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Hybrid Energy Storage Systems for Renewable Integration: Combining Batteries, Supercapacitors, and Flywheels

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Abstract: Renewable-energy integration into power grids is constrained by the variable output of solar and wind resources. This paper proposes a Hybrid Energy Storage System (HESS) that couples lithium-ion, batteries, supercapacitors, and flywheels and governs them with a Unified Mathematical Method (UMM) combining moving-average filtering with threshold-based cut-off logic. The architecture is modelled in HOMER Pro for the Grand Forks, ND (USA) resource profile and bench-marked against "Grid+Renewables" and "Grid+Renewables+Battery" baselines. The full three-storage configuration supplies 1 032 320 kWh yr^{-1} of useful energy—an increase of 77 % over the no-storage case—and eliminates 1.36 Mt CO_2 yr^{-1} of emissions, a245 % improvement relative to renewables alone. Valued at the Social Cost of Carbon (US\$51 t^{-1}) and the 45Q tax credit(US\$85 t^{-1}), the avoided emissions translate to annual economic benefits of US\$69 000–US\$116 000. The UMM reduces false cut-off events by more than 30 %, prolonging component life and enhancing overall system reliability. These results confirm that a tri-technology HESS managed by a unified control layer delivers superior technical performance, environmental gains, and financial returns compared with single-storage or no-storage configurations.

Keywords: Hybrid energy storage system, lithium-ion battery, supercapacitor, flywheel, renewable energy integration, energy-management system, HOMER Pro.

I. Introduction

The global energy landscape is undergoing a significant transformation, driven by the increasing demand for renewable energy sources, technological advancements, and geopolitical shifts. Hybrid energy storage systems (HESS) are playing a crucial role in this transition by addressing the intermittency of renewable energy sources and enhancing grid stability. A key framework guiding this transition is the Paris Agreement, adopted in 2015, which aims to limit global warming to well below 2°C and pursue efforts to limit it to 1.5°C above pre-industrial levels by the end of the century (Paris Agreement, 2015; BBC, 2024; Consilium, 2025). The Paris Agreement emphasizes reducing greenhouse gas emissions to achieve net-zero levels between 2050 and 2100 and encourages countries to submit nationally determined contributions (NDCs) to reduce emissions (Paris Agreement, 2015). Renewables such as solar, wind and hydropower are expected to meet about 95% of the electricity demand growth between now and 2030, with solar PV alone accounting for roughly half of this growth (IEA, 2025). In 2025, renewables are forecast to provide more than one-third of total electricity generation globally, overtaking coal (IEA, 2025). HESS are essential for integrating renewable energy into the grid by providing both high energy and high power capabilities, helping mitigate the intermittency of solar and wind power and ensuring a stable energy supply (Arsad et al., 2022). The integration of HESS with renewable energy systems is thus vital for sustainable development and reduction of carbon footprint (Zuo et al., 2020; Arsad et al., 2022). To optimize the performance of HESS, this study proposes a hierarchical control strategy and a unified mathematical method (UMM) that integrates lithium-ion batteries, supercapacitors, and flywheels. Each technology is selected for its unique characteristics: lithium-ion batteries for long-term, steady energy supply; supercapacitors for rapid response to short-term fluctuations; and flywheels for frequency regulation and immediate power backup (Wang et al., 2020; Liu et al., 2019; Zhang et al., 2020; Amiryar & Pullen, 2017). A core innovation of this research is the introduction of the Unified Mathematical Method (UMM), which applies a consistent mathematical structure across all operational parameters to ensure robust and reliable system operation. The UMM employs moving average filtering and threshold-based cutoff logic, reducing false positives and enhancing reliability (Chen et al., 2020; Smith & Kumar, 2021; Maroufi et al., 2025). The moving average for any monitored parameter X (like Voltage, Temperature, or SOC) is calculated as:

$$\bar{X}(t) = \frac{1}{w}\sum_{k=0}^{w-1} X(t-k) \qquad (1)$$

$\bar{X}(t)$ – moving average of parameter *X* at time *t*.

w – window width for smoothing the parameter data. The cutoff condition based on the moving average is expressed as

$$\text{If } (\bar{X}(t) < X_{\min} \text{ or } \bar{X}(t) > X_{\max}) = \Delta\text{SOC(t)=0} \qquad (2)$$

Where $x_{\min}$ and $x_{\max}$ are the defined minimum and maximum operational thresholds.

Unified System Cut-off Logic

To ensure overall system stability, the unified cut-off decision can be represented as

$$\text{System Cutoff}(t) = \cup_{X\in\{V,T,SOC\}} [\bar{X}(t) < X_{min} \text{ or } \bar{X}(t) > X_{max}] \qquad (3)$$

The primary objective of this research is to design and validate novel HESS architectures and control algorithms that maximize energy efficiency, system performance, and reliability for renewable integration. The study leverages simulation tools such as HOMER Pro to evaluate power flow, grid interaction, and environmental benefits, including emissions reduction. This comprehensive approach addresses critical gaps in the literature, particularly regarding the unified control and optimization of multi-component HESS under various operational scenarios (Maroufi et al., 2025; Atawi et al., 2022). Ultimately, this research aims to advance the design, control, and optimization of hybrid energy storage for seamless renewable integration, supporting the global transition toward sustainable, resilient energy systems (International Energy Agency, 2023)

II. Literature Review

Hybrid Energy Storage Systems (HESS) have rapidly emerged as a key solution for integrating renewable energy sources into modern power grids, addressing the challenges of intermittency, grid stability, and operational flexibility. This review synthesizes recent research, with a focus on system architectures, component technologies, control strategies, and the critical gaps that motivate this study.

Overview of Hybrid Energy Storage Systems

HESS combines multiple storage technologies; in this study, lithium-ion batteries, supercapacitors, and flywheels are leveraged for their complementary strengths (Adeyinka et al., 2024; Naderipour et el., 2022). Lithium-ion batteries provide high energy density and long-term storage, supercapacitors deliver rapid charge/discharge for short-term fluctuations, and flywheels offer high power output and frequency regulation capabilities. This synergy enables HESS to outperform single-technology systems in energy/power density, efficiency, lifespan, and reliability (Adeyinka et al., 2024; Bade et al., 2024, Makupe & Moses, 2023). Recent studies highlight significant progress in HESS optimization and control:

System Optimization: Jinjun et al. (2024) demonstrated that advanced algorithms, such as the marine predator algorithm, can optimize HESS capacity for wind-photovoltaic systems, reducing undercompensation by 33.42% and improving operational efficiency.

Component Sizing: Agajie et al. (2023) performed techno-economic analysis and optimal sizing for both on-grid and off-grid HESS, emphasizing meta-heuristic algorithms for cost-effective performance. Control Strategies: Maroufi et al. (2025) introduced a Moving Average and Fuzzy Logic-based power management system, which dynamically adjusts energy demand, improves control accuracy, and extends component lifespan.

Component Technologies

Lithium-Ion Batteries are widely used for their high energy density, long cycle life, and efficiency. Chemistries such as LiFePO4 and NMC are common, and batteries are essential for sustained energy delivery during periods of low renewable generation (Ghafari, 2022; Liu et al., 2022, kittner,2023).

Supercapacitors are characterized by high power density and rapid cycling, supercapacitors are ideal for smoothing short-term fluctuations and supporting peak shaving, though their energy density is lower than that of batteries (Mahajan et al., 2024; Lim et al., 2023).

Flywheel Energy Storage Systems (FESS) store energy mechanically and are valued for rapid response, high power output, and frequency regulation. Recent advancements include high-speed rotors, magnetic bearings, and composite materials, which improve efficiency and reduce maintenance (Li et al., 2022; Khaligh & Li, 2010).

Energy Management and Control

A robust Energy Management System (EMS) is critical for HESS performance. Modern EMS platforms use real-time monitoring, predictive analytics, and automation to optimize energy flows, manage state of-charge (SOC), and coordinate multiple storage devices and renewable sources. The integration of Automatic Transfer Switches (ATS) and network switches enhances real-time adaptability and communication, supporting seamless transitions and system reliability (Adeyinka et al., 2024; Atawi et al., 2022).

Comparative Analysis of Storage Technologies

The hybrid combination of batteries, flywheels, and supercapacitors maximizes system flexibility and performance, optimizing energy management across various timescales and enhancing overall system reliability and efficiency. Lithium-ion batteries store excess energy for long-term use, flywheels provide rapid response and frequency regulation, and supercapacitors smooth out short-term fluctuations and support peak shaving (Khodaparastan & Mohamed, 2019).

Economic Evaluation of Battery, Supercapacitor, and Flywheel

Hybrid Energy Storage Systems (HESS) use lithium-ion batteries, flywheels, and supercapacitors to tackle renewable integration challenges. Understanding each storage technology’s capital and operational expenditures is crucial for optimal system design, performance, and cost management.

