

Article

Duty Cycle-Based Optimization of the Usable Energy Buffer Ratio in a Battery–Supercapacitor HESS for Mining Electric Dump Trucks

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Abstract

Hybrid energy storage systems combining LiFePO₄ batteries and supercapacitors can reduce high-rate battery loading in battery electric mining dump trucks operating under intensive regenerative braking conditions. This study proposes a constrained multi-objective sizing methodology for a semi-active battery–supercapacitor hybrid energy storage system applied to a 65 t payload-class mining electric dump truck. The model combines segment-level mining duty cycles, longitudinal vehicle dynamics, a first-order Thevenin battery representation, a usable supercapacitor energy window, bidirectional DC/DC converter limits, and constrained supervisory power splitting. Three mining duty cycles are considered: production haulage, reclamation/backfill operation, and mixed operation. The final sizing result is reported using a dimensionless usable energy buffer ratio rather than a direct comparison between supercapacitor capacitance and battery energy capacity. The results show that the required supercapacitor buffer is strongly duty cycle-dependent. For the regenerative-dominant backfill cycle, the hybrid configuration reduced peak battery charging current from approximately -950 A to $-180 \dots -280\text{ A}$ and reduced battery root mean square (RMS) current by 52–64% relative to the pure battery configuration. The constrained stored fraction of regenerative energy also increased when the supercapacitor branch was included, while non-accepted braking power was assigned to the residual braking channel. The proposed approach provides a physically consistent basis for preliminary hybrid energy storage system (HESS) sizing and clarifies that battery current reduction should be interpreted as a degradation-relevant stress indicator rather than as a direct quantified lifetime prediction.



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Keywords: electric mining truck; hybrid energy storage system; LiFePO₄ battery; supercapacitor; regenerative braking; mining duty cycle; usable energy buffer ratio; multi-objective optimization; Pareto front

1. Introduction

1.1. Relevance of the Problem

The global climate agenda and tightening environmental standards stimulate the active decarbonization of industry, including the mining sector, which has traditionally been one of the largest consumers of fossil fuels and a source of significant emissions [1,2]. Mining dump trucks, as the basis of the transport link of open-pit mining, are characterized by high unit power, high diesel fuel consumption and, as a result, a significant carbon footprint [3,4]. In this regard, the electrification of mining equipment, the transition to battery electric dump trucks (BEDTs), is considered as a strategic direction to reduce local emissions, noise levels and operating costs [5,6].

A key advantage of the electric drive is the possibility of regenerative braking, which allows for energy to be returned to the storage device when descending or decelerating. However, as shown in our previous research, the effectiveness of this technology in mining is mixed. When operating in a classic mining cycle (moving the rock mass up from the quarry), the potential for recovery on the descent is limited, and the system itself complicates the design and increases the cost [7,8]. On the contrary, for the unique but important task of reclamation of exhausted open-pit mines, where logistics are inverted (downward movement with the load), regenerative braking becomes the central element capable of providing energy-neutral or even energy-generating mode of operation [9].

Regardless of the type of cycle, the onboard BEDT energy storage unit faces a fundamental technical contradiction: the need to simultaneously store a large amount of energy to ensure the required range (high specific energy, Wh/kg) and instantly receive/give high power during acceleration and, especially, during intensive regenerative braking on steep descents (high power density, W/kg) [10,11]. Lithium-ion batteries, in particular lithium iron phosphate (LiFePO₄) batteries, which are highly safe and durable, optimally solve the first problem but have physical limitations in terms of maximum charge currents. Exceeding these currents leads to overheating, accelerated degradation and a reduction in the service life of an expensive battery pack. Supercapacitors (SCs), having orders of magnitude higher specific power and almost unlimited cyclic life, are ideal for working with power peaks, but their specific energy is extremely small for use as a single source [12–14].

