind and the changing demand of the load. Load matching is to make sure that the energy is supplied in real-time without excesses of production or shortages. Storage facilities like batteries are important in the sense that, they absorb surplus energy and release it when it is needed. Energy flow design is done properly to reduce conversion losses among the parts of the system such as inverters and charge controllers. Thermodynamic analysis of these dynamics can help in optimization of system performance as well as enhancing energy use.

III. Thermodynamic Analysis Methods of Hybrid Energy Systems

Thermodynamic analysis is popular in evaluating the efficiency and improving the thermodynamic imperfections of mainly thermal engineering systems. Thermodynamic analysis mainly consists of three parts: the first part assesses the thermodynamic performance of the current operation [17]. The second part identifies the scope of improvements and retro-fits to reduce the cost of operation. The third part involves the assessment of the thermodynamics and economic effectiveness of the retrofits. Thermodynamic analysis of hybrid energy systems is shown in Figure 3.

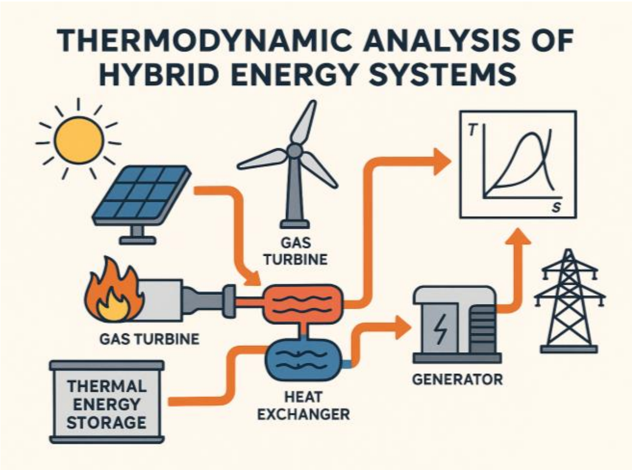

Fig. 3. Thermodynamic analysis of hybrid energy systems.

A. *Enery Analysis in Thermodynamics*

According to the First Law of Thermodynamics, one can never create or destroy energy, but only change it into a different form. The First Law is used to categorise 'the performance of cyclic conversion systems like fossil-fired, steam power cycles or geothermal cycles. This efficiency is a measure of the portion of heat added to a power cycle that is converted to work, i.e. the ratio of network produced to the heat added to the cycle.' The first law is a conservation law (Law of Conservation of Energy). Regarding geothermal power plants, 'the 1st Law requires that any electricity that is generated (energy out) must balance with the energy extracted from the geothermal resource ± any other energy uses and losses to the environment'.

1) *First-Law Efficiency Measurement*

- Measures the ratio of the useful energy to the total energy into the system.
- Applied to the individual performance of such components as solar panels, inverters, and generators.

2) *Energy Balance and Flow Tracking*

- Monitors energy flow among generation units, stores and load centers.
- Assists in locating energy losses in form of heat, friction or during conversion processes to enable redesigning of systems.

B. *Exergy Analysis in Thermodynamics*

The exergy method has been widely used for the analysis of industrial processes and energy productions. They involve power cycle operations, biomass and coal gasification, solar energy applications, refrigeration, application of waste heat as well as the use of distillation column systems. Exergy analysis is conducted to save the initial and operational costs of mainly thermal engineering systems. Application of exergy analysis to energy systems is shown in Figure 4. The main steps of exergy analysis are as follows:

- Develop the system boundary of processes to be analyzed.
- State all the assumptions and the reference temperature, pressure and composition.
- Consider possible heat recovery and heat integration strategies for all the processes analyzed.
- Determine the total exergy losses.
- Find out the thermodynamic efficiency.
- Find out the areas where exergy loss is ineffective using exergy loss profiles.
- Identify improvements and modifications to reduce the cost of energy and operation.

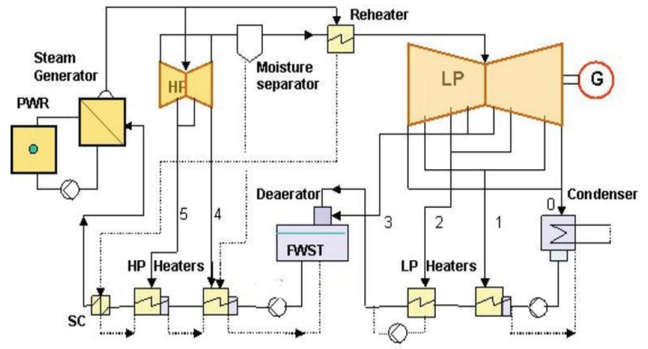

Fig. 4. Application of Exergy Analysis to Energy Systems

IV. Optimization Strategies in Thermodynamics Energy Sytems

Industrial and technological processes that are based on thermodynamic systems include power production, refrigeration, chemical processing, and propulsion. These mechanisms deal with energy, work, and heat transfer interaction, and do not violate the laws of thermodynamics. The desire to have the best performance in such systems is still a challenge because they are complex, nonlinear and sensitive to operational parameters [18]. Conventional optimization tools like Linear programming and genetic algorithms have helped a lot but, in most cases, cannot effectively deal with dynamic systems of high dimensions. It demonstrates different challenges, and opportunities involved in optimization of thermodynamic systems and the significance of effective analytical and optimization methods to enhance the efficiency and flexibility of the system.