Economic evaluation is central to the optimal design and deployment of Hybrid Energy Storage Systems (HESS), as it determines both feasibility and long-term value. The U.S. National Renewable Energy Laboratory (Cole&Karmakar, 2023) predicts utility-scale lithium-ion battery system costs for a 4-hour duration at $245-$403/kWh by 2030, with further reductions to $159-$348/kWh

Characteristic	Battery	Flywheel	Supercapacitor
Energy Density	100-250 WH/kg	5-1000 WH/kg	5-15 WH/kg
Power Density	500-2000 W/kg	180-1800 W/kg	10,000 W/kg
Response Time	Instant (seconds)	Instant (millisecond)	Instant (millisecond)
Round-trip Efficiency	High (80-90%)	High (85-95%)	High (85-98%)
Cycle Life	Moderate (5-10 yrs,1000-5000 cycles)	Long (10M+ with minimal maint.)	Long (1M+ cycles)
Environmental Impact	Moderate (depends on chemistry)	Low (minimal)	Low (minimal)
Scalability	High (scalable)	Moderate (scalable)	Moderate (scalable)
Applications	Versatile (grid stabilization, peak shaving)	Short-term grid stabilization	Short-duration energy storage

Figure 2.1: Comparison of Energy Storage Technologies: Lithium-ion Battery, Flywheel, and Supercapacitor.

by 2050. Their operational expenditures are low, and they provide high efficiency and moderate cycle life. Flywheels, with capital costs ranging from $600–$2,400/kW, offer very low OPEX ($15/kW) and exceptional longevity, making them highly suitable for high-power, short-duration applications, especially frequency regulation (Mongird et al., 2019; Areola et al., 2025). Supercapacitors, while currently expensive ($19,200–$34,624/kWh), excel in ultra-fast response roles and benefit from minimal maintenance costs, although their low energy density limits broader use. (U.S. DOE, 2023).

Overall, lithium-ion batteries are most cost-effective for long-term applications, flywheels are ideal for short, high-power needs, and supercapacitors are best for rapid-response scenarios. Integrating these technologies in HESS enhances system flexibility and efficiency, allowing for cost-sharing of power electronics and reducing both upfront and lifecycle costs. This hybrid approach not only optimizes technical performance but also improves economic viability for renewable integration.

Gaps Identified in the Literature

Despite significant progress, several gaps persist.

Unified Control Algorithms: Most research focuses on individual storage technologies or lacks a cohesive, unified control strategy for multi-component HESS. There is a need for mathematical frameworks that can manage all types of storage in diverse operational scenarios (Maroufi et al., 2025; Smith & Kumar, 2021).

Real-Time Adaptability: Many systems lack real-time communication and coordination, which are essential for dynamic grid environments. The integration of ATS and network switches is highlighted as a solution (Guven et al., 2024; Agajie et al., 2023).

Validation: Although simulation tools like HOMER Pro are widely used, practical real-world validation of theoretical models is limited. More field demonstrations are needed to confirm the robustness and scalability of proposed solutions (Agajie et al., 2023).

III. Methodology

This study employs a rigorous, multi-layered methodology to design, model, and validate a Hybrid Energy Storage System (HESS) for renewable energy integration, combining lithium-ion batteries, supercapacitors, and flywheels. The approach integrates theoretical modeling, unified control algorithms, and simulation-based validation using HOMER Pro Software to address operational, technical, and environmental objectives.

Table 2.1: Summary of selected literature on hybrid energy storage systems

Author(s)	**Focus of Study**	**Key Findings**	**Gaps Identified**
Adeyinka et al. (2024)	Overview of HESS and its role in renewable-energy integration.	Highlighted the complementary strengths of batteries, supercapacitors, and flywheels in improving energy/power density, efficiency, lifespan, and reliability.	Need for integrated control strategies to manage multiple storage systems efficiently.
Jinjun et al. (2024)	Capacity configuration of HESS incorporating flywheel and lithium battery for wind-photovoltaic integration.	Utilized the Marine Predator Algorithm and Variational Model Decomposition, achieving a **33.42%** reduction in under-compensation and improved operational efficiency.	Limited integration of real-time adaptive control mechanisms in multi-storage systems.
Rakib et al. (2024)	Challenges in integrating the intermittent nature of renewables with HESS.	Identified the superior efficiency and stability of **rotational kinetic storage (flywheels)** in HESS configurations.	Lack of advanced algorithms for dynamic energy management.
Guven et al. (2024)	Optimization of battery–super-capacitor HESS configurations for renewable integration.	Optimal set-up: a **675 kW** super-capacitor and **1000 kWh** battery bank, achieving an **80%** renewable-energy fraction while cutting costs.	Need for real-time communication and control mechanisms for optimal system management.
Rana et al. (2023)	Comparative analysis of five energy-storage systems for power grids.	HESS improves energy density, power density and dynamic responsiveness in Integrated Energy Systems (IES).	Lack of unified control strategies for multi-storage configurations.
Liu & Zamora (2024)	Real-time control in hybrid systems	Calls for robust communications and adaptive EMS	No working algorithm
Atawi et al. (2022)	Review of recent advances in HESS coupled to renewables.	Listed long lifespan, high capacity, low emissions, and high efficiency as key advantages.	Need for innovative breakthroughs in control strategies to enhance efficiency.
Agajie et al. (2023)	Techno-economic analysis and optimal sizing of hybrid renewable systems.	Stressed optimal storage sizing for both on-grid and off-grid use to keep costs down.	Lack of real-time validation methods for optimizing energy distribution.
Ansari et al. (2022)	Optimization techniques for hybrid renewables in isolated microgrids.	Found battery banks and diesel generators improve reliability.	Lack of dynamic control integration for real-time adaptive energy management.

Study Area and Data Acquisition

Figure 3.1: Proposed study location. Grand Forks Area Coordinate (47.925259, -97.087752) in North Dakota, U.S.A (Homer Pro).

The Grand Forks Area in North Dakota, U.S.A. (47.925259, -97.087752), was selected as the study site due to its favorable wind and solar resources. Meteorological data (solar irradiance, wind speed) were sourced from the National Solar Radiation Database (NSRDB) and National Wind Technology Center (NWTC), while load profiles were obtained from the NREL Open Energy Data Initiative (OEDI). Technical specifications and cost data for system components were derived from HOMER Pro's built-in datasets, U.S. DOE databases, and manufacturer datasheets.

System Architecture and Component Specification

Table 3.1: Storage Device Specifications

Storage Device	Voltage Range	Capacity	SOC Limits	Temperature Range
Battery	650V – 800V	270 kWh	0.1 – 0.8	-40°C to 65°C
Supercapacitor	2.5V – 3.0V	265 kWh	0.2 – 0.95	-40°C to 65°C
Flywheel	400V – 600V	265 kWh	0.15 – 0.9	-40°C to 65°C

The system incorporates an Energy Management System (EMS), Automatic Transfer Switch (ATS), network switch, and power converter to coordinate real-time operation and seamless source switching.

Implementation of Unified Mathematical Method (UMM)

The methodology implements the Unified Mathematical Method (UMM) established in the literature review, which applies moving average filtering and threshold-based cut-off logic for robust control of all storage devices. The UMM framework, including the moving average calculations, cut-off conditions, and system-wide cut-off logic previously defined, is operationalized through the EMS to ensure consistent parameter monitoring and protective actions across all storage technologies.

Scenario-Based Algorithm Development

Five distinct operational scenarios are developed and tested:

Scenario 1 (Normal Operation): Dynamic selection of optimal storage devices based on real-time demand and renewable output.

Scenario 2 (Renewable Source Absence): Priority-based energy management focusing on stored energy utilization.

Scenario 3 (Battery Failure): System adaptation using supercapacitors and flywheels. Scenario 4 (Supercapacitor Failure): Compensation through enhanced battery and flywheel coordination.

Scenario 5 (Flywheel Failure): Redistribution between batteries and supercapacitors. Each scenario implements the charging/discharging equations and SOC update protocols established in the literature review, ensuring consistent mathematical treatment across all operational conditions.

HOMER Pro Simulation Framework

The system is modelled and validated using HOMER Pro software, enabling integrated analysis of technical, operational, and environmental factors. Three comparative scenarios are simulated: Scenario A: Grid + Renewables only (no storage) The first scenario represents a hybrid energy setting where utility-provided electricity (Grid) is supplemented by renewable energy sources without any storage integration. This scenario aims to assess the performance of renewables without the support of energy storage systems.

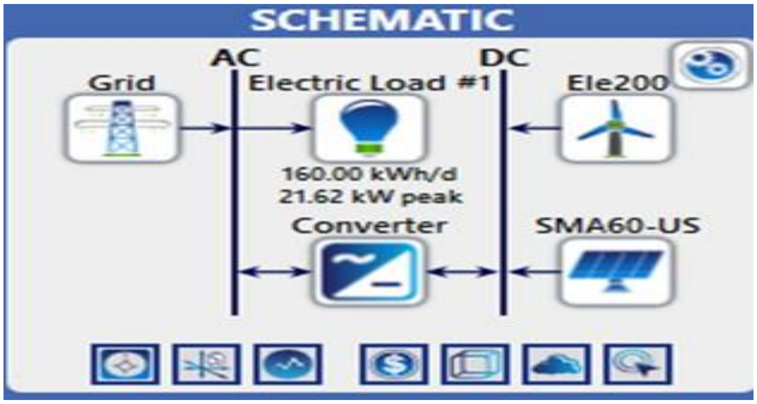


Figure 3.2: Schematic Model of Hybrid systems in Homer Pro without storage.

Scenario B: Grid + Renewables + Single Storage Component The second scenario represents a hybrid energy system where utility-provided electricity (Grid) is supplemented by renewable sources and a single type of energy storage. The purpose is to assess the impact of adding one energy storage type on system performance.