Thus, the hybrid energy storage system (HESS), which combines the advantages of a battery and a supercapacitor into a single energy buffer, seems to be the most rational and promising technical solution for heavy BEDTs [15]. In such a system, the battery acts as the main “fuel tank”, providing a range, while the supercapacitor acts as a power buffer, smoothing out peak loads and protecting the battery from harmful high-amplitude currents [16].

1.2. Literature Review and Scientific Contribution

A significant number of works are devoted to the problems of HESS application in electric vehicles, the main focus of which is on passenger transport and city buses. These studies tend to focus on connectivity topologies, energy flow control algorithms, and demonstrating overall efficiency gains. For quarry equipment, the topic of HESS is also beginning to be studied, but existing publications, including our previous work [17,18], are more qualitative or comparative. They substantiate the feasibility of a hybrid approach

and compare a limited set of discrete configurations (e.g., “battery only”, “battery + fixed capacity SC”).

A critical analysis of the literature reveals a significant gap in research: the lack of methods for quantifying the optimal ratio of HESS components (primarily battery and supercapacitor capacity), strictly tied to specific, detailed modeled operating cycles of a mining dump truck [19]. The choice of these parameters today is often based on empirics or intuition, which can lead to non-optimal solutions: overestimation of the weight and cost of the system with excess SC capacity or, conversely, to the risk of rapid degradation of the battery and incomplete use of the recovery potential with insufficient SC capacity [20,21].

In modern open-pit mining conditions, the transportation of rock mass by mining dump trucks is a key element of the technological process of mining and stripping operations. National and international studies confirm that the correct mathematical description of the operating cycle significantly affects the accuracy of modeling the reliability of power and chassis systems of dump trucks [22].

The scientific novelty of this study lies in overcoming this gap by developing and applying a comprehensive methodology for parametric optimization of onboard HESS for a mining dump truck [23]. In contrast to previous studies, in this study:

1. The optimization task is formalized as a multi-criteria one, where the target functions are not only the minimization of net power consumption from the grid but also the key durability indicators (RMS current of the battery) and the mass and size characteristics of the system.
2. The dependence of the optimal usable energy-buffer ratio on the specific segment-level mining duty cycle on a specific, detailed modeled operating cycle of the dump truck—taking into account the geometry of the route (slope, length of sections), cargo weight and speed mode—has been quantitatively established.
3. Based on the results of the parametric analysis of the mathematical model for fundamentally different typical cycles (“mining”, “reclamation”, “combined”), practical engineering recommendations and simplified design dependencies (nomograms) were developed for the preliminary determination of HESS parameters at the design stage.

1.3. Aim and Objectives

The purpose of this work is to develop and apply a constrained multi-objective methodology for sizing a semi-active LiFePO₄ battery–supercapacitor hybrid energy storage system for a 65 t payload-class mining electric dump truck. The methodology determines the duty cycle-dependent supercapacitor energy buffer required to reduce high-rate battery current during regenerative braking while satisfying mass, voltage, current, converter power, and energy balance constraints. The final sizing result is expressed through a dimensionless usable energy buffer ratio, whereas the equivalent supercapacitor capacitance is treated only as an electrical design variable.

To achieve this goal, the following tasks were consistently solved:

1. Based on the data in [1,2], as well as the technical characteristics of mining dump trucks, a detailed mathematical model has been developed, including
 - Longitudinal dynamics model of the Komatsu HD605-7 dump truck (E-Dumper).
 - Electromechanical models of HESS components: LiFePO₄ batteries (taking into account the dependence of internal resistance on state of charge, SOC) and supercapacitor module.
 - Algorithm for managing the power distribution between the battery and the supercapacitor.