A. *Single and Multi-objective Optimization*

The aim of optimization in hybrid energy systems (HES) is to enhance the performance of a system in terms of reduction in cost, emission, and efficiency. Optimization can either be single-objective or multi-objective based on the design objectives. Multi-objective optimization considers two or more (often conflicting) criteria simultaneously, where single-objective optimization considers only one objective, e.g. increasing energy efficiency or reducing fuel costs. As an example, the minimization of emissions can lead to a decrease in reliability [19], and optimization can lead to an increase in the cost of the system. Multi-objective optimization can also be useful in HES, to come up with reasonable and balanced design decisions since various sources of energy and components are dynamically coupled.

1) Single-objective Optimization

- Makes optimal one performance indicator, i.e. cost, energy loss, or fuel consumption.
- Simpler to implement, can fail to consider trade-offs with other key goals such as the impact on the environment or reliability.

2) Multi-objective Optimization

- Maximizes two or more conflicting goals (e.g. cost vs. emissions, efficiency vs. reliability).
- Needs highly specialized algorithms (e.g., NSGA-II, MOPSO) to provide a Pareto front of optimal solutions, so that stakeholders can select the ones that best suit them.

V. Literature of Review

The literature states that the existing strategies of hybrid energy systems increase efficiency and reliability of the system, yet difficulties are observed in scaling the solutions, making the models more accurate, and obtaining better real-life validation.

Xue, Zhang and Li (2025) examined interdisciplinary developments and the major challenges in European HES research. The results show that there are large geographical inequalities: Southern Europe is dominated by photovoltaic systems, North energy is focused on optimal thermal energy storage, and Eastern Europe is still dependent on classic energy. The implementation of HESs past pilot stage is motivated by policy regulations, economic incentives, and sociocultural factors. Hybrid energy storage and the application of artificial intelligence-based controls to optimize a system is becoming a key driver of economic viability and self-sufficiency in system optimization [20].

Pijiang et al. (2025) have reduced the number of terms of the MIMO model of the renewable energy integration and formulates a SISO model to analyze ultra-low frequency oscillation of a system, which reduces the order of the system. The effects of photovoltaic (PV) generation on ultra-low frequency oscillations are explored using the method of the vector margin analysis and demonstrate the fact that the introduction of PV integration has a positive effect in reducing the oscillations. It suggests a parameter tuning method of PV active controllers and proves it on the two-area four-machine system [21].

Jegede, Fayomi and Azubuike (2024) studied the thermodynamic performance improvement of thermal systems by using energy, exergy and complicated computational methods with the main emphasis on the growing role of Computational Fluid Dynamics (CFD) in improving the efficiency of systems. The energy analysis shows that the efficiency of thermal and boiler arrangements is greatly enhanced because of the integration of the closed feedwater heaters, whereas the exergy analysis offers information about the energy transformation losses as a result of irreversibility. Further exergy analysis points out the avoidable exergy destruction to make the necessary improvements in system design [22].

Kong et al. (2023) experimented the energy efficiency and examined to 20 energy storage system contending in frequency regulation ancillary in Guangdong Province. The findings indicate that energy efficiency of low power charge-discharge is usually superior to high power charge-discharge and the percentage of auxiliary energy consumption of low power and small capacity system is more; the overall efficiency of energy storage system depends on the system capacity, charge-discharge rate and auxiliary energy consumption [23].

R et al. (2023) proposed a combined strategy of power management and strategic control of an independent hydrogen-based DC micro-grid, a combination of PV, wind, and fuel cells, and a hybrid of a battery and a supercapacitor energy storage. The suggested hybrid energy storage management is a solution to the voltage of the DC-bus and reduces the amount of stress on the battery current due to the intermittence of the PV system and wind system. Also, frequency domain analysis is used in developing the hybrid energy storage controllers. The control algorithm should be used to maximize the use of PV and wind systems, which is achieved through maximum power point tracking mode, which is linked to the DC load, and converts DC to DC[24].

Tephiruk et al. (2022) introduced a hybrid energy storage (HESS) technology that is based on the principle of collaboration of the battery energy storage system (BESS) and solid oxide fuel cells (SOFC). The energy storage system has its responsibilities that are divided into two. The former is in the case of transient condition; BESS is useful in making the system adjust to sudden load changes. The second section would be the steady-state condition; SOFC will maintain the system in the long term to accommodate fluctuations and facilitate renewable energy to provide smooth power supply to the system [25].