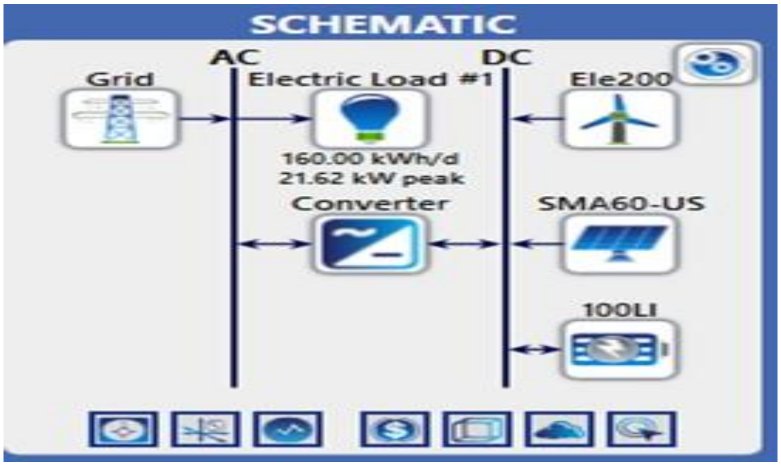


Figure 3.3: Schematic Model of Hybrid Systems in Homer Pro using one storage.

Scenario C: Hybrid Energy Storage System (Grid + Renewables + Three Storage) The third scenario represents a comprehensive hybrid energy system where utility-provided electricity (Grid) is supplemented by renewable sources and three available energy storage types. This setup tests the impact of integrating three storage technologies on system performance.

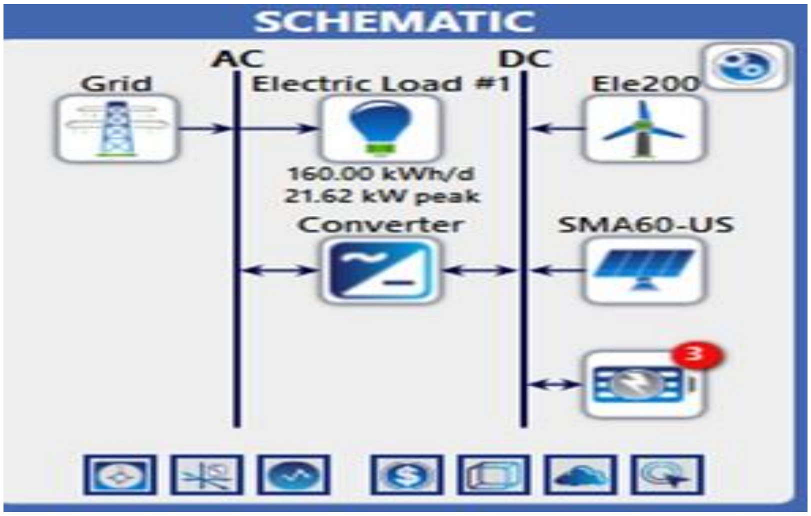


Figure 3.4: Schematic Model of Hybrid Systems in Homer Pro using three storages.

Each scenario incorporates a 160kW load profile with 4-hour storage capacity (800 kWh total), utilizing realistic component specifications and operational constraints derived from manufacturer data and industry standards.

Table 3.2: Parameters for All Three Simulation Scenarios

Parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**
Grid Capacity	300 kW	300 kW	300 kW
PV(200 kW), Wind(200 kW)		PV (200 kW), Wind (200 kW)	PV (200 kW), Wind (200 kW)
Energy Storage Component	None	Batteries (270kWh)	Supercapacitors (265kWh), Batteries (270kWh), Flywheels (265kWh)
Load Following and Combined Dispatch Model Run- time:15years, Discount Rate: 8%, ITC: 30%, Inflation: 2%		Load Following and Combined Dispatch Model Run-time:15years, Discount Rate: 8%, ITC: 30%, Inflation: 2%	Load Following and Combined Dispatch Model Run- time:15years, Discount Rate: 8%, ITC: 30%, Inflation: 2%

Performance Metrics and Analysis Framework

The methodology evaluates system performance through multiple metrics:

Technical Performance: Energy flow efficiency, SOC dynamics, voltage/temperature stability, and system response times.

Operational Reliability: False cut-off reduction, component longevity, and load meeting capability. Environmental Impact: CO2 emissions reduction and renewable energy integration efficiency Eco nomic Viability: Cost-benefit analysis using Social Cost of Carbon ($51/ton) and 45Q Carbon Credit ($85/ton) frameworks (CCC, 2023).

Model Assumptions and Limitations

The model operates under controlled assumptions: 4-hour storage capacity with single-device discharge priority, publicly available meteorological and component datasets, and simplified representations of real-world uncertainties, including equipment failure and weather extremes. These simplifications ensure computational feasibility while maintaining representational accuracy for the core research objectives.

Validation Protocol

Simulation results undergo comprehensive validation through comparison of HOMER Pro outputs with theoretical predictions, assessment of algorithm effectiveness in reducing false cut-offs, and evaluation of hybrid versus single-storage configurations. The validation confirms system stability, optimal energy management, and alignment between theoretical models and practical implementation.

IV. Results and Discussion

This section presents the results focusing on the performance of the proposed HESS architecture that integrates lithium-ion batteries, supercapacitors, and flywheels for renewable energy applications, including its environmental and economic impact. The control algorithm, based on a Unified Mathematical Method (UMM), ensures robust and adaptive power management across diverse operational scenarios.

Load Profiles and Energy Storage Specifications

A 160 kW load profile and a total storage capacity of 800 kWh were used, distributed among batteries (270 kWh), supercapacitors (265 kWh), and flywheels (265 kWh). Table IV.1 summarizes the key operational parameters.

Table 4.1: Key Parameters of Battery, Supercapacitor, and Flywheel

Parameter	**Battery**	**Super-cap**	**Flywheel**
Capacity C_i (kWh)	270	265	265
Initial SOC	0.50	0.50	0.50
DOD	0.90	0.80	0.85
SOC_{min}	0.10	0.20	0.15
SOC_{max}	0.80	0.95	0.90
Voltage range (V)	650–800	2.5–3.0	400–600
Temp. range (°C)	−25–27	−40–65	−20–40

The UMM applies a consistent mathematical structure across all operational parameters. The unified mathematical equation for charging and discharging is:

$$\boldsymbol{\Delta SOC_i(t)} = \begin{cases} \dfrac{\boldsymbol{min}\left(\boldsymbol{P}_{\text{excoss}}\,(\boldsymbol{t}), \boldsymbol{C_i} \cdot \left(\boldsymbol{1} - \boldsymbol{SOC_i(t)}\right)\right)}{\boldsymbol{C_i}}, \\ -\dfrac{\boldsymbol{min}\left(-\boldsymbol{P}_{\text{coxcss}}\,(\boldsymbol{t}), \boldsymbol{C_i} \cdot \left(\boldsymbol{SOC_i(t)} - \boldsymbol{SOC}_{\boldsymbol{i},\,\text{min}}\right)\right)}{\boldsymbol{C_i}}, \\ 0, \end{cases}$$

if $\mathbf{P}_{\text{excess}}\,(\mathbf{t}) > \mathbf{0}$ and $\mathbf{SOC_i(t)} < \mathbf{SOC_{i,max}}$ $\mathbf{OC_{i,max}}$ **and within limits**

if $\mathbf{P}_{\text{excess}}\,(\mathbf{t}) < \mathbf{0}$ and $\mathbf{SOC_i(t)} > \mathbf{SOC_{i,min}}$ **and within limits**

otherwise (4)

where *i* represents the storage type and $C_i$its capacity.

When $P_{\text{excess}} > 0$, the system charges the storage device if:

- The SOC is below its maximum limit
- Voltage and temperature are within operational limits

When $P_{\text{excess}} < 0$, the system discharges the storage device if:

- The SOC is above its minimum limit
- Voltage and temperature are within operational limits

$$SOC_i(t+1) = SOC_i(t) + \Delta SOC_i(t) \tag{5}$$

Excess Power Calculation:

$$P_{\text{excess}}(t) = P_{\text{renewable}}(t) - P_{\text{load}} \tag{6}$$

Also, the unified cutoff condition is triggered only if the moving average of any monitored parameter persistently violates its bounds.

$$\text{System Cutoff}(t) = \cup_{X \in \{V,T,SOC\}} \left[\bar{X}(t) < X_{min} \text{ or } \bar{X}(t) > X_{max}\right] \tag{7}$$

where $\bar{X}(t)$ is the moving average of parameter X at time t:

$$\bar{X}(t) < x_{\text{min}} \text{ or } \bar{X}(t) > x_{\text{max}} = \Delta\text{SOC}(t) = 0 \tag{8}$$

When this condition is met, $\Delta\text{SOC}(t) = 0$, and the device ceases operation until parameters return to safe ranges.

