# OPTIMIZATION AND ECONOMIC FEASIBILITY OF HYBRID RENEWABLE ENERGY SYSTEMS FOR DATA CENTER POWER MANAGEMENT

MSc Research Project
Cloud Computing


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**MSc Project Submission Sheet**

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# OPTIMIZATION AND ECONOMIC FEASIBILITY OF HYBRID RENEWABLE ENERGY SYSTEMS FOR DATA CENTER POWER MANAGEMENT

Rishika Podila
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**Abstract**

This study focuses on how renewable energy systems including but not limited to solar and wind energy systems can be integrated into data centre power management systems with a view of increasing sustainability, reliability, and cost-effectiveness. The paper examines the prospects and prospects of using these renewable resources, and the procedure of integrating energy power for the uninterrupted power supply system through batteries and hydrogen sources. The work focuses on optimization algorithms of hydro/micro combined systems covering load dispatching, cost-effectiveness, and profitability aspects.

This research uses secondary qualitative data and simulates techniques based on the deductive approach for analysing the integration of renewable energy sources, storage systems, and data centres. Energy productivity and regulatory indexes like energy conservation, carbon dioxide emissions reductions, and profitability indicators are also assessed to measure the effect of integrating renewable energy. In other ways, the study responds to the environmental and economic consequences of the change in energy sources to renewable ones indicating that there a potential savings in costs and reduction in carbon footprints.

The evidence presented here confirms that the optimization of renewable energy and energy storage systems can increase the effectiveness of data centres' function while considering climate impact. The book also describes the problems that arose during the implementation and further advances are suggested to enhance the hybrid energy systems in the data centre.

# 1. Introduction

## 1.1 Introduction

This research area is therefore concerned with the enhancement of the HRES for data center power supply systems, with strong regard for sustainability and the expense account. It tracks issues in energy reliability, operational cost, and energy impact by embracing renewable energy resources that include solar and wind energy in conjunction with superior energy storage resolution, optimization algorithms, and machine intelligence studies.

### 1.2 Background

Data centers are among the biggest energy consumers and one of the biggest sources of greenhouse gas emissions. SWOT analysis: The change from the use of grid electricity to renewable energy sources like solar and wind is an opportunity that holds the potential to increase sustainability as well as decrease operating expenses. However, different resources of renewable energy supply power in an intermittent cycle, which poses difficulties in maintaining supply reliability (Gao *et al.* 2020). For these challenges, solutions involve incorporating other renewable energy systems (HRESs) with storage systems such as batteries and hydrogen systems. Furthermore, optimization algorithms and machine learning approaches allow sufficient energy control soothing the significance of reliability, cost, and environment resultantly HRES is an area of focus for sustainable data centers.

## 1.3 Rationale

***What is the issue?***

Server rooms on the other hand require large amounts of energy particularly from conventional sources such as fossil materials resulting in high costs of operations while producing high amounts of carbon.

***Why is it an issue?***

Depending on non-renewable energy sources leads to soil pollution, causing greenhouse effects hence the issue of sustainability. Further, there is the unreliability of energy supply resulting from the growing demand for data center services around the globe.

***Why is it an issue now?***

Energy costs and global energy demands are on the rise while the concerns about climate change are reaching a critical point, it is high time people embraced efficient and sustainable solutions such as hybrid renewable energy systems to support reliable energy supply for data centers.

## 1.4 Research Aim and Objectives

***Aim***

The main aim of the research is to maximise energy use while ensuring sustainability and dependability has become apparent and doable.

***Objectives***

- To investigate mixed models and subsystems–problems and approaches–of incorporating renewable power resources, specifically solar and wind energy systems, specifically solar and wind Ey systems.
- To assess the applicability of energy storage systems to improve the sustainability and availability of data centers, a case study will be performed to compare the effectiveness of battery systems and hydrogen storage technologies.
- To load balancing, cost optimization, and business cases for employing HE systems in data centers are explored including the use of various optimization algorithms.

## 1.5 Research Questions

- What are the models for incorporating renewable energy sources into data center power management systems' architecture and what are the issues and solutions?
- What manner have battery and hydrogen technologies which are part of ESS enhanced the sustainability and resilience of the data centers?

- What algorithms optimized the hybrid energy systems contributing load balancing, cost-optimized, and economically viable solutions for data centers?

## 1.6 Research significances

It is useful to notice that this is a direction of the research, because at present the issue of efficient and renewable energy sources utilization in data centers, which steadily increases their consumption, remains rather acute. From the integration of renewable energy appliances and storage systems together with optimization algorithms, the study outlines a way of minimizing operational costs and environmental hazards (Sinsel *et al.* 2020). The conclusions submitted here provide valuable guidelines for enhancing energy reliability, sustainability, and cost-effectiveness in data center power distribution.

## 1.7 Research Structure

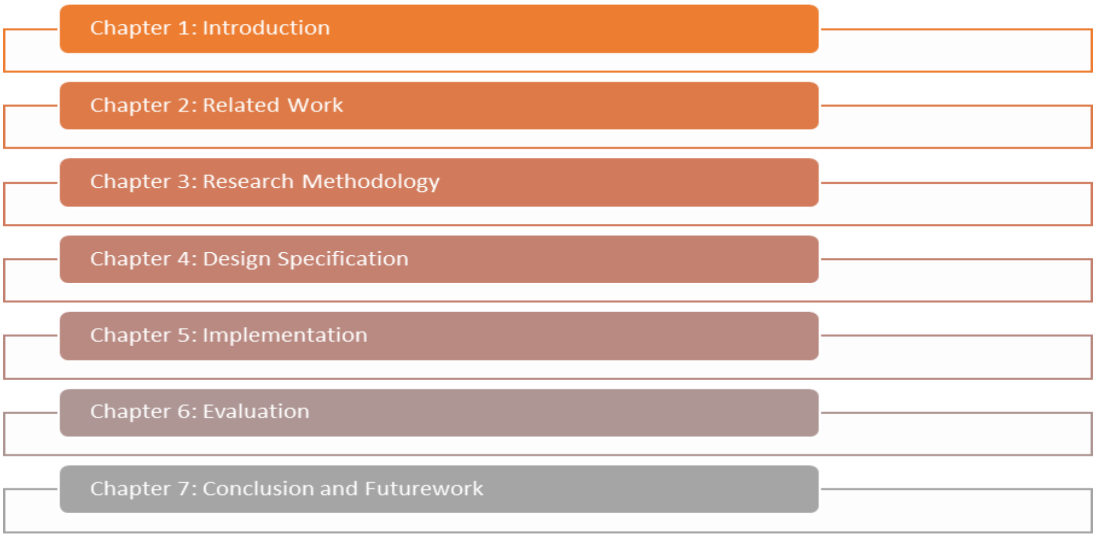



***Figure 1.7.1: Research Structure***

(Source: Self-created)

## 1.8 Summary

This chapter outlined an introduction to the optimization of hybrid renewable energy systems for data center power supply. A need to incorporate renewable energy such as solar and wind and energy storage technologies in the energy mix to cut operational expenses as well as minimize eco impacts. The research focuses on investigating the models, issues, approaches, and optimization algorithms for improving energy reliability and sustainability in data centers. The relevance of the study is predicated on its ability to offer both affordable and sustainable power technologies for the current data centers.

# 2. Related Work

## 2.1: Introduction

Efficient utilization of renewable energy forms like solar or wind power is key to achieving optimizations in modern energy systems' sustainability. While including high penetrations of VREs, systems integration issues emerge in dispatch, storage, and reliability that need to be solved. This chapter also focuses on the use of energy storage technologies and demand-side management techniques in HRES and learning models. Furthermore, energy storage, load balancing, and demand response are explored to increase the effectiveness and affordability of renewable energy connections in reducing operational costs and carbon footprint.

## 2.2 Renewable Energy Integration in Data Centres: Models, Challenges, and Solutions

The use of renewable energy in data centers offers advantages and disadvantages, as outlined below. Data centers themselves are rather energy-consuming infrastructures with vast environmental footprints – the majority of the facilities solely utilize grid power (Sinsel *et al.* 2020). On the same note, changing to the use of renewable energy such as solar and wind energy can assist in overcoming such impacts since they relieve decreased carbon footprints. Concentrated solar and wind power generation are stochastic by their very nature, which complicates the problem of ensuring a stable and continuous flow of electricity. In response to these challenges, several models and technologies have been suggested, which include energy storage and hybrid renewable energy systems or microgrids.