Nesterenko et al. (2022) have demonstrated the concepts of frequency regulation in off-grid power system basing on autonomous hybrid power plant (AHPP). AHPP serves territories, which are not linked to the centralized supply of electric power. AHPP composition of power sources comprises of traditional generators, renewable energy source (RES) and electric energy storage system (EESS). The control principles are to regulate deviations of limitations frequencies in the power system, which gives the balanced utilization of the adjustable capacities of power sources [26].

Table I provides an overview of the major works of hybrid energy systems, its focus, findings, difficulties, contributions, and gaps. Although it can be seen that it has made significant advancements in efficiency and stability, there are still some concerns such as scalability and a small amount of validation. Automation and real-life implementation should be bolstered in the future.

TABLE I. Recent Studies on Thermodynamic Optimization and Control in Hybrid Energy Systems

Reference	Focus Area	Key Findings	Challenges	Key Contribution	Limitations / Gap
Xue, Zhang & Li (2025)	Interdisciplinary issues in European research of HES	Geographical disparities: South, PV-dominant, North, thermal storage, East, classic energy, AI-based controls, hybrid storage enhancing self-sufficiency	Heterogeneous implementation in Europe; sociocultural and economic issues	Illustrates the importance of policy, economic, and cultural factors in HES adoption; demonstrates the use of AI control as one of the most important optimization factors	More thorough examination of long-term HES performance, not pilot-stage

Pijiang et al. (2025)	PV influence on ultra-low frequency oscillations	SISO model of reduced MIMO model; PV integration reduces oscillations; gives tuning technique to PV controllers	Complexity in renewable integration modeling effects	Makes the modeling of systems less intricate and shows constructive PV influence on stability	Only tested using two-area four-machine system; scalability has not been verified
Jegede, Fayomi & Azubuike (2024)	Exergy and CFD based on the thermodynamic performance enhancement	The closed feedwater heaters enhance the efficiency of the boiler; exergy demonstrates the destruction that is avoidable because of irreversibility	Expensive computer work; sophistication of CFD-based optimization	Demonstrates the significance of CFD and locates the exergy losses to improve the design	Restrained to thermal and boiler systems; not evaluating systems that integrate renewable
Kong et al. (2023)	Frequency regulation of 20 ESSs at energy efficiency	The low-power charge-discharge is more effective; efficiency is dependent on capacity, rate and the use of auxiliary	Small capacity systems consume high auxiliary energy	Offers comparative efficiency analysis of deployments of real ESS	Local specialisation (Guangdong Province); cannot apply to the whole world
R et al. (2023)	Hydrogen-based DC micro-grid micro-grids with PV, wind, fuel cells- Hybrid	Hybrid stabilizes DC bus, alleviates battery stress, MPPT improves the use of PV and wind	Controlling PV/wind intermittency; complexity of real time control	Suggests combined hybrid storage control and frequency-domain control	The real-world implementation outcomes; primarily simulation outcomes
Tephiruk et al. (2022)	BESS + SOFC hybrid storage	BESS is transient; SOFC is long-term stable; smooth delivery of renewable energy	BESS- SOFC system coordination.	Develops two-stage operation of HESS to the transient and steady-state reliability	Lacks no cost, degradation or long-term sustainability
Nesterenko et al. (2022)	Off-grid Hybrid power plants Frequency regulation	AHPP is used in conjunction with generators, RES, and EESS; the frequency deviation is controlled effectively	Capacity balancing in remote AHPP systems	Shows the principles of demonstrating control to allow stable off-grid hybrid power	Only able to do autonomous off-grid systems; no research on grid-linked cases

VI. Conclusion and Future Work

The growing adoption of renewable energy sources requires hybrid systems that will be able to provide a stable, efficient, and sustainable power under a wide range of conditions. This paper has critically assessed the thermodynamic performance, energy transfer mechanisms and optimization techniques of Hybrid Energy Systems with the aim of determining their performance and potential to work. The conclusions demonstrate that energy and exergy analysis can be useful in finding the losses, enhancing the efficiency of the components, and optimizing the system design in general. Flexibility, reliability and load control are distinct benefits of the modern hybrid systems in the form of PV wind fuel cell systems and battery SOFC hybrid storage and new generations of microgrids. Nonetheless, complexity in the system, model scalability and lack of real-world validation continue to be obstacles. Optimization methods, specifically multi-objective and intelligent control methods are at the center of stage to maximize output of such systems at a balance between cost, emissions, and efficiency.

The future studies should be oriented on the validation of the hybrid energy systems on a large scale and integration of more sophisticated AI-based control methods in order to enhance prediction, stability and real-time optimization. Long-term reliability will be enhanced by broadening multi-objective optimization models and addition of component degradation models. Furthermore, the feasibility of experimental investigations on hybrid storage coordination, economic viability and grid-interactive behavior is required to enhance feasible deployment and speed up the adoption of resilient, thermodynamically optimized hybrid energy systems.

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