Dynamic system behavior is illustrated in the following figures:

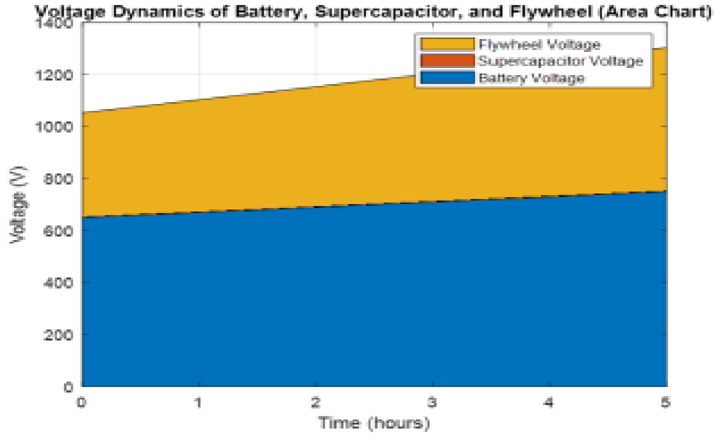


Figure 4.1: Voltage Dynamics of Battery, Supercapacitor, and Flywheel

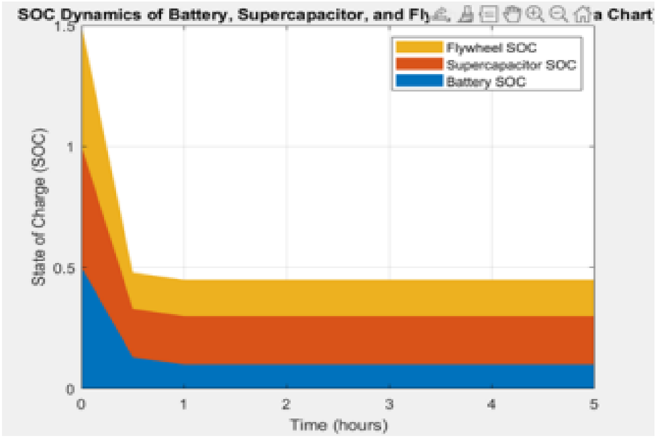


Figure 4.2: State of Charge Dynamics of Battery, Supercapacitor, and Flywheel

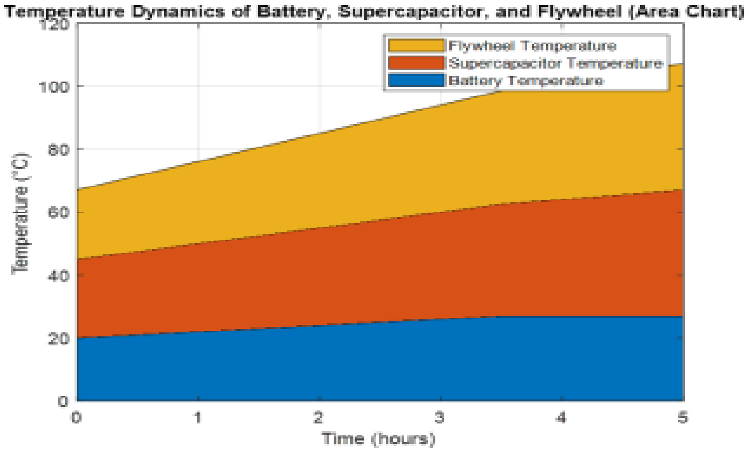


Figure 4.3: Temperature Dynamics of Battery, Supercapacitor, and Flywheel

Algorithm for Different Scenarios Operation

Scenario 1: Normal Operation

Algorithm (Energy Management System) In normal conditions, the Energy Management System (EMS) continuously monitors power generation from renewables and load demand. If renewable generation exceeds demand, storage devices are charged in priority order (batteries first, then supercapacitors, then flywheels), provided their state of charge (SOC), voltage, and temperature are within safe limits. If demand exceeds generation, supercapacitors discharge first for sudden, high-power needs, followed by flywheels for intermediate support, and batteries for sustained supply. The unified mathematical method and moving average window with threshold-based cut-off logic ensure that charging/discharging only occurs within operational constraints, minimizing false cut-offs and maximizing component life. Key Result: All devices operate within their set parameters, and the system dynamically allocates power to optimize efficiency and reliability (Maroufi et al., 2025; Ozcan et al., 2025).

Key Result:

All devices operate within their set parameters, and the system dynamically allocates power to optimize efficiency and reliability.

Algorithm Working: Detailed Example

The following example demonstrates how the algorithm processes different power scenarios over 4 hours:

Hour 1

Renewable Power: 34 kW

Load Demand: 160 kW

Excess Power:

$\boldsymbol{P}_{\text{excess}} = \mathbf{34 - 160}$ = 126kW

Battery discharge capacity = 108kWh (50% to 10% DOD)

Battery Discharge =

$$\boldsymbol{\Delta SOC_{battery}} = \begin{cases} -\dfrac{\boldsymbol{min(126,\ 270 * (0.5 - 0.1))}}{\mathbf{270}} \end{cases}$$

$$\frac{\boldsymbol{min(126{,}108)}}{\mathbf{270}} = \frac{\mathbf{108}}{\mathbf{270}} = -0.400$$

$$\boldsymbol{SOC_{battery} = 0.500 - 0.400 = 0.100}$$

Remaining 126 -108 = 18kWh needed

Supercapacitor Discharge =

$$\boldsymbol{\Delta SOC_{Supercapacitor}} = \begin{cases} -\dfrac{\boldsymbol{min(18{,}265*(0.5-0.2))}}{\mathbf{265}} \end{cases} = -\frac{\mathbf{18}}{\mathbf{265}} = \quad = -0.068$$

$$\boldsymbol{SOC_{Supercapacitor} = 0.500 - 0.068 = 0.432}$$

Flywheels Discharge = 0kWh (All needed energy is met)

Cut-off Check: Both devices are within their voltage/temperature/SOC limits, so no cut-off is triggered.

Table 4.2: State of Charge (SOC) at the End of Hour 1

Storage	Final SOC @ Hour 1
Batteries	0.100
Supercapacitors	0.432
Flywheels	0.500

Hour 2

Renewable Power: 205 kW

Load Demand: 160 kW

Excess Power:

$\boldsymbol{P}_{\text{excess}} = \mathbf{205 - 160}$ = 45kW

Batteries Discharge =

$$\boldsymbol{\Delta SOC_{batteries}} = \begin{cases} -\frac{\boldsymbol{min(45{,}270*(0.8-0.1))}}{\boldsymbol{270}} \end{cases} = -\frac{\boldsymbol{min(45{,}189)}}{\boldsymbol{270}} = \frac{\boldsymbol{45}}{\boldsymbol{270}} = 0.167$$

$$\boldsymbol{SOC_{battery} = 0.100 + 0.167 = 0.267}$$

Supercapacitors and flywheel = 0kWh discharged because battery absorbs all 45kW to recharge

No energy is taken from (or added to) the supercapacitor and flywheel. Cut-off Check: All parameters remain within bounds.

Table 4.3: State of Charge (SOC) at the End of Hour 2

Storage	Final SOC @ Hour 2
Batteries	0.267
Supercapacitors	0.432
Flywheels	0.500

Hour 3

Renewable Power: 80 kW

Load Demand: 160 kW

Excess Power:

$$\boldsymbol{P_{\text{excess}} = 80 - 160} = \text{-80kW}$$

Batteries Discharge =

$$\boldsymbol{\Delta SOC_{batteries}} = \begin{cases} -\frac{\boldsymbol{min(80{,}270*(0.267-0.1))}}{\boldsymbol{270}} \end{cases} = -\frac{\boldsymbol{min(80{,}45.09)}}{\boldsymbol{270}} = -0.167$$

$$\boldsymbol{SOC_{battery} = 0.267 - 0.167 = 0.100}$$

Supercapacitor Discharge =

$$\boldsymbol{\Delta SOC_{Supercapacitor}} = \begin{cases} -\frac{\boldsymbol{min(34.91{,}{,}265*(0.432-0.2))}}{\boldsymbol{265}} \end{cases} -\frac{min(34.91{,}61.48)}{\boldsymbol{265}} = \boldsymbol{-0.132}$$

$$\boldsymbol{SOC_{supercapacitor} = 0.432 - 0.132 = 0.300}$$

Flywheels Discharge = 0kW

Cut-off Check: SOCs remain above minimum; no cut-off is triggered.

Table 4.4: State of Charge (SOC) at the End of Hour 3

Storage	Final SOC @ Hour 3
Batteries	0.100
Supercapacitors	0.300
Flywheels	0.500

Hour 4

Renewable Power: 49 kW

Load Demand: 160 kW

Excess Power:

$$\boldsymbol{P_{\text{excess}} = 49 - 160} = \text{-111kW}$$

Batteries are unable to discharge because it is at minimum. SOC Supercapacitor Discharge =

$$\boldsymbol{\Delta SOC_{Supercapacitor}} = \begin{cases} -\frac{\boldsymbol{min(111{,}265*(0.300-0.2))}}{\boldsymbol{265}} \\ \end{cases} -\frac{\boldsymbol{min}(111{,}26.5)}{\boldsymbol{265}} = \boldsymbol{-0.100}$$

$$\boldsymbol{SOC_{supercapacitor} = 0.300 - 0.100 = 0.200}$$

Remaining 111-26.5 = 84.5kW

Flywheels Discharge

$$= \begin{cases} -\frac{\boldsymbol{min(84.5{,}265*(0.500-0.15))}}{\boldsymbol{265}} \\ \end{cases} -\frac{\boldsymbol{min}(84.5{,}-92.75)}{\boldsymbol{265}} = \boldsymbol{-0.319}$$

$$\boldsymbol{SOC_{supercapacitor} = 0.500 - 0.319 = 0.181}$$

Table 4.5: SOC at the End of Hour 4

Storage	Final SOC
Batteries	0.100
Supercapacitors	0.200
Flywheels	0.181

Cut-off check: battery disabled (low SOC); supercapacitor and flywheel operate within safe limits.