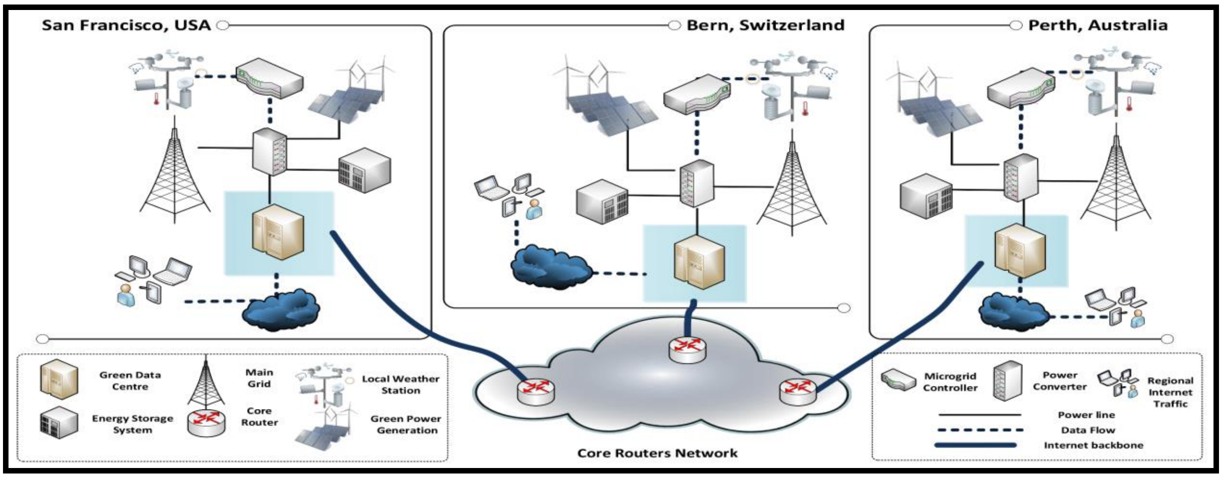



***Figure 2.2.1: Inter-continental Data Centre Power Load Balancing for Renewable Energy Maximization***

(Source: Rahmani *et al.* 2022)

The techno-economic feasibility analysis in integrating renewable energy systems into data centers is conducted using modeling tools like the hybrid optimization model for electric renewables known as HOMER (Bassey, 2023). These models capture the potential of applying renewable energy in various climatic zones and the most optimal costs. However, some problems, for instance, energy variability, load fluctuations, and handling of intermittent power supply are beyond a basic level and may entail demand-side management and load shifting. The use of machine learning (ML) has also been used in enhancing the prediction of system performance and energy storage. Moreover, energy storage technologies like lithium-ion, flow batteries, and demand response management are vital to improving energetic reliability as well as decreasing the operational cost of renewable energy systems in data centers.

## 2.3 Energy Storage Systems for Data Centre Sustainability: Battery and Hydrogen Storage Technologies

Renewable energy systems require energy storage systems to provide appropriate power solutions for differing data center system loads. The nature of the production of solar and wind energy being inconsistent, energy storage receives more interest to enhance supply chain demand. These storage systems allow data centers to continue to operate during times when renewable energy is not being generated, or is available in limited quantities, thereby mitigating dependence on grid power and minimizing the carbon legacy.

Lithium Ion and Flow Batteries are very popular because of their high energy density and efficiency as well as the scalability of battery energy storage technologies (Elio *et al.* 2021). Most of these function by holding renewable power produced at maximum production seasons and letting it out whenever renewable energy production is low. However, the grand applications present an attractive opportunity for the desired goal, and hydrogen storage technologies are viewed as a possible solution, especially for long-duration storage. Hydrogen is an excellent means of storing energy for long durations and generating electricity when the need arises – with a proposal that can benefit large data centers situated off the grid or in rural areas.

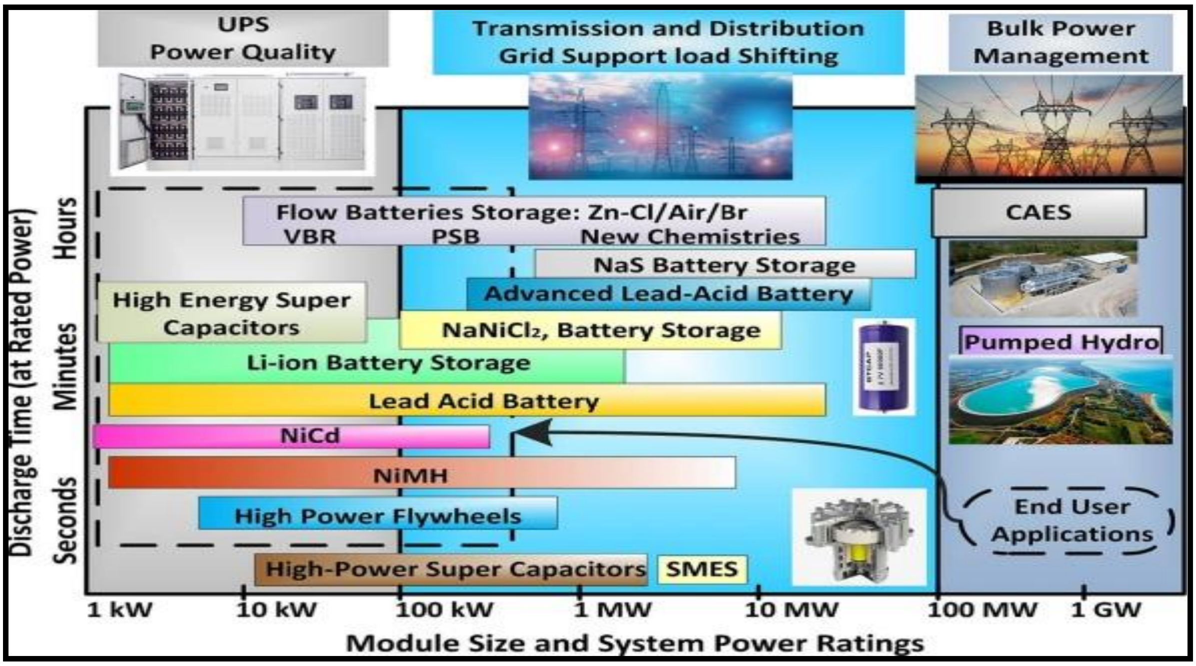



***Figure 2.3.1: Energy storage technologies***

(Source: Amir *et al.* 2023)

Battery and hydrogen storage management system integration with data centers improves the dependability of renewable energy, in general. In the literature, machine learning methods enhance the efficiency of the storage systems by forecasting energy consumption rates and the corresponding charge and discharge cycles efficiently (McPherson and Stoll, 2020). These technologies combined make it possible for data centers to use RE and have a balance of load while having minimum variability, low operational costs, and environmental impact.

## 2.4 Optimization Algorithms in Hybrid Energy Systems: Load Balancing and Economic Feasibility

Optimization algorithms entail great importance when it comes to control and cost of hybrid power systems particularly data centers that tap into renewable resources. Two of the essential roles these algorithms play in improving the effectiveness and cost of hybrid renewable energy systems (HRES) are load shaving and economic optimization. Take load balances for data centers; it optimizes in its way by distributing the load it demands dynamically across renewable energy systems, storage systems, and grid powers to avoid energy wastage and disruption (Das *et al.* 2021).

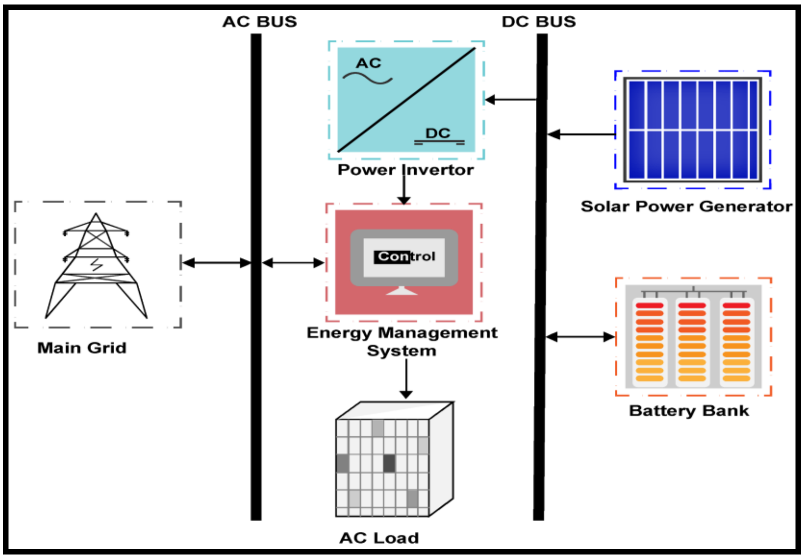



***Figure 2.4.1: Hybrid Renewable Energy System Design***

(Source: Abdullah *et al.* 2023)

As linear programming optimization, dynamic programming, and artificial neural networks, real-time resource processing and control is an important application area. These algorithms are helpful for a deep understanding of the suitable energy mix that can fill the available solar, wind, and storage systems according to availability, demand, and cost. As documented in the literature, optimization models play a critical role in ensuring operations are done at a lower cost while reducing dependency on the grid, which not only lowers energy costs but also fixed carbon emissions.

Measures such as return on investment and payback-period tests are essential when conducting economic feasibility analysis to determine the sustainability of HRES in data centers (Olaleye *et al.* 2024). These optimization models factor both CAPEX and OPEX while searching for cost-efficient energy processes. The use of machine learning advances optimization by constantly adjusting based on live data feedback, increasing life-cycle power plant productivity, and enabling cost-cutting scenarios in a hybrid energy system.