2. Three characteristic work cycles are defined and parameterized, reflecting the main operating scenarios: the traditional mining cycle (empty-down, loaded up), the inverse reclamation cycle (empty-up, loaded down) and the average combined cycle.
3. The constrained parametric optimization problem is formulated using nominal battery energy capacity and equivalent supercapacitor module capacitance as design variables, while the final sizing result is reported through the dimensionless usable energy buffer ratio.
4. A parametric computational analysis is performed for each mining duty cycle with variation of battery energy capacity and equivalent supercapacitor module capacitance within a unified design range. Objective function maps are obtained for net cycle energy, battery RMS current, stored regenerative energy fraction, residual braking energy, and HESS mass.
5. Pareto-optimal solution regions are identified, and duty cycle-specific recommendations are formulated using the usable energy buffer ratio rather than a direct capacitance-to-energy ratio.

1.4. Practical Significance and Article Structure

The results of the study have a direct applied value for various participants in the process of creating and operating quarry electrical equipment:

- For designers and engineers of mining and transport equipment, the developed methodology provides a tool for a reasonable selection of HESS parameters at the design stage, allowing for them to find a balance between cost, weight, energy efficiency and durability of the system for specific customer requirements.
- For technologists and planners of mining enterprises, the obtained dependencies allow for a more accurate assessment of potential energy savings and payback period when implementing electric dump trucks with HESS at a specific site, taking into account the real profile of routes and logistics.
- For designers of electric drive control systems, data on the required power characteristics of the supercapacitor buffer serves as the basis for the synthesis of effective algorithms for managing energy flows in real time, maximizing battery life.

The remainder of the article is organized as follows. Section 2 describes the reference vehicle class, mining duty cycle construction, HESS topology, component models, control constraints, optimization problem, and benchmark-based verification. Section 3 presents the simulation results, including duty cycle power profiles, Pareto-optimal configurations, battery current stress indicators, and sensitivity analysis. Section 4 summarizes generalized optimization findings and engineering sizing outputs derived from the mining duty cycle simulations. Section 5 discusses the interpretation of the results, comparison with previous studies, limitations, and future work. Section 6 presents the main conclusions.

2. Materials and Methods

The methodology of mathematical modeling includes the selection of the object of study, parameterization of operating cycles, mathematical models of the dynamics and energy of the dump truck, models of the components of the hybrid energy storage system (HESS), control strategy, formalization of the optimization problem, as well as tools and procedure for calculation verification [24].

2.1. Object of Research and Initial Data

The study is based on a benchmark-verified mathematical model of a battery electric mining dump truck belonging to the 65 t payload class. To avoid mixing vehicles of different tonnage classes, the revised model uses a single reference vehicle class corresponding to

the Komatsu HD605-7/E-Dumper parameter range. Other mining trucks mentioned in the literature review are used only for contextual comparison and are not used to synthesize the vehicle mass, payload, battery capacity, speed, or duty cycle parameters. The unified reference parameters used in the model are presented in Table 1.

Table 1. Unified reference parameters of the 65 t payload-class battery electric mining dump truck used in the model.

Parameter	Designation	Baseline Value Used in Simulations	Range Used in Sensitivity/Optimization	Comment
Reference vehicle class		Komatsu HD605-7/E-Dumper class		Used as a public data benchmark class, not as manufacturer-specific proprietary data
Tare mass	m_0	45,000 kg		Empty vehicle mass
Nominal payload	m_{pay}	65,000 kg	0–65,000 kg	Payload class used consistently throughout the model
Loaded vehicle mass	m_{loaded}	110,000 kg	45,000–110,000 kg	Sum of tare mass and payload
Battery energy capacity, baseline	$E_{\text{bat,base}}$	600 kWh		Baseline value used for the reference configuration
Battery energy capacity, optimization variable	E_{bat}		400–800 kWh	Design range used in parametric HESS sizing
External benchmark battery capacity	$E_{\text{bat,bench}}$	700 kWh		Used only for comparison with public E-Dumper-class data
Nominal DC bus voltage	$U_{\text{dc,nom}}$	700 V	600–800 V	Voltage range used for converter and storage system matching
Rolling resistance coefficient	f_r	0.020	0.015–0.025	Depends on haul road surface condition
Aerodynamic drag coefficient	C_x	1.0	0.8–1.2	Typical range for heavy off-highway equipment
Frontal area	A	13.5 m ²	12–15 m ²	Used in aerodynamic force calculation
Traction drive efficiency	η_{drive}	0.92	0.91–0.94	Traction mode
Regenerative drive efficiency	η_{regen}	0.88	0.85–0.92	Regenerative braking mode before storage limitations
Rotating-mass inertia factor	γ	1.20	1.05–1.40	Equivalent inertia correction
Haul distance per one direction	L	2.5 km	2.0–3.0 km	Segment-level mining duty cycle parameter
Loaded travel speed	v_{loaded}	25 km/h	20–30 km/h	Used for loaded haul or loaded descent segment
Empty return speed	v_{empty}	30 km/h	25–35 km/h	Used for unloaded return segment
Loading time	t_{load}	5 min	4–6 min	Non-traction technological phase
Dumping time	t_{dump}	3 min	2–4 min	Non-traction technological phase
Full operating cycle duration	t_{cycle}	Approximately 19 min	Depends on route and speed	Calculated from segment durations