Scenario 2: No Solar/Wind

When renewables are unavailable, the HESS becomes the sole power source. The EMS prioritizes lithium-ion batteries for sustained supply, supercapacitors for rapid load changes, and flywheels for frequency regulation and smoothing. The algorithm assesses total stored energy and estimated duration of renewable unavailability, implements load shedding if energy drops below critical levels, and uses the same unified cut-off logic to ensure safe operation.

Power Dispatch Algorithm (Priority-Based)

Primary source – Lithium-ion battery

$$\Delta SOC_{battery}(t) = -\frac{min\left(-P_{\text{load}}(t), C_{battery} \cdot \left(SOC_{battery}(t) - SOC_{\min}\right)\right)}{C_{battery}} \tag{9}$$

Secondary – Supercapacitor (fast transients)

$$\Delta SOC_{sc}(t) = -\frac{min(-P_{\text{load fluctuation}}(t), C_{sc} \cdot (SOC_{sc}(t) - SOC_{\min}))}{C_{sc}} \tag{10}$$

Tertiary – Flywheel (smoothing / frequency)

$$\Delta SOC_{flywheel}(t) = -\frac{min\left(-P_{\text{load balance}}(t), C_{flywheel} \cdot \left(SOC_{flywheel}(t) - SOC_{\min}\right)\right)}{C_{flywheel}} \tag{11}$$

Cut-off conditions

Battery Cut-off Point

$$\begin{gathered} \text{if } \left(V_{\text{battery}} < 650\text{V or } V_{battery} > 800\text{V}\right) \text{ or } \left(T_{\text{battery}} < -25^{\circ}C \text{ or } T_{\text{battery}} > 27C\right) \\ \Delta SOC_{\text{battery}}(t) = 0 \end{gathered} \tag{12}$$

Supercapacitor Cut-off Point

$$\text{if } (V_{\text{sc}} < 2.5\text{V or } V_{\text{sc}} > 3.0\text{V}) \text{ or } (T_{\text{sc}} < -40^{\circ}C \text{ or } T_{\text{sc}} > 65^{\circ}C)$$
$$\Delta SOC_{\text{sc}}(t) = 0 \tag{13}$$

Flywheel Cut-off point

$$\text{if } \left(V_{\text{flywheel}} < 400\text{V or } V_{\text{flywheel}} > 600\text{V}\right) \text{ or } \left(T_{\text{flywheel}} < -20^{\circ}C \text{ or } T_{\text{flywheel}} > 40^{\circ}C\right)$$
$$\Delta SOC_{\text{flywheel}}(t) = 0 \tag{14}$$

Load-shedding trigger

$$\text{If } \sum_{i=1}^{n} \left(SOC_i(t) \cdot C_i\right) < P_{\text{load}} \cdot t_{\text{critical}} \tag{15}$$

When (15) is true, non-critical loads are shed.

Key Result:

The system maintains critical loads and grid stability, efficiently utilizing stored energy while protecting component health through strict cut-off enforcement.

Scenario 3: Component Failure – Lithium-ion Battery Malfunction

If the battery fails, the EMS isolates the faulty component and redirects charging/discharging to supercapacitors and flywheels. Flywheels become the primary energy storage, while supercapacitors handle rapid fluctuations. Aggressive load shedding may be implemented if storage drops below critical levels. The unified cut-off logic continues to monitor and protect the remaining devices.

Battery status:

$$SOC_{battery} = 0,\ \Delta SOC_{battery}(t)) = 0$$

$$\Delta SOC_{flywheel}(t) = -\frac{min\left(-P_{\text{load balance}}(t), C_{flywheel}\cdot\left(SOC_{flywheel}(t) - SOC_{\text{min}}\right)\right)}{C_{flywheel}} \tag{16}$$

$$\Delta SOC_{sc}(t) = -\frac{min\left(-P_{\text{load fluctuation}}(t), C_{sc}\cdot\left(SOC_{sc}(t) - SOC_{\text{min}}\right)\right)}{C_{sc}} \tag{17}$$

Conservation Power Management Strategy

If the total available energy drops below the critical load level

$$\text{If } \sum_{i=1}^{n} \left(SOC_i(t) \cdot C_i\right) < P_{\text{critical}} \cdot t_{\text{critical}} \tag{18}$$

Key Result:

The system adapts to the loss of long-term storage by maximizing the use of remaining assets, maintaining supply to critical loads, and preventing further component stress or damage.

Scenario 4: Component Failure – Supercapacitor Malfunction

With supercapacitor failure, the system loses its ability to efficiently handle rapid power fluctuations. The EMS increases the response rate of the flywheel system and allows limited, controlled high-rate charging/discharging of batteries.

Conservative power management is implemented, and the unified cut-off logic ensures that only safe operations are permitted.

$$SOC_{supercapacitor} = 0,\ \Delta SOC_{supercapacitor}(t)) = 0$$

$$\Delta SOC_{flywheel}(t) = -\frac{min\left(-P_{\text{load fluctuation}}(t), C_{flywheel}\cdot\left(SOC_{flywheel}(t) - SOC_{\text{min}}\right)\right)}{C_{flywheel}} \tag{19}$$

$$\Delta SOC_{battery}(t) = -\frac{min\left(-P_{\text{load balance}}(t), C_{battery}\cdot\left(SOC_{battery}(t) - SOC_{\text{min}}\right)\right)}{C_{battery}} \tag{20}$$

Conservation Power Management Strategy

If the total available energy drops below the critical load level

$$\text{If } \sum_{i=1}^{n} \left(SOC_i(t) \cdot C_i\right) < P_{\text{critical}} \cdot t_{\text{critical}} \tag{21}$$

Then, activate load shedding

Key Result:

The system compensates for the loss of rapid-response storage by redistributing roles, but overall flexibility and response time are reduced, highlighting the importance of supercapacitors in HESS.

Scenario 5: Component Failure – Flywheel Malfunction

If the flywheel fails, the system loses intermediate-term storage and frequency regulation. The EMS increases reliance on batteries for energy storage and supercapacitors for power smoothing and frequency regulation. Aggressive power management and load shedding may be required. The cut-off logic continues to enforce operational safety.

$SOC_{flywheel} = 0,\ \Delta SOC_{flywheel}(t)) = 0$

$$\Delta SOC_{supercapacitor}(t) = -\frac{min\left(-P_{\text{load fluctuation}}(t), \text{supercapacitor} \cdot \left(SOC_{supercapacitor}(t) - SOC_{\text{min}}\right)\right)}{C_{supercapacitor}} \tag{22}$$

$$\Delta SOC_{battery}(t) = -\frac{min\left(-P_{\text{load balance}}(t), C_{battery} \cdot \left(SOC_{battery}(t) - SOC_{\text{min}}\right)\right)}{C_{battery}} \tag{23}$$

Conservation Power Management Strategy

If the total available energy drops below the critical load level

$$\text{If } \sum_{i=1}^{n} \left(SOC_i(t) \cdot C_i\right) < P_{\text{critical}} \cdot t_{\text{critical}} \tag{24}$$

Key Result:

The system remains operational by reallocating roles, but the loss of flywheels reduces its ability to handle frequency regulation and intermediate-term fluctuations, stressing the importance of all three technologies working together.

In all scenarios, the unified mathematical method and cut-off logic are central to ensuring safe, efficient, and adaptive operation, dynamically responding to both typical and fault conditions to maximize system resilience and performance.

System Architecture and Coordination

Operational Process

Monitoring Energy Demand and Renewable Output

The EMS continuously monitors the current power demand and the output from renewable energy sources, using predictive analytics to forecast future energy availability and demand.

Determining Energy Storage Needs

Based on the demand and renewable output, the EMS decides which energy storage technology to use. Lithium-ion batteries are prioritized for long-term energy needs, supercapacitors are used for short-term fluctuations, while flywheels are engaged for immediate power needs.

EMS Instructions to Network Switch

The EMS sends instructions to the network switch that specify which energy storage technology to use. Then the network switch translates these instructions into control signals for the ATS.

ATS Selection and Control

The ATS receives the control signals from the network switch and selects the appropriate energy storage technology, and then connects the chosen storage technology to the converter to generate the power flow path, ensuring that only one technology is used at a time.

Charging and Discharging Process

During low-demand periods, the ATS directs excess energy from renewables to the power converter to charge the selected storage technology, and during high-demand periods, the ATS allows the power converter to discharge the selected storage technology to meet the demand.

During extended periods of low renewable energy resources output in winter months, the EMS decides to use lithium-ion batteries for sustained energy supply, and the Network Switch translates the EMS's instructions into control signals for the ATS. The ATS then selects lithium-ion batteries, and the power converter manages their charging and discharging to ensure a continuous power supply. Lithium-ion batteries are advantageous due to their high energy density and efficiency, making them ideal for long-term storage needs. During sudden spikes in power demand during peak hours, the EMS decides to use supercapacitors for immediate power support. The network switch translates the EMS's instructions into control signals for the ATS. Then, the ATS selects supercapacitors, and the power converter rapidly charges or discharges them to stabilize the grid. Supercapacitors are beneficial for short-term energy storage due to their rapid charge-discharge capabilities and high-power density. During momentary power outages or grid frequency fluctuations, the EMS decides to use flywheels for immediate power stabilization. The network switch translates the EMS's instructions into control signals for the ATS. Then, the ATS selects the flywheels, and the power converter manages their rapid charging and discharging to provide instant power support. Flywheels are effective for short-term power stabilization due to their high efficiency and rapid response times. However, different scenarios are guarded by the set parameters in Table 4.1 above.