Machine learning enables effective energy distribution and dynamic load balancing to improve the predictive capabilities of supply and demand energy forecasting. The analysis of live data by machine learning algorithms allows prediction of renewable energy generation variability through changes in solar and wind resources and enables matching of predictions to energy storage and grid requirements. Using this capacity power producers can sustain reliable energy management while lowering their dependency on conventional power generation when renewable energy output falls (Jahannoosh *et al.* 2021). The application of machine learning techniques extends the life and boosts performance of energy storage hardware (batteries and hydrogen systems) through optimized charging and discharging operations. The algorithms simultaneously promote better renewable energy usage while cutting down energy losses and consequently decrease operational expenses. The integration method provides both contemporary solutions to renewable energy system challenges and establishes a scalable framework enhancing data center power management sustainability and economic viability.

## 2.5 Literature Gap

The following gaps in the literature can be identified even when considering substantial advancements in hybrid renewable energy systems (HRES) for data centers. Though extensive attention has been given to renewable integration and energy storage systems, few studies have investigated the efficient algorithms for real-time load management and cost-effectiveness in these systems. Further, most of the prior research ignores the fact that deploying such systems at data centers requires handling various ephemeral issues and does not consider their feasibility in terms of costs and practical applicability for the long term. In addition, the application of machine learning techniques for optimizing system performance and forecasting in dynamic energy contexts can be considered an avenue for further research.

The literature review functions to reveal present research areas that require exploration while simultaneously establishing well-grounded reasons for approaching the investigation. The review can become more rigorous by analyzing additional strategies while maintaining the suggested approach's broader initial foundation. The forecasting accuracy for hybrid renewable energy systems (HRES) would improve when sophisticated models such as ensemble learning methods and neural networks replace current predictive models (Bassey *et al.* 2023). These technologies show promising capabilities for precise renewable energy prediction together with optimal control of dynamic energy systems. Alternatives such as compressed air energy storage and thermal energy storage would extend the available selection of storage options. These technologies solve renewable energy source intermittency by offering both scale-up capabilities and extensive storage options. Analyzing potential energy storage systems against battery and hydrogen technologies would provide better understanding about how they operate in real-world contexts. By incorporating emerging solutions and technologies into the literature review the study would achieve better understanding of next-generation implementations. Strengthening the comparison alongside highlighting novel aspects from the proposed energy management system will improve its enterprise solution merit evaluation.

## 2.6 Conceptual Framework

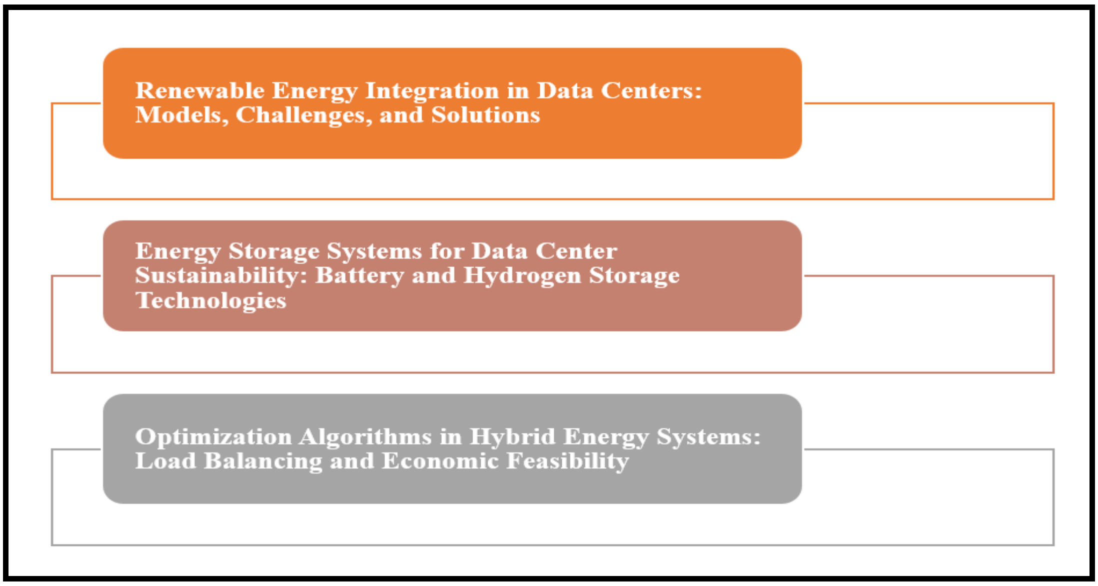



***Figure 2.6.1: Conceptual Framework***

(Source: Self-created)

## 2.7 Summary

The exploration of renewable energy specifically solar and wind systems in data center systems presents a way of cutting energy use and emissions. However, barriers like occasional Blackouts and the state of battery technology, where and how it is best useful are some of the ambiguities that make this transition slightly difficult. During recent decades, electric storage systems, such as batteries and hydrogen systems, have been pivotal in guaranteeing the continuity of power supply (Kanellopoulos and Sharma, 2022). System improvement methodologies like load balancing and economic practicability of the renewable hybrid system are critical factors in improving hybrid renewable energy systems in data centers. Nevertheless, this study identifies several shortcomings as a significant amount of work remains to be done in real-world usage of advanced machine learning techniques, and the scalability and cost-effectiveness of such systems, in terms of their operational efficiency, need further elaboration.

# 3 Research Methodology

## 3.1 Introduction

The current chapter describes the research approach to deriving efficient hybrid renewable energy systems for the power requirement of data centers. It describes how the research was conducted, the instruments used to collect data, and the analysis conducted in assessing the integration of renewable energy, energy storage systems and the optimization algorithms used. The paper's purpose is to consider significant issues within energy reliability, sustainability, and cost to offer a systematized methodology for data centers to enhance their energy strategy.

## 3.2 Research Philosophy

This research opts to use the positivist philosophy of research which presupposes that knowledge is obtained through observation and measurement. It is an impersonal approach as it bases its analysis and conclusions, on accurately measurable and modellable hybrid renewable energy systems for dealing with data center power (Chen *et al.* 2022).

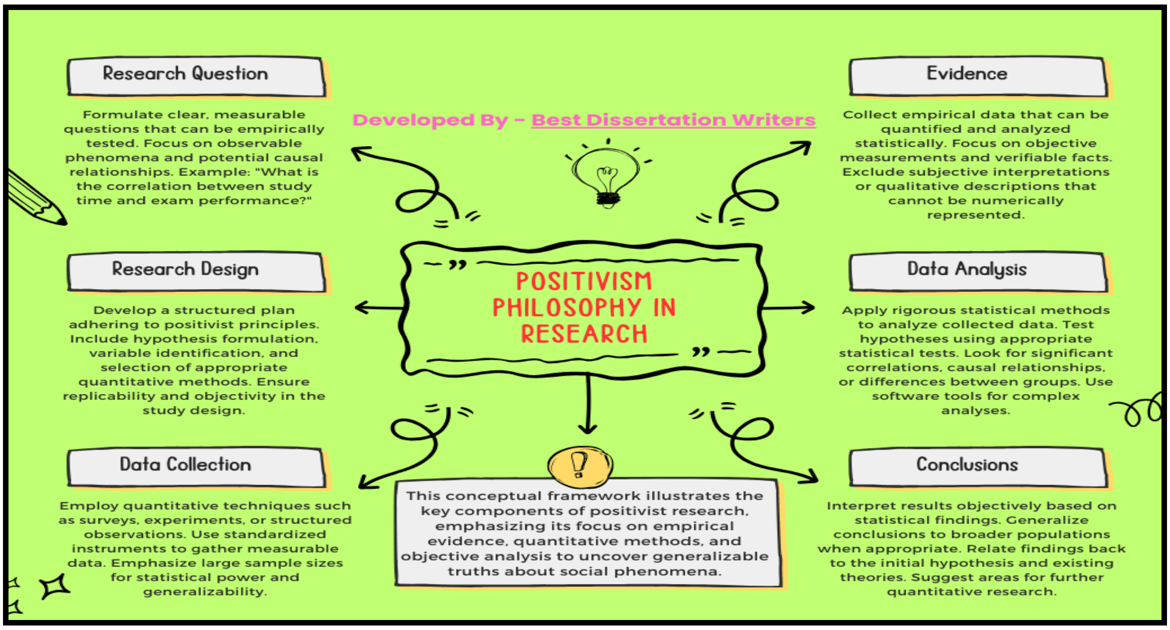



***Figure 3.2.1: Research Philosophy***

(Source: bestdissertationwriter.com, 2024)

The advantages include the fact that it is possible to obtain results that can be replicated, determine causality, and guarantee systematicity. On account of this, positivism aids in the demarcation of factual grounds of useful knowledge in making objective conclusions and evaluations that need to be done for assessing the efficiency of renewable integration, storage technologies, and optimization algorithms of data centers.

## 3.3 Research Approach

This study uses a deductive research approach whereby, research questions and hypotheses stem from a set of existing theories, models, and propositions. Specifically, as applied to this work, the deductive approach is employed to examine and validate the interrelation of renewable energy, energy storage, and optimization algorithms in data centers.