The parameters in Table 2 define one internally consistent vehicle class rather than an aggregate of several trucks with different payload ratings [25]. The tare mass, payload, loaded mass, voltage range, and duty cycle parameters are used consistently in the longitudinal dynamics model, HESS sizing procedure, and benchmark verification. Publicly available Komatsu HD605-7/E-Dumper-class information is used only to define the reference scale of the model and to compare the order of magnitude of energy consumption and battery capacity [26]. No proprietary manufacturer data, confidential design documentation, or restricted commercial information is used in this study. A detailed description of the traffic profiles based on these parameters is given in Section Operating Cycle of a 65 t Payload-Class Mining Dump Truck.

Operating Cycle of a 65 t Payload-Class Mining Dump Truck

To form physically and technologically consistent input data for the mathematical model, a formalized operating cycle of a 65 t payload-class battery electric mining dump truck was used. The operating cycle was constructed for the same reference vehicle class as Table 2 and therefore uses a tare mass of 45 t, a nominal payload of 65 t, and a loaded vehicle mass of approximately 110 t [27]. The structure of the cycle and its time characteristics correspond to the data of industrial observations and the generalized results of research on the operation of mining dump trucks of this class.

The operational cycle is considered as a closed sequence of technological and transport operations and includes the following main phases:

- Loading phase at the face;
- Phase of transportation of the loaded dump truck;
- Unloading phase;
- Phase of reverse movement of an empty dump truck.

The total cycle duration is defined by the following expression:

$$T_{\text{cycle}} = t_{\text{load}} + t_{\text{haul}} + t_{\text{dump}} + t_{\text{return}},$$

where

t_{load} —loading time;

t_{haul} —travel time with the load;

t_{dump} —unloading time;

t_{return} —return time without cargo.

For the adopted 65 t payload-class reference truck, the operating cycle is characterized by the following average segment-level parameters:

- One-way haul distance $L = 2.0\text{--}3.0$ km;
- Loaded vehicle speed $v_{\text{loaded}} = 20\text{--}30$ km/h;
- Empty vehicle return speed $v_{\text{empty}} = 25\text{--}35$ km/h;
- Loading time $t_{\text{load}} = 4\text{--}6$ min;
- Dumping time $t_{\text{dump}} = 2\text{--}4$ min;
- Vehicle mass range $m(t) = 45,000\text{--}110,000$ kg depending on the payload state.

With typical values of $L = 2.5$ km, $v_{\text{haul}} = 25$ km/h, and $v_{\text{return}} = 30$ km/h, the time parameters of the transport phases are

$$t_{\text{haul}} = \frac{L}{v_{\text{haul}}} \approx 6 \text{ min}, \quad t_{\text{return}} = \frac{L}{v_{\text{return}}} \approx 5 \text{ min}$$

As a result, the total duration of the typical cycle is about the following:

$$T_{\text{cycle}} \approx 18 \dots 20 \text{ min}$$

The resulting cycle structure is then used to construct longitudinal velocity, mass, and slope profiles of the track, which serve as inputs to the calculation of drag forces, instantaneous power on the wheels, and energy flows in a hybrid energy storage system [28].