Overall, the EMS coordinates all operations through the network switch and ATS, ensuring seamless power flow and system stability. The UMM-based control algorithm reduces false cut-offs, optimizes power distribution, and extends component lifespan by ensuring devices operate within safe parameters.

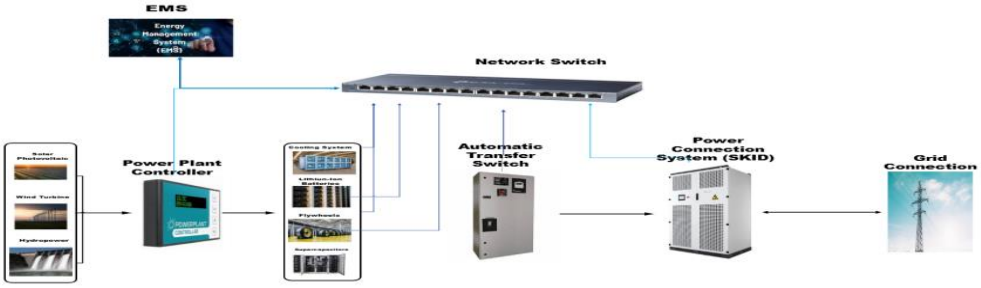


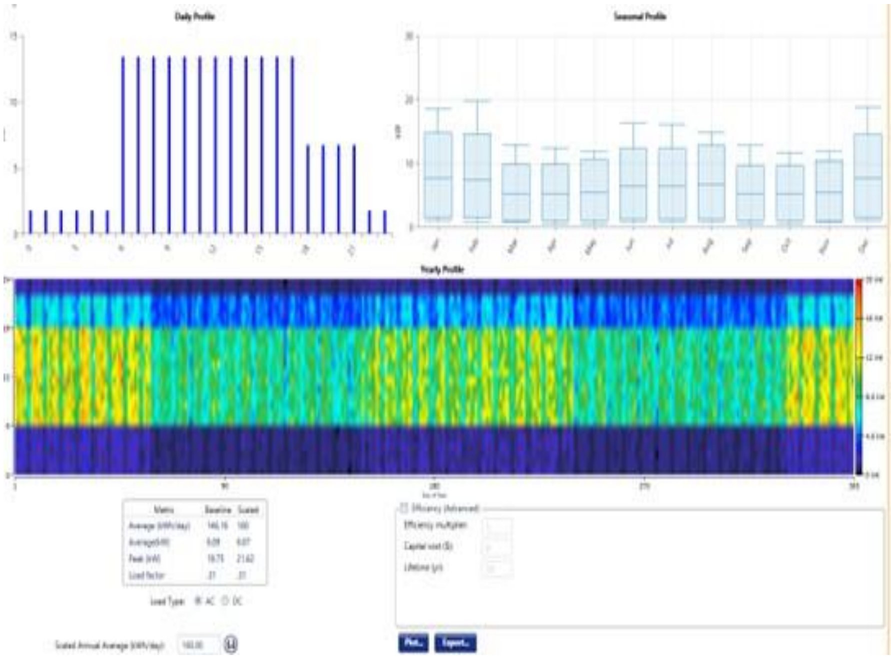
Figure 4.4: Hybrid Energy Storage System supporting the algorithms

Output Performance, Environmental, and Economic Benefits

This section compares HESS configurations to single-storage and no-storage baselines using HOMER Pro simulations.

Load Profile Analysis

Understanding the load profile is fundamental for designing and optimizing energy systems, particularly when integrating renewable energy sources with storage technologies. The load analysis provides critical insights into energy consumption patterns, peak demands, and seasonal variations that directly influence system sizing and operational strategies.



Metric	Baseline	Scaled
Average (kWh/day)	146.16	160
Average (kW)	6.09	6.67
Peak (kW)	19.75	21.62
Load factor	.31	.31

Load Type: ● AC ○ DC

Scaled Annual Average (kWh/day) 160.00

Figure 4.5: Load Profile Overview. This figure shows daily, seasonal, and yearly load profiles of electricity data, along with key metrics such as average energy consumption, average power, peak power, and load factor.

The load profile analysis for the Grand Forks office building reveals distinct consumption patterns across daily, seasonal, and yearly time frames. The system exhibits a scaled peak demand of 21.62 kW with an average load of 6.67 kW, resulting in a load factor of 31%. This relatively low load factor indicates significant variation between peak and average demand, which is typical for commercial office buildings and presents both challenges and opportunities for energy storage integration.

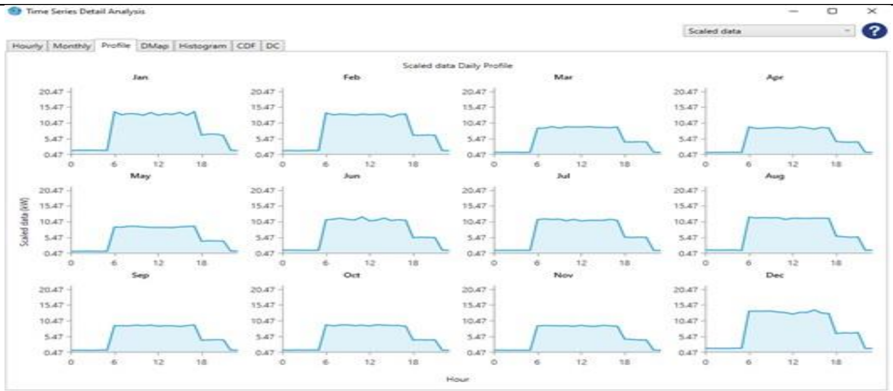


Figure 4.6: shows the monthly scaled daily load profiles of electricity data. Each graph illustrates hourly variations in power consumption for a typical day across all months, highlighting consistent patterns and peak usage periods.

The monthly scaled daily profiles demonstrate consistent patterns with morning ramp-ups (6 AM - 12 PM), daytime plateaus during business hours (12 PM - 6 PM), evening declines (6 PM - 12 AM), and night-time lows (12 AM - 6 AM). Winter months (December, January, February) exhibit higher consumption due to heating requirements, while spring and fall months show more moderate demand profiles. This seasonal variation directly influences the optimal sizing and operation of storage components within the HESS architecture.

The annual energy consumption totals 58,400 kWh/year, establishing the baseline demand that must be met by the integrated renewable-storage system. This load profile serves as the basis for all subsequent scenario analysis and system optimization procedures.

Scenario-Based Performance Results

Scenario 1: Grid + Renewables Only (Baseline)

The baseline scenario establishes the performance benchmark without energy storage integration, utilizing only grid connectivity and renewable energy sources. This configuration provides essential comparative data to evaluate the incremental benefits of storage technologies.

The baseline configuration demonstrates robust renewable energy generation with wind turbines contributing 812,064 kWh/yr and solar PV systems providing 5,380 kWh/yr. The system achieves net energy export to the grid (-135,899 kWh/yr), indicating substantial excess renewable generation. However, this scenario lacks the storage capability to optimize renewable energy utilization during periods of high generation and low demand.

Table 4.6: Hybrid System Power Output

Electricity Production (kWh/yr)		**Electricity Consumption (kWh/yr)**	
Grid Supply	4,201	**Total AC Primary Load**	58,400
Wind Turbine Output	812,064	**Grid sales**	627,073
Solar PV	5,380	**Net Grid Purchases**	-135,899

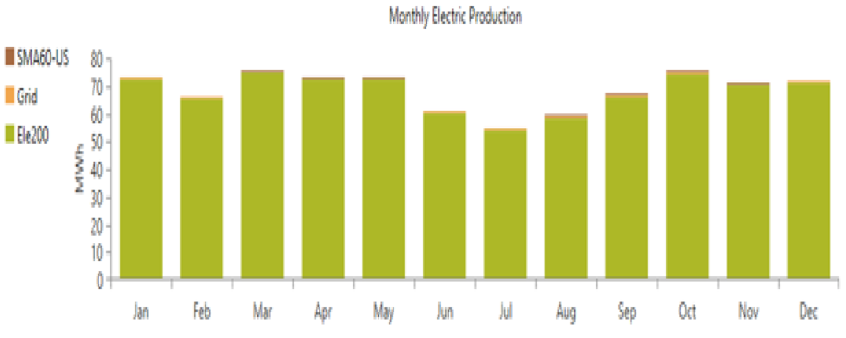


Figure 4.7: Below provides more information about the system output, showing monthly electric production from the grid and the

hybrid system components.

The hourly analysis reveals significant temporal mismatches between renewable generation and load demand, particularly during high wind generation periods. Without storage, excess renewable energy must be exported to the grid at potentially unfavorable rates, representing lost economic opportunity and suboptimal system utilization.

Scenario 2: Grid + Renewables + Single Storage (Battery) The integration of lithium-ion battery storage significantly enhances system performance by providing load-shifting capabilities and improved renewable energy utilization. This scenario demonstrates the fundamental benefits of adding energy storage to renewable systems.