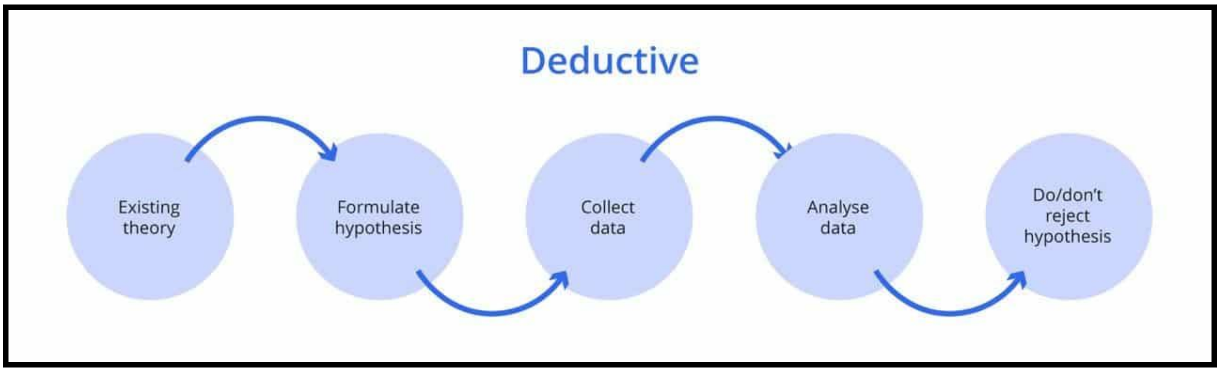


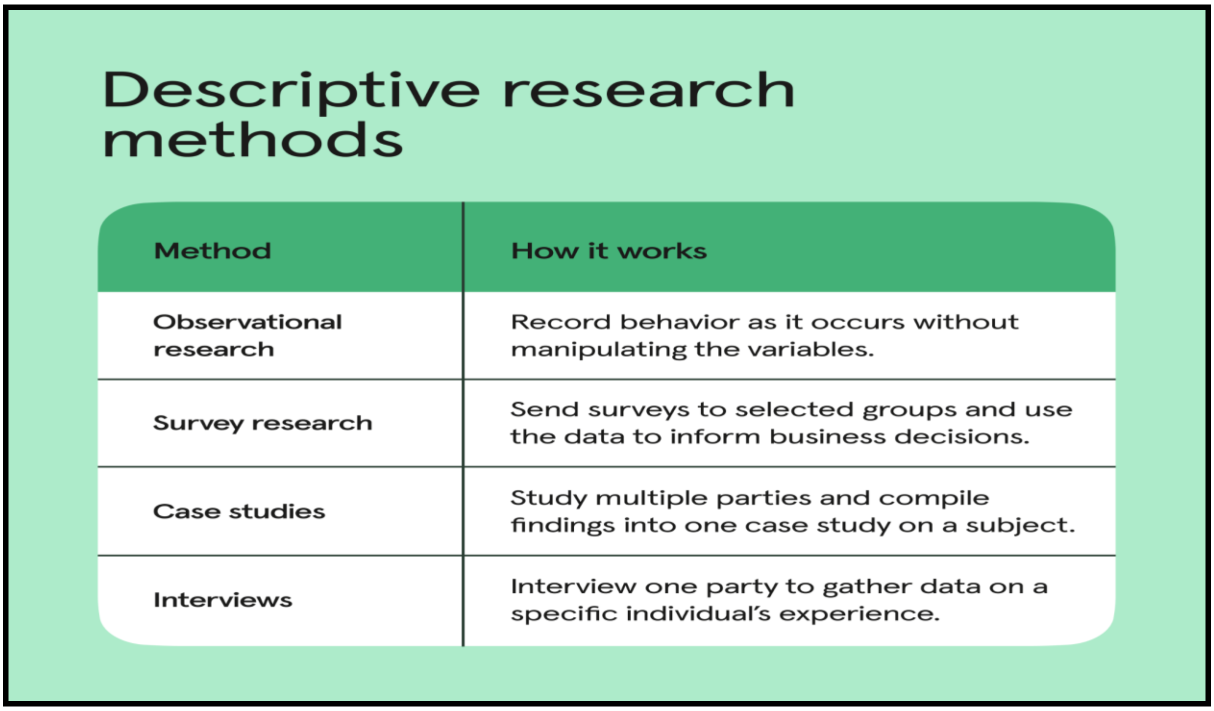

***Figure 3.3.1: Deductive Approach***

(Source: voxco.com, 2024)

The use of this approach has the following attributes; systematic approach makes it possible to systematically test theories and concepts that are developed (Katal *et al.* 2023). It supports the establishment of proper hypotheses for which data can be collected and analyzed, allowing the user to arrive at valid conclusions for the improvement of hybrid renewable energy systems suitable for data center functionality.

## 3.4 Research Design

In this respect, this study is descriptive due to the aim of the research, which is centered on describing and interpreting several characteristics concerning the integration of hybrid renewable energy systems and power management of the data centers. The descriptive design assists in defining the current models, problems, and prospects of renewable energy, storage systems, and optimization techniques (Denholm *et al.* 2021).



Descriptive research methods

| Method | How it works |
|---|---|
| Observational research | Record behavior as it occurs without manipulating the variables. |
| Survey research | Send surveys to selected groups and use the data to inform business decisions. |
| Case studies | Study multiple parties and compile findings into one case study on a subject. |
| Interviews | Interview one party to gather data on a specific individual's experience. |

***Figure 3.4.1: Descriptive Research***

(Source: typeform.com, 2024)

It gives an insight into what is known about the subject area and what has already been done towards the development of the knowledge base (Sorley *et al.* 2021). The benefits include the possibility to collect such particularistic data, and then analyses the patterns retrieved from this approach, to get a coherent understanding of the interactions of different systems to make relevant decisions regarding the optimization of energy consumption in the data centers.

## 3.5 Data Collection Method

This research adopts secondary means of data collection which includes qualitative data in the form of published data sourced from academic journals, reports, case studies as well as industry publications. The benefit of using this technique is that you can get a lot of existing information to further enhance the understanding of incorporating hybrid renewable energy systems in data centers. It has cheaper and faster options since one does not need to collect original data while at the same time guaranteeing inclusiveness (Hoang and Nguyen, 2021).

## 3.6 Ethical Consideration

This research follows ethical standards to guarantee the credibility of the results produced by this study. As the current study only involves secondary qualitative data collection all the sources cited to support the study are done without plagiarism and adequately acknowledging the original authors (Chen *et al.* 2022). Reducing issues of privacy and confidentiality is done by only employing data that is available in the public space. Accordingly, the research does not seek to impose any preconceived opinions but seeks to provide an account of the data. Keeping with the ethical issues, credibility and honoring other people's work are maintained throughout the study's investigation.

## 3.7 Research Limitation

This research relies mainly on secondary qualitative data to provide an understanding on the topic the research topic; hence, it lacks firsthand information on implementing hybrid renewable energy systems in data centers (Koot and Windhaven, 2021). Furthermore, the utilization of previous research indicates the possibility of the problem or solution not being presented comprehensively due to missing some latest technology. The study is also conducted based on the information that is publicly available and thus may exclude some essential case studies or data from specific industries.

## 3.8 Summary

This chapter provides a blueprint of the method that has been used in this study including the choice of the positivist philosophy, the deductive approach, and descriptive design in assessing renewable energy integration in data centers. Secondary research involves the collection of qualitative data through surveys, observation, and interviews but in this case, the emphasis is made on published literature and case studies. As noted above, ethical factors are used to maintain the credibility of the research whereas limitations like secondary data analysis and omission of some commercial data are also accepted. This allows for better structure in an approach to addressing the research objectives and questions as stated above.

# 4 Design Specification

## 4.1 Introduction

Chapter 4 Section: “Introduction” explains the design requirements and goals for incorporation of renewable energy systems and energy storage solutions in data centers’ respective operating environments. There can be identified a necessary need for an efficient, sustainable, and cost-effective energy management system, including the aspects of energy resources, storage, and operations.

## 4.2 System Overview

This is detailed in the “System Overview” which identifies and describes the core features of the proposed EM system for data centers. The system thus combines renewable energy generation systems including solar and wind power with storage systems including battery generation and hydrogen storage. The design is centered on power density, dependability, and efficiency in energy use to reduce operating expenses (Gao *et al.* 2020).

The system will include both; grid-tied, off-grid, and hybrid systems with the ability to self-adjust load balancing and optimal energy storage handling depending on the power load. Also, the economic aspect will be measured through the cost-benefit analysis to be conducted by the developed system, while the environmental aspect will be checked through de minimis usage of carbon and efficient energy use.

## 4.3 Renewable Energy Integration

The “Renewable Energy Integration” section deals with the integration of renewable energy sources including solar and wind into the data center energy management system. The availability of these renewable sources will be effectively maximized by power generation variations within the new system.

Solar power will be generated according to the sinewave pattern, while the wind power output will be generated randomly.

```
%Step 1: Initialize Renewable Energy and Storage System Models
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Example initialization for solar and wind power
time = 1:24; % Hours in a day
solar_power = max(0, 100 * sin(pi * (time - 6) / 12)); % Simplified solar power model
wind_power = 50 + 10 * randn(1, 24); % Randomized wind power generation


% Battery and hydrogen storage parameters
battery_capacity = 500; % kWh
hydrogen_capacity = 1000; % kWh equivalent
battery_charge_efficiency = 0.95;
hydrogen_charge_efficiency = 0.85;
battery_soc = battery_capacity * 0.5; % Starting at 50% capacity
hydrogen_soc = hydrogen_capacity * 0.5;
```

***Figure 4.3.1: Initialize Renewable Energy and Storage System Models***

(Source: Extracted from MATLAB)

The design guarantees that renewable energy integration is optimally achieved given real-time calculations of availability and congruence with data center power requirements. Also, it will improve the possibility of switching between renewable energy and the grid, improving system stability and minimizing utilization of conventional power (Obringer *et al.* 2021).