2.2. Mining Duty Cycle Construction

For HESS sizing in mining electric dump trucks, the operating cycle must reflect not only vehicle speed but also road slope, payload state, haul distance, loading and dumping phases, and the direction of gravitational energy exchange [29]. Therefore, the primary simulations in this study are based on three segment-level mining duty cycles rather than on a passenger car driving cycle [30].

Cycle A represents conventional production haulage, in which the truck descends empty to the loading point, receives the payload, and then travels uphill in the loaded state. This cycle is dominated by traction energy demand during loaded uphill motion and has a limited regenerative braking potential during empty descent.

Cycle B represents reclamation or backfill operation, in which the truck travels uphill empty, receives material, and then descends loaded toward the backfill area. This cycle is dominated by high-power regenerative braking during loaded downhill motion and therefore imposes the most severe requirements on the supercapacitor buffer and the regenerative energy absorption capability of the HESS.

Cycle C represents mixed operating conditions, including both uphill and downhill segments with empty and loaded vehicle states. This cycle is used to evaluate intermediate HESS requirements between production haulage and reclamation/backfill operation.

Each duty cycle is represented as a sequence of segments with specified length, slope, target speed, payload state, vehicle mass, and duration. This segment-level representation makes it possible to calculate the instantaneous wheel power, distinguish traction and regenerative intervals, and evaluate the required battery and supercapacitor power flows under physically interpretable mining conditions. In Table 2 segment-level parameterization of the mining duty cycles used as primary simulation inputs is presented.

Table 2. Segment-level parameterization of the mining duty cycles used as primary simulation inputs.

Cycle	Segment	Operating Phase	Payload State	Mass Used in Model, kg	Length, km	Slope, %	Target Speed, km/h	Duration, min	Energy Role
A	A1	Empty descent to loading point	Empty	45,000	2.5	−8	30	5.0	Low-to-moderate regenerative braking
A	A2	Loading	Loading	45,000–110,000		0	0	5.0	Auxiliary / non-traction phase
A	A3	Loaded ascent to dumping point	Loaded	110,000	2.5	+8	25	6.0	Dominant traction energy demand
A	A4	Dumping	Emptying	110,000–45,000		0	0	3.0	Auxiliary / non-traction phase
B	B1	Empty ascent to loading point	Empty	45,000	2.5	+8	30	5.0	Moderate traction energy demand
B	B2	Loading	Loading	45,000–110,000		0	0	5.0	Auxiliary / non-traction phase
B	B3	Loaded descent to backfill area	Loaded	110,000	2.5	−8	25	6.0	Dominant regenerative braking pulse
B	B4	Dumping	Emptying	110,000–45,000		0	0	3.0	Auxiliary / non-traction phase
C	C1	Empty mixed-profile travel	Empty	45,000	1.2	+5	30	2.4	Traction
C	C2	Empty descent	Empty	45,000	1.3	−5	30	2.6	Regeneration
C	C3	Loading	Loading	45,000–110,000		0	0	5.0	Auxiliary / non-traction phase
C	C4	Loaded ascent	Loaded	110,000	1.2	+8	25	2.9	High traction
C	C5	Loaded descent	Loaded	110,000	1.3	−8	25	3.1	High regeneration
C	C6	Dumping	Emptying	110,000–45,000		0	0	3.0	Auxiliary / non-traction phase

The segment-level description in Table 3 defines the only primary simulation input used for HESS sizing in this study. The proposed mining duty cycles explicitly include payload variation, long low-speed haul segments, large positive and negative road grades, non-traction loading and dumping phases, and high-power regenerative braking during loaded descent. Therefore, all subsequent HESS sizing, Pareto filtering, energy-balance calculations, and sensitivity analyses are based on Cycles A–C and not on passenger car driving cycle assumptions.