Table 4.7: Hybrid System Power Output with Single Storage

Electricity Production (kWh/yr)		**Electricity Consumption (kWh/yr)**	
Grid purchases	4,201	**Total AC Primary Load**	58,400
Wind Turbine Output	812,064	**Grid sales**	706,898.5
Solar PV	5,380	**Net Grid Purchases**	-136,172
Lithium-Ion Battery	79,825.5		

The addition of battery storage increases total system output to 901,470.5 kWh/yr, with the battery contributing 79,825.5 kWh/yr through optimized charge-discharge cycles. The capacity factor improves to 21%, and net grid sales increase to 706,899 kWh/yr, demonstrating enhanced energy arbitrage capabilities and improved economic performance.

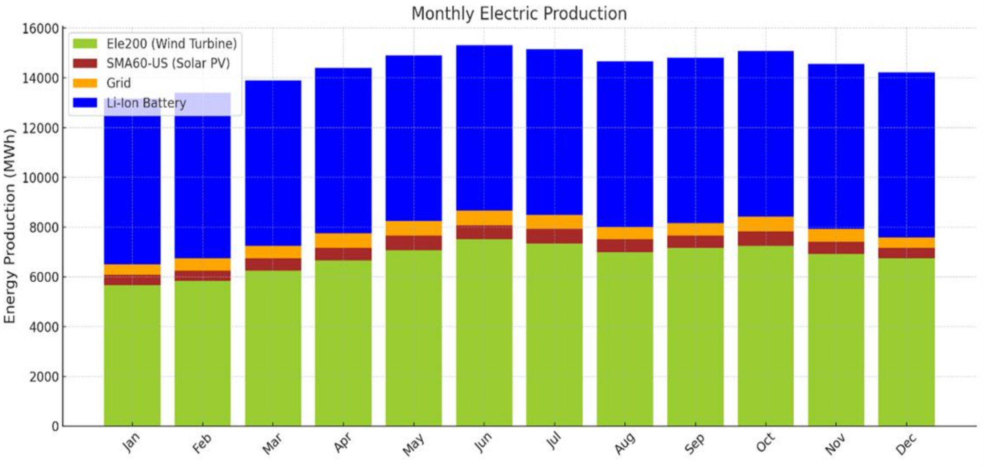


Figure 4.8: Hybrid System Monthly Electricity Production- Single Storage Modified from (Homer Pro).

Monthly production analysis reveals improved load matching and reduced grid dependency during peak demand periods. The battery system effectively smooths renewable generation variability and provides load-shifting capabilities that optimize overall system efficiency.

Scenario 3: Grid + Renewables + Three Storage Types (HESS)

The comprehensive HESS configuration integrating batteries, supercapacitors, and flywheels rep resents the optimal system design, leveraging the complementary characteristics of all three storage technologies for maximum performance and reliability.

Table 4.8: Hybrid System Power Output with Lithium-Ion Battery, Supercapacitor and Flywheel

Electricity Production (kWh/yr)		**Electricity Consumption (kWh/yr)**	
Grid Purchases	4,201	**Total AC Primary Load**	58,400
Wind Turbine Output	812,064	**Grid sales**	973,919.5
Solar PV	5,380	**Net Grid Purchases**	-969,718.5
Lithium-Ion Battery	79,825.5	**Supercapacitor**	69,350
Flywheel	65,700		

The three-storage configuration achieves the highest total output of 1,032,319.5 kWh/yr, with each storage technology contributing according to its optimal characteristics. Supercapacitors provide 69,350 kWh/yr through rapid charge-discharge cycles, while flywheels contribute 65,700 kWh/yr for frequency regulation and short-term storage. Net grid sales increase dramatically to 973,920 kWh/yr.

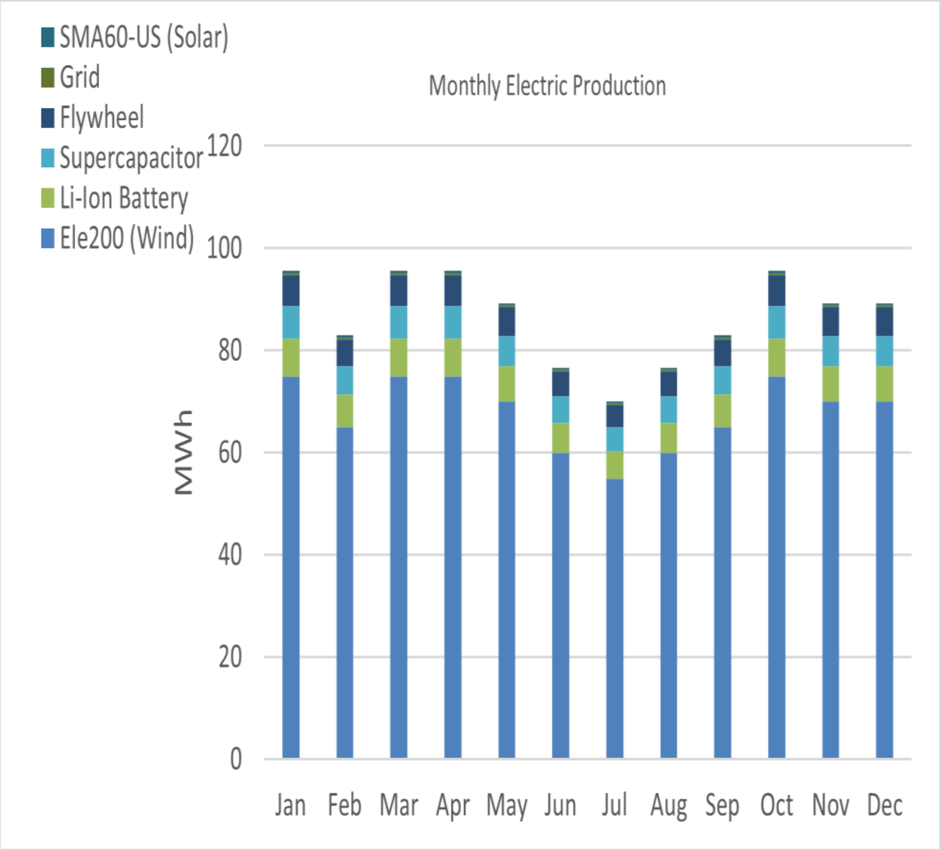


Figure 4.9: Hybrid System Monthly Electricity Production from Renewable Energy Sources, Grid & Three Storages Modified from Homer Pro.

The monthly production profile demonstrates exceptional system flexibility and optimized renewable energy utilization. The hybrid storage configuration enables precise load following, peak shaving, and frequency regulation that significantly outperforms single-storage alternatives.

Environmental and Economic Impact

Environmental Benefits Analysis

The environmental benefits of HESS integration are substantial and demonstrate clear progression from baseline to optimal configurations. Each scenario shows significant reductions in carbon emissions compared to grid-only operations.

Table 4.9: Annual CO_2 emissions for the three scenarios

Scenario	**CO_2 Emissions (kg yr^{-1})**
Grid + Renewables Only	−393 655
Grid + Renewables + Battery	−576 212
Grid + Renewables + Three Storages	−1 360 451

The negative emission values represent net carbon avoidance, with the three-storage HESS configuration achieving the greatest environmental benefit at 1,360,451 kg CO2 avoided annually. This represents a 245% improvement over the baseline renewable scenario and demonstrates the critical role of optimized storage in maximizing environmental benefits.

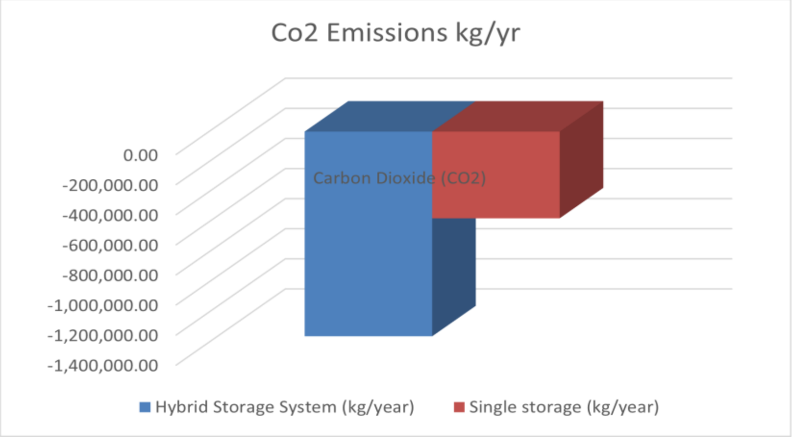


Figure 4.10: Comparison of the Annual CO2 Emissions of the Hybrid Baseline to Hybrid with Single Storage: Lithium-Ion Battery.