## 4.4 Energy Storage Systems

The “Energy Storage Systems” section is devoted to the battery and hydrogen storage systems to improve the data center energy supply reliability and effectiveness. The system will incorporate a battery of a defined capacity and charge/discharge efficiency to store energy that is more than what is produced by RE sources. Long-duration energy storage will also be examined where hydrogen storage will be regarded due to its potentiality in this area.

The energy storage systems shall similarly be incorporated to provide power during situations where renewable energy generation is low (Haldar and Sethi, 2022). This design can meet the supply-demand relationship, increase the decoupling degree of the data center from the grid, and enable uninterrupted operation in different energy statuses.

## 4.5 Optimization Algorithms for Energy Management

The 3rd section “Optimization Algorithms for Energy Management” is dedicated to exploring the energy optimization strategies implemented in the data center. These algorithms will help decide how to share the load between renewable energy sources, energy storage facilities, and the grid to eliminate high energy costs and power disruptions.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Step 2: Model Energy Distribution Configurations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Grid-tied power calculation
grid_power_usage = zeros(1, 24);
for t = 1:24
    renewable_available = solar_power(t) + wind_power(t);
    demand = 400; % CDC power demand in kWh
    if renewable_available >= demand
        renewable_usage = demand;
        grid_power_usage(t) = 0;
    else
        renewable_usage = renewable_available;
        grid_power_usage(t) = demand - renewable_available;
    end
end
```

### *Figure 4.5.1: Model Energy Distribution Configuration*

(Source: Extracted from MATLAB)

These are goals such as achieving efficient use of power; balancing the load, and cutting energy losses. The algorithms will also work based on the real-time data generated on energy production and demands present over the internet to operate the system in an optimum manner to control and reduce the costs with the environmental impacts and ensure sustainability at the same time (Ali *et al.* 2021).

## 4.6 Economic Feasibility and Performance Evaluation

The “Cost Effective Analysis and System Performance” sub-chapter reviews the economic rationality and utilization efficiency of the proposed plans.

```
%Step 4: Economic Feasibility Analysis
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Economic Analysis example

capex = 200000; % Initial setup cost in dollars
opex = 0.1 * capex; % Operational expenses as 10% of CAPEX

% Define the cost per kWh (for example, $0.12 per kWh)
energy_cost = 0.12;

% Example grid power usage over a specific period in kWh
grid_power_usage = [1000, 950, 980, 1020, 1100]; % Array of power usage readings

% Calculate energy cost savings
energy_savings = sum(grid_power_usage) * energy_cost; % Total energy cost savings

% Calculate Return on Investment (ROI)
roi = (energy_savings - opex) / capex;

% Calculate Payback Period
payback_period = capex / (energy_savings - opex);

% Display the results
fprintf('Return on Investment (ROI): %.2f\n', roi);
fprintf('Payback Period (years): %.2f\n', payback_period);
```

### *Figure 4.6.1: Economic Feasibility Analysis*

(Source: Extracted from MATLAB)

They embrace cost with breakdown, return on investment, payback period, and energy savings.

```
% Carbon savings analysis
carbon_emission_factor = 0.4; % kg CO2 per kWh for grid energy
grid_power_usage = [1000, 950, 980, 1020, 1100]; % Example power usage in kWh

% Calculate carbon savings
carbon_savings = sum(grid_power_usage) * carbon_emission_factor;