The three primary mining duty cycles used in the model are summarized in Figure 1. The figure is intended to connect the technological operating phases with the corresponding traction and regenerative braking intervals [31]. Figure 1 is used as a generalized physical and technological interpretation of the operating cycle, built on the basis of the analysis of typical operating parameters of heavy-duty mining dump trucks and used in the work as a methodological basis for the formation of input modeling data and the subsequent interpretation of the calculated results [32].

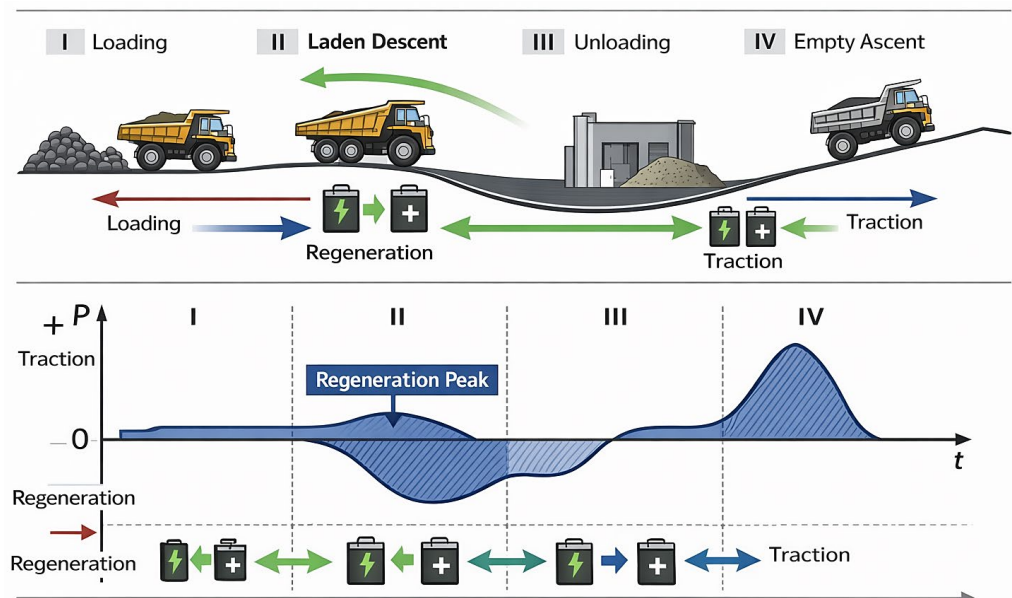


Figure 1. Segment-level mining duty cycle structure used for HESS sizing: production haulage, reclamation/backfill operation, and mixed operation. The diagram shows payload state, road slope sign, traction intervals, and regenerative braking intervals.

Figure 1 shows that Cycle B differs fundamentally from the production cycle because the loaded segment occurs on the downhill path. This produces the highest regenerative-braking power and therefore defines the most severe sizing case [33] for the supercapacitor branch.

The loading phase (I) is characterized by the absence of traction and, accordingly, insignificant energy flows, which can be negligible in further calculations. The main interest from the point of view of energy is the phase of loaded descent (II), during which the gravitational component of the force of motion exceeds the total drag forces. As a result, the traction electric drive enters the regenerative braking mode, forming pulses of negative power of high amplitude and limited duration, indicated on the graph as regeneration peak.