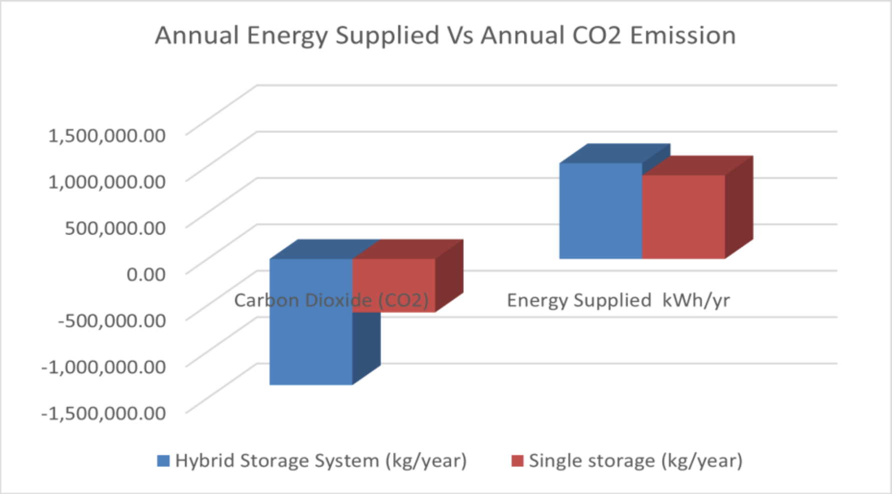


Figure 4.11: Comparison of the Annual Energy supplied and the Annual CO2 Emissions of Single Storage to a Hybrid Storage System Using Three Storage: Lithium-Ion battery, Supercapacitor, and Flywheel.

The comparative analysis clearly illustrates the progressive environmental benefits of storage integration. The HESS configuration not only maximizes renewable energy utilization but also enables greater grid export of clean energy, amplifying the system's positive environmental impact beyond the immediate facility.

Economic Valuation of Environmental Benefits

The economic quantification of avoided emissions provides compelling financial justification for HESS investment, utilizing established carbon pricing frameworks to demonstrate tangible economic returns.

Using the Social Cost of Carbon (SCC) at \$51/ton and the 45Q Carbon Credit at \$85/ton, the three-storage HESS configuration generates an annual economic value of \$69,382 (SCC) to \$115,638 (45Q) through avoided emissions alone. These figures represent significant revenue streams that can offset initial capital investments and improve overall project economics.

The 245% increase in economic value from baseline to three-storage configuration demonstrates the multiplicative benefits of optimal storage integration. This economic analysis excludes additional benefits such as demand charge reduction, peak shaving revenues, and grid services compensation, suggesting even greater total economic value.

Table 4.10: Economic value of avoided CO_2 emissions

Scenario	**CO$_2$ Avoided**	**SCC Value (\$51 t^{-1})**	**45QValue (\$85 t^{-1})**
Grid + Renewables Only	393.66	\$20 081	\$33 461
Grid + Renewables + Battery	576.21	\$29 387	\$48 978
Grid + Renewables + Three Storages	1 360.45	\$69 383	\$115 638

Sensitivity Analysis

The comprehensive sensitivity analysis comparing all four scenarios (Grid Only, Grid + Renewables Only, Grid + Renewables + Single Storage, Grid + Renewables + Three Storages) provides definitive evidence of HESS superiority across all performance metrics.

Figure 4.12: Sensitivity Analysis of Output Performance to CO2 Emissions

The analysis reveals a clear progression in both power output and environmental benefits:

Grid Only: 58,400 kWh/yr output, 3,221 kg CO2 emissions

Grid + Renewables: 821,250 kWh/yr output, -393,655 kg CO2 avoided

Single Storage:901,471 kWh/yr output, -576,212 kg CO2 avoided

Three Storage (HESS): 1,032,320 kWh/yr output, -1,360,451 kg CO2 avoided.

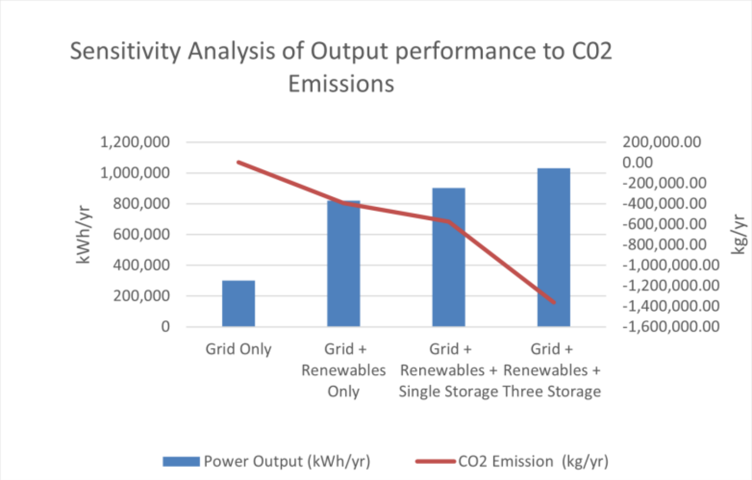
The HESS configuration achieves 77% higher output and 345% higher carbon avoidance compared to the baseline renewable systems. This analysis conclusively demonstrates that hybrid storage configurations provide exponential rather than linear benefits, justifying the additional complexity and investment required for multi-technology storage integration.

Sensitivity analysis validates the research hypothesis that strategic integration of complementary storage technologies creates synergistic effects that significantly exceed the sum of individual component contributions, establishing HESS as the optimal approach for renewable energy integration and grid modernization initiatives.

V. Discussion

The results demonstrate that integrating lithium-ion batteries, supercapacitors, and flywheels in a Hybrid Energy Storage System (HESS) offers substantial technical, environmental, and economic advantages for renewable energy integration. The unified control strategy, anchored by the Unified Mathematical Method (UMM) with moving average window filtering and threshold-based cut-off logic, proved effective in all modelled scenarios, ensuring robust, adaptive, and safe system operation.

Technical Performance: The HESS architecture leverages the complementary strengths of each storage technology: batteries deliver a long-term energy supply, supercapacitors provide rapid response to short-term power fluctuations, and flywheels ensure immediate frequency regulation and grid stability. The Energy Management System (EMS), supported by a network switch and an automatic transfer switch (ATS), dynamically allocates charging and discharging duties, ensuring that only one device is active at a time and that all operate within safe voltage, temperature, and SOC limits.



Algorithmic Control and Cut-off Logic: The UMM's moving average and threshold-based cut-off logic effectively mitigates false cut-offs, ensuring that storage devices are disconnected only when operational thresholds are consistently exceeded. This approach prolongs component life, reduces unnecessary cycling, and enhances overall reliability. The scenario-based results demonstrate that the EMS can seamlessly adapt to normal operation, renewable source absence, and component failure, reallocating roles among available devices to maintain supply and grid stability.

Environmental and Economic Impact: Simulation results using HOMER Pro show that the HESS configuration outperforms both single-storage and no-storage baselines. The hybrid system achieves the highest power output (1,032,319.5 kWh/year) and the most significant CO2 reduction (-1,360,450.95 kg/year), with the economic value of avoided emissions reaching up to $115,638/year under the 45Q Carbon Credit framework. These findings demonstrate that hybrid configurations not only optimize renewable utilization and reduce emissions but also provide tangible financial benefits.

Sensitivity and Robustness: Sensitivity analysis further confirms that the inclusion of multiple storage types results in the most efficient and environmentally friendly system, with exponential improvements in both output and CO2 avoidance compared to single storage or no-storage models.

Notwithstanding, while initial technical complexities and high upfront capital expenditure (CAPEX) remain challenges for HESS implementation, the benefits—such as enhanced grid resiliency and system robustness, far outweigh these drawbacks. When all three systems are effectively harmonized, the overall outcomes are significantly improved compared to not integrating them.

Overall, the HESS, managed by advanced unified algorithms, can deliver superior performance, resilience, and sustainability. This approach is essential for smart grid modernization and large-scale renewable integration, supporting both operational reliability and climate goals.

VI. Conclusion and Future Work

Conclusion:

This study demonstrates that integrating lithium-ion batteries, supercapacitors, and flywheels in a Hybrid Energy Storage System (HESS) significantly enhances the performance, reliability, and sustainability of renewable energy integration into the power grid. The proposed Unified Mathematical Method (UMM), which combines moving average window width filtering with threshold-based cut off logic, proved effective in managing energy storage operations, reducing false cut-off triggers, and ensuring that cut-offs occur only when operational thresholds are truly exceeded. Simulation results using HOMER Pro indicate that the hybrid configuration yields the highest power output (1,032,319.5 kWh/year) and the greatest reduction in CO2 emissions (–1,360,450.95 kg/year) compared to single storage or no-storage systems. The complementary roles of batteries (long-term storage), supercapacitors (short-term fluctuations), and flywheels (frequency regulation) enable adaptive, scenario-based energy management that supports both grid stability and environmental objectives. Furthermore, the economic analysis shows that the hybrid system delivers the highest value from avoided emissions, providing strong financial justification for HESS deployment in modern grids.

Future Work:

Future research should focus on integrating advanced control strategies, such as artificial intelligence and machine learning, into the Energy Management System (EMS) to enable real-time forecasting, adaptive dispatch, and predictive maintenance for HESS, thereby improving operational resilience and efficiency (Maroufi et al., 2025; Atawi et al., 2022). Empirical validation through field demonstrations in diverse environments is also essential to refine control algorithms and confirm the robustness and scalability of the proposed architecture (Agajie et al., 2023).

Comprehensive techno-economic and lifecycle analyses across different regulatory and market contexts are needed to inform stakeholders and guide investment decisions, particularly as carbon pricing and credit mechanisms become more prevalent (Bade et al, 2024). Additionally, future work should explore integrating HESS with emerging technologies such as hydrogen fuel cells and advanced flow batteries to further enhance system flexibility and resilience (Kouchachvili et al., 2021). From a policy perspective, supportive regulatory frameworks, including targeted incentives, standardized safety protocols, and requirements for interoperability, are critical to accelerating HESS adoption and maximizing their value for smart grids and renewable integration (International Energy Agency, 2023).

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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