% Print the result
fprintf('Total Carbon Savings: %.2f kg CO2\n', carbon_savings);
```

### *Figure 4.6.2: Economic Feasibility Analysis*

(Source: Extracted from MATLAB)

Further, other quantitative efficiency measures common in performance assessment will be carried out including energy consumption, carbon emissions reduction, and overall system reliability.

## 4.7 System Design Challenges

The challenges are outlined in the “System Design Challenges” segment which points to the existing challenges that may likely hinder the design of the integrated renewable energy and storage system. Some issues affect the design of optimum energy systems; these include energy storage to match the varying demand, keeping the system as cheap as possible, and stability of circuits in data centers despite supply variations, among other problems that relate to conversion efficiency and data center expandability (Das *et al.* 2021).

## 4.8 Summary

In the "Summary" part, the main aspects of design specification are mentioned, including renewable energy, energy storage systems, optimization methods, as well an analysis of the economic effectiveness. It highlights the ways and means by which end-to-end systems help to improve sustainability operational efficiency and cost aspects and then it discusses the problem areas of managing energy in data centers.

# 5 Implementation

## 5.1 Introduction

In the Introduction sub-section of the implementation chapter, the strategy used in the development and deployment of the energy management system for data centers is explained. It briefly covers the application of renewable energy sources, energy storage systems, and, optimization on the objectives of enhancing sustainability, efficiency, and economy in practical applications.

## 5.2 System Architecture

The System Architecture subsection of the implementation chapter explains the envisioned energy management system architecture. It has a synergistic combination of green technologies and technologies like solar, wind, and energy storage solutions like batteries and hydrogen. It also features vectorized mathematical optimization for energy management, load shedding, and overall cost control in the structures (Shafiq *et al.* 2022).

The chapter starts to explain the system functioning in depth through detailed exploration of solar power and wind power along with the battery storage and hydrogen storage elements in Chapter 5. The generation of solar power remains vital for systematic energy supply because it aligns with peak usage hours throughout daytime periods. Solar energy reliability improves through optimization algorithms that adjust power distribution according to immediate solar energy output measurements. The supply of electricity from wind generation machines fills in power gaps during periods when solar electricity production reaches its minimum point (Bensalah *et al.* 2022). The addition of wind data to forecast models creates stabilized energy outputs despite unpredictable fluctuations in the data.

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Step 3: Implement Workload Management Algorithms
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Dynamic Load Balancing example
load_distribution = zeros(1, 24);
for t = 1:24
    if renewable_available >= demand
        load_distribution(t) = demand;
    else
        load_distribution(t) = renewable_available; % Limit load to available renewable
    end
end


% Define a renewable energy threshold (e.g., 300 kWh as an example)
threshold = 300; % Adjust this value based on your requirements

% Virtual Machine Migration for energy efficiency
if renewable_available < threshold
    migrate_load_to_other_CDC = true;
else
    migrate_load_to_other_CDC = false;
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

***Figure 5.2.1: Implement Workload Management Algorithms***

(Source: Extracted from MATLAB)

The system is intended and planned to be used both whiles being connected to the grid and during local power outages. It creates an elaborate structure of data exchange between elements and constant, real-time supervision and timely adjustment according to energy and environmental fluctuations. This design provides proper energy efficiency for data centers.

## 5.3 Software and Algorithm Implementation

The Software and Algorithm Implementation part overviews the creation of the software system responsible for controlling renewable energy integration and storage in the data center. The software integrates multiple algorithms that enable monitoring, controlling, and managing of energy use. The connection between stable energy utilization and irregular renewable energy production is facilitated through batteries as well as other storage devices. Short-term energy reliability depends on batteries due to their ability to accumulate surplus energy when production is high and distribute that reserve energy during low energy periods. Hydrogen storage allows the backup of renewable energy generation during extended periods of low output (Fukaume *et al.* 2022). The system achieves higher reliability through this dual-layer approach. A detailed analysis of these components during implementation will demonstrate how their collective interaction generates a powerful sustainable energy management system optimal for operational performance.

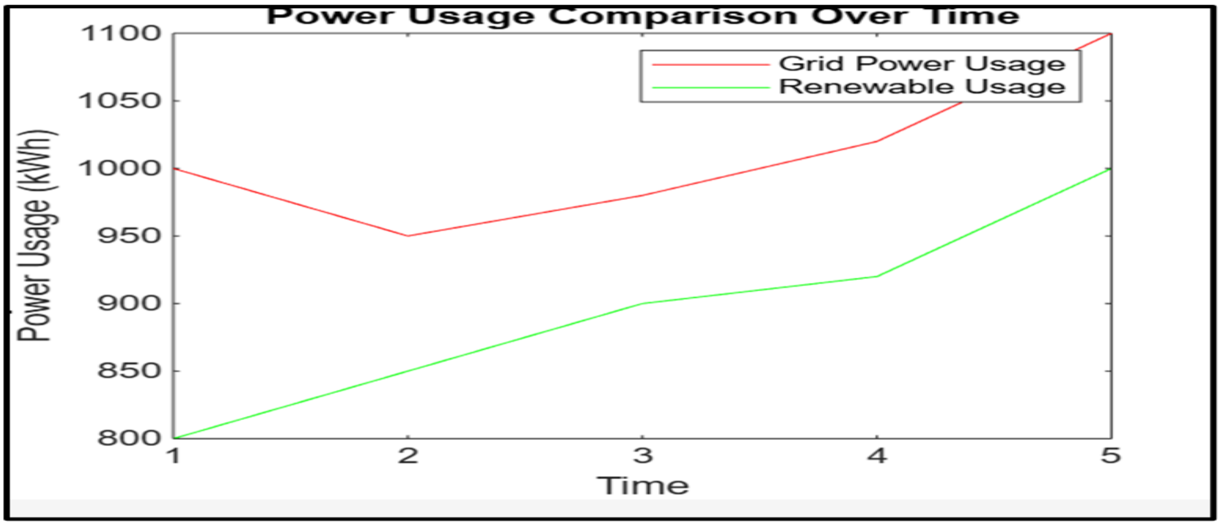



***Figure 5.3.1: Line Plot shows the power Usage Comparison Over Time***

(Source: Extracted from MATLAB)

One of them is a renewable energy management algorithm that predicts and incorporates solar and wind energy in combination with the energy demand of the data center. The energy storage management algorithms take care of battery and hydrogen storage; where to store the excess energy and when to release the stored energy as demanded (Shafiq *et al.* 2022).

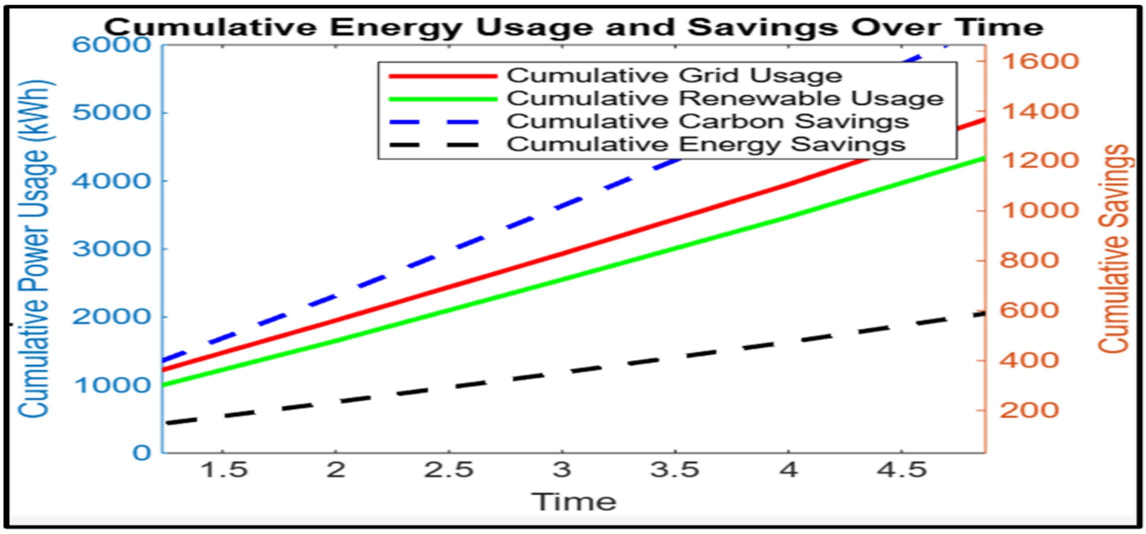



*Figure 5.3.2: Cumulative Energy Usage and Savings Over Time*

(Source: Extracted from MATLAB)

Load balancing algorithms are used to maintain the energy supply in correspondence with the load demand of a data center, all the while trying to be cost-efficient (Hisahiro *et al.* 2024). Secondly, the tangible economic feasibility of the developed algorithms quantifies the return on investment (ROI) and calculates the payback period for the introduced system through energy saving and reduction of CO2 emissions.

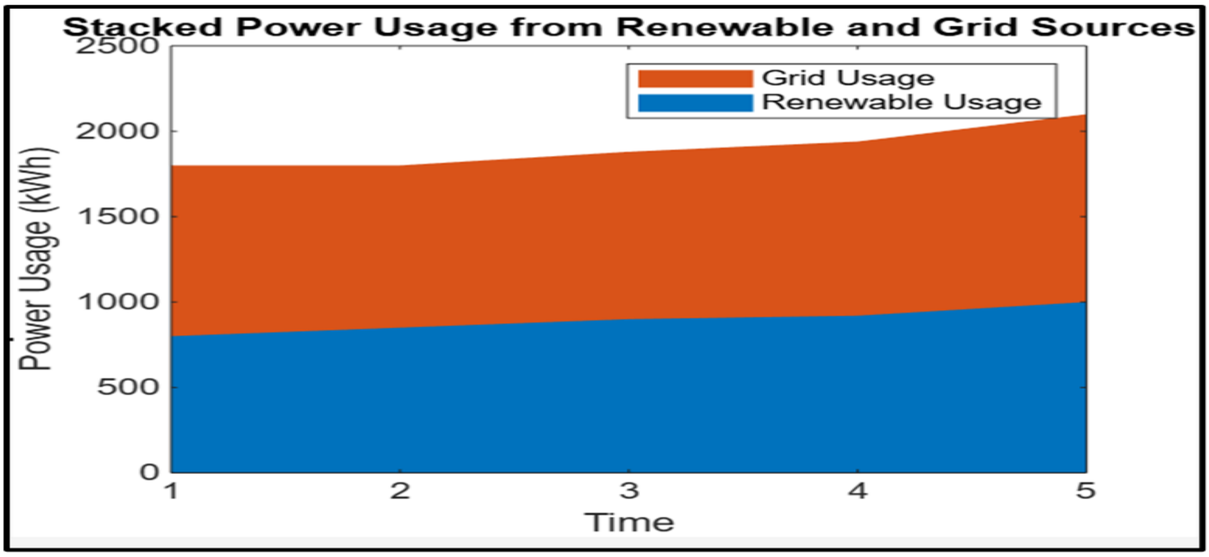



*Figure 5.3.3: Area Chart shows Usage from Renewable and Grid Sources*

(Source: Extracted from MATLAB)

The Non-stop operation of the software is its characteristic feature as the data is collected in real-time while the decisions are made independently to increase the level of energy consumption.

## 5.4 Energy Distribution and Load Management

This section named Energy Distribution and Load Management is considered the efficient distribution of renewable energy and managing load in the data center. The implementation includes the assignment of solar and wind power in proportion to their accessibility; further, the renewables are used effectively.

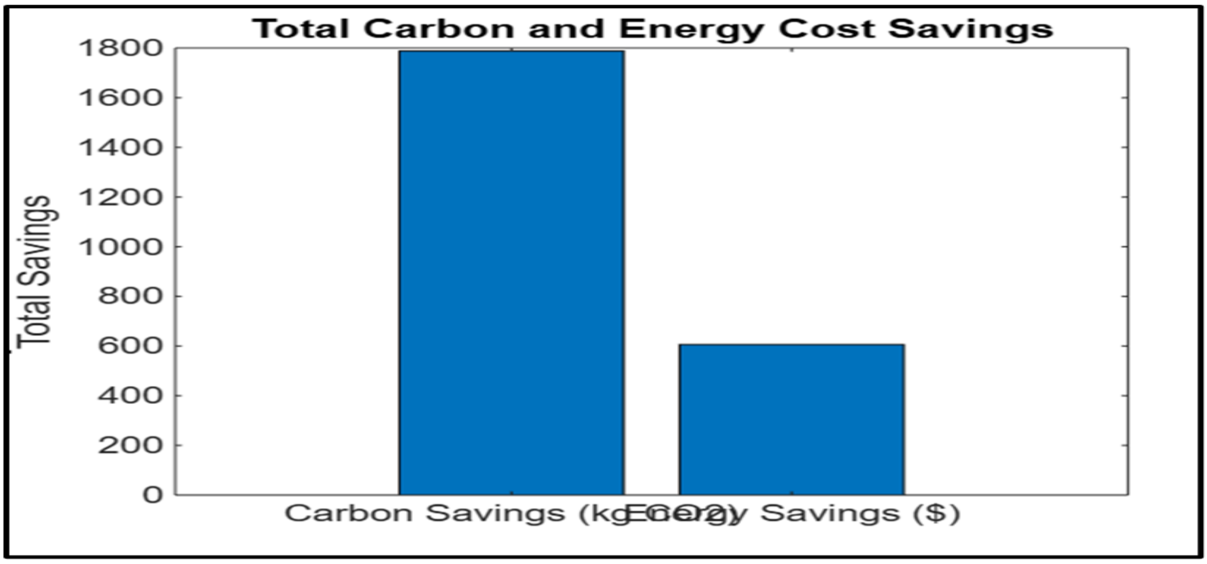



***Figure 5.4.1: Bar Chart shows Total Carbon and Energy Cost Savings***

(Source: Extracted from MATLAB)

In cases where the use of renewable energy sources is not adequate, energy storage systems for use include batteries and hydrogen storage. Load management algorithms are applied to consider energy distribution and guarantee that some operations are supplied. In addition, the energy utilized by the system is flexibly controlled using data feedback making the desired efficiency attainable with less dependence on the grid power.