The unloading phase (III), like loading, makes a minimal contribution to the energy balance and serves as a transitional stage between the recuperative and traction parts of the cycle. In the phase of the reverse movement of the empty dump truck on a hill (IV), positive traction power is dominant, associated with overcoming the slope, rolling resistance and aerodynamic drag [34]. It is at this stage that the storage battery provides the bulk of the energy costs, while the supercapacitor performs the function of smoothing short-term power peaks [35]. Figure 1 clearly demonstrates the key feature of the operating cycle of mining dump trucks: energy-significant recovery is implemented in the form of short-term but high-power pulses, which are fundamentally different in time scale from the phases of traction energy consumption. This asymmetry in power and duration is a fundamental

factor that determines the feasibility of using a hybrid energy storage system and the need to optimize the parameters of the supercapacitor buffer [36].

Thus, the diagram presented in Figure 1 serves as a link between the technological description of the operating cycle and the formalized mathematical model used further to calculate the dynamics, energy balance and multi-criteria optimization of the parameters of the hybrid energy storage system.

2.3. Longitudinal Dynamics and Energy Balance Model

The instantaneous power required on the truck's wheels $P_{\text{wheel}}(t)$ is calculated based on the longitudinal dynamics equation:

$$P_{\text{wheel}}(t) = v(t)F_{\Sigma}(t),$$

where $P_{\text{wheel}}(t)$ is the mechanical power on the wheels; $v(t)$ is the instantaneous velocity, and is $F_{\Sigma}(t)$ the total force of resistance to motion (H), defined as

$$F_{\Sigma}(t) = F_{rr}(t) + F_{aero}(t) + F_{grade}(t) + F_{in}(t)$$

1. Rolling Resistance Force:

$F_{rr} = mgf_r \cos(\alpha)$ —rolling resistance force, where m is the total weight of the dump truck; g —acceleration due to gravity (9.81 m/s^2); f_r —rolling resistance coefficient; α —slope angle of the route (rad).

2. Aerodynamic Drag Force:

$F_{aero} = \frac{1}{2}\rho C_x A v^2$, where ρ is the density of the air (1.225 kg/m^3), C_x is the coefficient of aerodynamic drag, A and is the frontal area.

3. Gravitational Component (Grade Force):

$$F_{grade} = mg \sin(\alpha).$$

Takes a positive value on the ascent ($\alpha > 0$) and a negative value on the descent ($\alpha < 0$).

4. Inertial Force:

$F_{in} = \gamma ma$, where γ is the coefficient of inertia reduction of rotating and distributed masses (for electromechanical transmission $\gamma = 1.05 - 1.40$, usually, a is the longitudinal acceleration (m/s^2)).

The instantaneous HESS electrical power at the terminals $P_{\text{ess}}(t) = \begin{cases} \frac{P_{\text{wheel}}(t)}{\eta_{\text{drive}}\eta_{\text{conv}}}, & P_{\text{wheel}}(t) \geq 0 \\ P_{\text{wheel}}(t)\eta_{\text{regen}}\eta_{\text{conv}}, & P_{\text{wheel}}(t) < 0 \end{cases}$ is calculated taking into account the efficiency of the power circuit, where η_{drive} is the efficiency of the traction drive, η_{conv} is the efficiency of the power converter and electronics, and η_{regen} is the efficiency of recuperation.

The instantaneous power entering the energy storage system was determined based on the power on the wheels, taking into account the direction of the energy flow. In the traction mode, losses in the traction electric drive and power converters were taken into account, while in the recuperation mode, coefficients describing the efficiency of the reverse conversion and the limitations of the recuperation system were additionally introduced [37,38].

To avoid ambiguity in the interpretation of regenerative braking magnitudes, three power levels are distinguished in the model. The wheel-side mechanical power is calculated from the longitudinal dynamics equation before drivetrain conversion losses are applied.

The DC bus regenerative power is the electrical power available at the traction DC bus after regenerative drive efficiency is considered. The HESS-accepted regenerative power is the portion of the DC bus regenerative power that is actually absorbed by the battery and supercapacitor branches after SOC, voltage, current, ESR, and DC/DC converter power constraints are imposed. Any remaining power is assigned to the residual braking channel and is not counted as stored regenerative energy.