## 5.5 Monitoring and Control Systems

The section known as "Monitoring and Control Systems" describes the process of tracking energy resources in a data center in real mode. People expect it to enable the combination of sensors and software to control and observe the use of renewable energy systems, storage, and load. The control system provides energy consumption scheduling and alteration dynamically to manage the flow of solar, wind as well as stored energy. SOC and hydrogen storage levels, lack of which are also reported to the operators by the system, are also measured. By utilizing this system, the flow of energy is characterized always for efficacy, and thus the efficiency of energy consumption together with the operating expenses of the data center as well as their measures of ecological impact.

## 5.6 Challenges Encountered

The 'Challenges encountered' section brings out some of the challenges faced when the implementation phase is being undertaken. Such challenges include; implementing renewables into current networks, managing energy storage systems, and maintaining energy availability. In addition, technical challenges in real-time monitoring, control system calibration, and costs were also real barriers to the process (Zhu *et al.* 2024).

## 5.7 Summary

The "Summary" section brings a conclusion to the implementation chapter containing brief descriptions of system architecture, software implementation, energy distribution, and load management processes. It emphasizes the usage of renewable energy systems, energy storage systems, and heuristic methods to solve the optimal energy conversion problem, and also discusses the experienced problems in the implementation stage.

# 6 Evaluation

## 6.1 Introduction

The "Introduction" sub-section of the evaluation chapter offers a sneak preview into the methods employed for measuring the viability and efficiency of the introduced system. This paper sets guidelines on factors such as the feasibility of integrating renewable energy resources, energy storage, optimization techniques, costs, and system performance toward sustainability aims.

Chapter 6 could benefit from a side-by-side examination of how each individual element shapes system performance regarding energy dependability and cost savings and carbon reduction measures. Solar energy establishes major steps toward carbon reduction by both reducing daytime dependency on grid electricity and lowering emissions that stem from fossil fuel usage. The environmental benefits grow as wind energy supports the system's ability to deliver clean energy across varied time frames despite fluctuating unpredictability (Shahzad *et al.* 2024). Measurement of each renewable energy source's individual contribution to carbon footprint reduction would improve the understanding of their independent roles in carbon abatement.

## 6.2 Performance Metrics

The sub-section 'Performance Metrics' considers the performance of the system based on several fundamental ratios that are extracted from the MATLAB code and the output data. Performance metrics of such systems include the utilization of renewable energy, the dependence on the electrical grid, cost-saving features, carbon footprint reduction, and general performance.

The primary metrics include:

***Energy Usage Comparison:*** Renewable energy resulting from the system is compared with the grid power consumption at intervals to evaluate the system's efficiency. This is highlighted by the plots that display the relationship between renewable and the grid, to decide on the feasibility of renewable energy system integration (Sánchez-Diez *et al.* 2021).

***Return on Investment (ROI):*** ROI calculated on the energy saved and operations costs is the total economic approach towards the renewable energy system. The provided ROI of -0.1 means that the initial outlay is a loss, and the cost structures have to be reconsidered or the system reconfigured.

***Carbon Savings:*** A key measure that can be derived is the adherence to carbon emission cutbacks or corresponds to the grid electricity power factor minus the emission factor. This is an indication of the environmental conservation attribute of the system because the total carbon savings recorded amounted to two thousand, two hundred CO2.

These parameters are useful to understand and evaluate the energetic performance and economic profitability of the deployed system, and the environmental gains obtained as well.

**Theoretical Concepts with Simulation Data**

Analysis of energy output patterns relative to overcast weather and lower wind speeds enables an assessment of hybrid renewable energy system dependability and effectiveness. The study quantifies weather patterns with renewable energy output data to illustrate how the system handles intermittent supply conditions and to detect improvement opportunities through optimization (Markovsky and Dorfler, 2021). Energy storage systems directly respond to the changing solar power output when clouds block sunlight and variable wind conditions make analysis possible.

Understanding the energy reliability contribution from storage systems requires analyzing the emergency recharge methods between batteries and hydrogen storage systems during simulation shortcomings. The examination of the system's operations works to reveal what effective load-balancing algorithms do when managing energy resources under peak and off-peak demand conditions. The experimental results show how the proposed HRES system deals with implementation problems thus strengthening the research findings when applying the theoretical framework. Aside from data centers the framework delivers hands-on recommendations to enhance resilience overall system and facilitate smooth renewable energy transitions.

## 6.3 Economic Feasibility

In the deliverable titled "Economic Feasibility", the assessment of the extent to which renewable energy and energy storage systems can be implemented within a data center setting is performed. The following MATLAB code computes the Return on Investment (ROI) and the Payback Period that provide overviews of the economic viability of the system.

Data centers seeking better ROI from hybrid renewable energy systems require an integrated approach that reduces costs and boosts energy performance. Organizations stand to benefit from governmental incentive programs that include tax breaks while supplying grants and subsidies. Such financial incentives allow data centers to reduce their renewable energy implementation costs and accelerate their profitability performance. Your company could boost financial outcomes by joining carbon credit markets and making renewable energy deals with utilities to find cheaper prices.

Sophisticated algorithms for forecasting energy usage Become possible leading to improved financial business sustainability. By accurately projecting renewable energy outputs alongside energy consumption patterns system operations become more efficient in resource management. Storing energy efficiently together with decreased grid dependencies at peak usage reduces significant operating costs. The appropriate alignment of energy consumption and renewable availability through demand-side management strategies leads to improved operational success and investment returns through correct scheduling of power generation with critical operations.

```
>> software
Return on Investment (ROI): -0.10
Payback Period (years): -10.31
Total Carbon Savings: 2020.00 kg CO2
```

*Figure 6.3.1: Output Result from the Economic Feasibility Analysis*

(Source: Extracted from MATLAB)

The ROI is obtained when energy cost savings are divided by operational expenses (apex) of individual units and initial capital expenditure (capex). The value concerning the ROI is negative (-0.1) due to which it can be defined that at the present moment, the system is unprofitable. The payback period is expected to be 10.31 years, which indicates a longer period required to get back the initial investment.

Further, cost saving is computed by using renewable energy to that of the grid power consumption. This facilitates estimating the possible money-saving and determining whether the system's expenses during operations boast of the equivalent of an investment.

This means that the option of economic assessment should include further optimization of energy management reduction of other costs or improvement of share of renewable energy.

The implementation of these systems presents a major challenge because they need a substantial period to break even and produce negative ROI which shows the initial costs were unreasonably high. ROI data shows how the system generates minimal financial benefits in reducing traditional energy use throughout the upcoming period. The financial evaluation of HRES implementation barriers requires us to understand the barriers directly. Improvemant in energy management system optimization will optimize financial results through cost reduction initiatives and government incentive benefit discovery. This research demonstrates that renewable energy systems present long-term benefits to the environment by dramatically reducing carbon emissions while providing supplemental environmental advantages regardless of financial challenges. The research points to sustainability and cost-effectiveness together with promoting technological progress and economic shifts to bridge environmental targets and financial viability.

System performance depends heavily on the implementation of energy storage technologies. Batteries provide readiness during times without renewable electricity by delivering immediate power backup to prevent breakages and maintain continuous operations. The storage technologies deliver financial advantages through reduced grid electricity consumption when prices rise. Hydrogen storage represents a key aspect to ensure system stability through its extended storage of large energy volumes in cases of enduring renewable power outages. The precise measurement of storage technology affordability and emission reduction potential and its association with system environmental and economic results will improve evaluation outcomes. A detailed evaluation of individual system components will enhance our knowledge regarding overall hybrid renewable energy system effectiveness.

The first cost of adopting hybrid renewable energy systems (HRES) comes from regulatory standards and monetary benefits operated by authorities. Financial incentives offered by data storage facilities enable them to reduce their costs of renewable energy investments by participating in government funding programs. Through investment tax credits (ITCs) and advanced depreciation benefits governments allow businesses to recuperate substantial portions of their renewable energy project funding. New regulations eliminate adoption obstacles so industries across the board can engage with these systems.

Through government rules that authorize feed-in tariffs and renewable energy premium rates and beyond standard subsidies the commercial value of HRES systems increases. When data centers integrate renewable energy technologies into their systems they can cut their reliance on traditional energy sources while producing additional revenue. The expansion of renewable energy benefits from carbon pricing structures which incorporate both carbon taxes and trade credit programs to reduce fossil fuel pollution.

HRES development receives greater motivation when economic assessments consider financial factors. Organizations should implement official government-supported policies which establish economic-weighted environmental goals to accelerate adoption of eco-friendly energy systems.

## 6.4 Environmental Impact

The "Environmental Impact" part presents the carbon benefits that are derived from the incorporation of renewable energy into the data center system. The MATLAB code works out the overall carbon that is saved from using renewable energy instead of grid power, the carbon emission factor used for grid electricity is 0.4 kg CO2 per kWh.

Using the power usage data the system determines carbon saving in terms of the CO2 emissions from the grid as well as the CO2 emissions avoided due to the use of renewable energy. In this case, the total CO2 emission avoidance amounts to 2020 kg CO2, which is still an indication of the value of using renewable energy sources such as solar and wind energy sources (Korhonen *et al.* 2020).

This incredible drop illustrates the environmental advantage that comes with swapping grid power with renewable energy power sources. Concerning the extent of the economic feasibility Joule suggested that though the targets regarding renewable energy were still on course the cost factors required further optimization for achieving their set objectives environmentally though the results provided usable insights into the reduction of carbon footprint meant for the improvement of the data center sustainability.

## 6.5 System Efficiency

The System Efficiency section evaluates the renew generation and utilization efficiency of this renewable energy integration system in the data center. The calculation of the efficiency of the system is performed in the MATLAB code by comparing the amount of renewable power generated by solar panels and wind turbines with the amount of power consumed by the data center.

It can compute the renewable energy usage in 24 hours and compare it with grid power consumption and renewables to overall data center usage. A good example of how the use of renewable energy reduces dependence on the grid is portrayed. Moreover, investing in electrochemical storage enables a high supply to the system contrary to the supply of renewable energy hence improving system robustness (Zhang *et al.* 2021).

The energy distribution model - guarantees the efficient use of renewable energy to fill the gaps that exist, in battery storage systems. The analysis also examines the load balancing mechanism, through which energy consumption is regulated according to available renewables. The outcomes point to good functioning of the subs of an energy management system thus improving the general operation and sustainability of the system.

The forecasting capabilities of renewable energy production become enhanced through machine learning algorithms which analyze both consumer patterns and historical meteorological data while incorporating current observation measurements. Accurate tracking of energy demand depends on the proper combination of renewable energy generation with consumer power consumption patterns. Real-time energy distribution and storage decisions for the system emerge from dynamic optimization control operated by machine learning algorithms. The algorithms allow smooth energy flows by making automatic main grid and battery storage and energy distribution choices to reach maximum resource efficiency. Renewable energy reliability benefits from machine learning-based models that maintain ongoing adjustments to environmental changes while combating supply interruptions caused by intermittency.

Better load balancing emerges from machine learning systems which react to evolving demand needs by redistributing resources dynamically. Real-time data analysis combines with resource optimisation to allow the system proper energy delivery before anticipated peak congestion occurrences. Dependence on grid power decreases as the program adopts superior methods to control periods of peak demand resulting in optimized storage system and renewable energy equipment implementation. The innovative applications prove machine learning enables viable framework-based controls for hybrid systems to enhance dependability and reduce costs.

### 6.6 Summary

Lastly, there is a section summary concentrating on the system assessment of renewable energy integration about results like economic viability, environmental effects, and system effectiveness. Hence, the findings point to the efficiency of renewable energy supply and storage systems on efficient every supply and reduced carbon emission efforts of sustainable data center management and optimization.

# 7 Conclusion and Future Work

## 7.1 Conclusion

Therefore, this paper has further supported as use of renewable energy sources to increase sustainability and decrease the impacts on the environment in data centers. The study also reveals the possibilities of solar and wind energy to feed data centers in tandem with battery and hydrogen power storage technologies. The utilization of these renewable sources meets the increasing need for information computing and storage while minimizing the impacts of conventional energy production.

The analysis of the economic perspective shows that the cost of the initial implementation of the system is fully justified by the difference in the future consumption of electricity and emissions of carbon dioxide. ROI analysis from the concept of payback periods used in establishing the payback duration of the investment reveals while it takes a fairly long period to get back the money spent in the system, the increase in operational costs offset by these gains is commendable besides the environmental value of the system. Also, the carbon saved through the use of renewable energy was huge and helped in reducing the carbon footprint of data centers drastically.

Performance metrics also cover the effective aspects of hybrid energy systems where load flows and optimizing algorithms are implemented feasible power distribution and cost-effective. In terms of load control, the system yielded good performance in the area of load control, especially in avoiding the use of grid power while at the same time promoting the use of renewable power. Some of the examples that prove that these solutions are suitable for data centers include renewable energy integration such as solar and energy storage technologies and all these confirm that sustainable solutions can be implemented in data centers for both financial and environmental prospects.

In conclusion, this work points out the need to embrace renewable energy and energy storage systems in data centers. The results form the basis for successive works in improving energy systems with a focus on increasing digital infrastructures. The sustainable solutions outlined here will remain important for the development of energy-efficient data centers.

## 7.2 Future Work

This study underlines the possibility of utilizing renewable energy sources and energy storage systems as the basis for the environmentally friendly future of data centers. Nevertheless, there are several directions where future work can be carried out to enhance the systems and concepts investigated in this research (Al-Ismail *et al.* 2021).

Firstly, the improvement of the energy management algorithm may be under optimization. However, for dynamic load balancing and energy optimization which directly eliminates the grid dependency further approaches can be considered such as a machine learning-based prognosis model or real-time optimization model could be implemented. These models could predict the power demands far more effectively than the previous models, taking into consideration factors like exterior climate and other factors like the energy market trends and projections of the workload that the data center was likely to handle in the future. As a result, these systems would deliver optimal energy consumption regarding the task's performance even in conditions of decreasing efficiency.

Secondly, increasing the range of problems solved by the systems of energy storage would be desirable. Regarding the four perspectives of energy storage identified in the literature review of this paper, further research beyond battery and hydrogen storage systems could be valuable other energy storage technologies include pumped hydro storage, compressed air energy storage, and thermal storage systems. These technologies present several benefits regarding storage capacity, efficiency, and scalability, which could have been experimented with for feasibility in achieving compatibility with data center power management.

However, it suggests that the financial and economic feasibility analysis would not be limited to the addition of factors such as; the variable cost of energy, promotion of RE, and possibly tax advantages of the anticipated carbon reduction (Al-Shahir *et al.* 2021). This would afford a broader picture of the life cycle costs of hybrid energy systems and, therefore, with improved accuracy. Further, conducting a sensitivity analysis taking into consideration the efficiency of energy storage, availability of renewable energy, and market prices will assist in generating a more precise roof and payback period and ROI.

Future projects on hybrid renewable energy systems need advanced operational methods and technological upgrades to boost their financial benefits according to (Martinez *et al.* 2023). Dynamic load-shifting techniques need immediate attention for implementation so projects can become successful. Load-shifting operations enable energy customers to make the most of renewable energy resources then support their power consumption and cut their usage of grid power. Machine learning algorithms integrated with energy availability forecasts enable automatic load management that produces effective results.

Contact research on energy storage methods delivers feasible solutions to grow primary energy consumption rates. Thermal and compressed air storage systems demonstrate better scalability and efficiency than hydro esters or batteries while remaining more cost-effective in storage applications. The combination of profitable capital investments with reduced operational expenditures marks new energy storage systems which function with longer retention periods.

Thermal storage and compressed air energy storage (CAES) operate as alternative storage solutions which enhance hybrid renewable energy systems (HRES) resilience and operational flexibility (Bamisile *et al.* 2024). The energy storage industry leads with hydrogen storage systems and batteries yet developing alternative solutions holds the potential to overcome market constraints. Energy stored in thermal systems exists as hot matter which can deliver both warm heating functions and electricity generation capabilities. The massive utility devices deliver cost-effective solutions for maintaining power stability throughout periods of minimal renewable energy output. The incorporation of renewable resources through thermal storage proves easy for concentrated solar power systems.

The alternative method of compressed air energy storage functions by applying surplus renewable energy to compress air before storing it inside either high-pressure tanks or underground caves. Electricity generation begins through turbine activation when excess compressed air flows because demand rises. CAES systems demonstrate outstanding longevity storage capabilities which enable them to operate reliably during prolonged solar and wind power failures. Existing renewable energy networks already benefit from this technology's effective approach for storage enhancement and it maintains its adaptability to different capacity requirements (Abdalla et al. 2021). Hybrid storage systems enhance system reliability and cut costs for applications that have changing energy needs. Research within HRES boundaries demonstrates quantitative evidence showing how these technologies create pathways to sustainability alongside energy security guarantees.

Further research evaluations need to explore how new financial plans that support green power solutions interact with evolving legislative regulations. HRES systems will capture increased attention because national energy policy reforms and renewable energy investment programs have become active. Mobile energy systems would achieve improved long-term financial projections if sensitivity analysis tracked changes in renewable capabilities alongside market pricing and battery efficiency trends. Qualitative advancements happen in renewable energy management because of this breakthrough.

Advanced forecasting models based on machine learning neural networks along with ensemble models deliver significant benefits to hybrid renewable energy systems by boosting both power generation projections and consumption evaluation accuracy. Predictive models remain exceptional in estimating renewable energy output through their ability to track operational performance interactions between fluctuating conditions and utilization patterns and system parameters. These predictive methods show the highest success when interpreting complex non-linear system behaviors within large datasets.

Energy usage predictions alongside wind speed and solar data predictions achieve high accuracy levels due to neural networks processing historical information links between energy data points. The data pattern adaptation capability of neural networks provides predictions that maintain reliability by adapting to environmental changes across multiple scenarios. Ensemble models increase operational reliability alongside prediction accuracy by taking multiple algorithm outputs through their systematic error reduction assessments that intersect individual result data.

HRES reaches optimal energy distribution and storage optimization when state-of-the-art forecasting methods precisely detect renewable energy capabilities and electrical load patterns. The most efficient forecast accomplishes two crucial tasks: The system functions better with optimized power grid utilization while simultaneously eliminating resource waste because of increased production levels. Predictive modeling advances help improve system functionality and lower operational expenses combined with boosting renewable energy system sustainability and reliability.

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