The net change in HESS energy over the full cycle ΔE_{cycle} is the integral of the power over the cycle time:

$$\Delta E_{\text{cycle}} = \int_0^{T_{\text{cycle}}} P_{\text{ess}}(t) dt$$

2.4. HESS Component Models and Semi-Active Topology

The HESS is modeled as a semi-active battery–supercapacitor topology. The LiFePO₄ battery branch is connected to the traction DC bus as the main energy source, whereas the supercapacitor branch is connected to the same DC bus through a bidirectional DC/DC converter. This converter provides voltage matching, current limitation, and bidirectional power exchange between the supercapacitor module and the traction bus. Therefore, the battery and supercapacitor are not treated as two ideal parallel sources; their power contributions are determined by a constrained supervisory control algorithm.

To clarify the physical structure of the proposed hybrid energy storage system and the logic of constrained power distribution, the semi-active HESS topology adopted in the present study is shown in Figure 2. The scheme highlights the functional roles of the LiFePO₄ battery branch, the supercapacitor branch, the bidirectional DC/DC converter, and the residual braking channel. In addition, Figure 2 identifies the key state and constraint variables used in the supervisory control algorithm, including the battery state of charge, supercapacitor voltage, branch currents, converter power, and residual braking power.

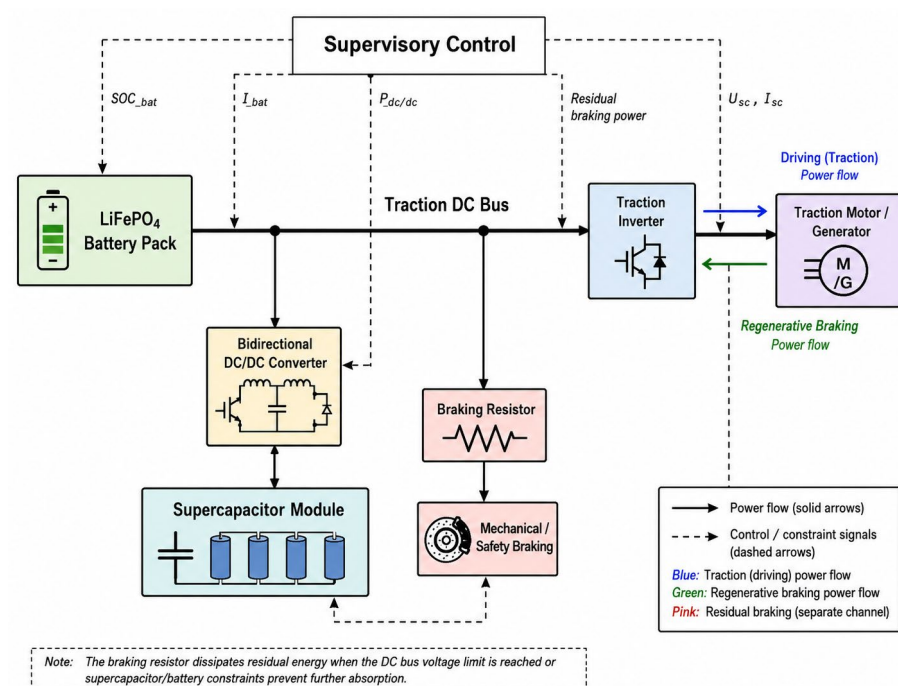


Figure 2. Semi-active battery–supercapacitor HESS topology used in the model: LiFePO₄ battery branch connected to the traction DC bus, supercapacitor branch connected through a bidirectional DC/DC converter, traction inverter and motor, regenerative braking path, braking resistor, and mechanical/safety braking channel. The diagram also indicates the limiting variables used in the control algorithm: SOC_{bat} , U_{sc} , I_{bat} , I_{sc} , $P_{\text{dc/dc}}$ and residual braking power.

As shown in Figure 2, the battery branch acts as the main energy source and is primarily responsible for supplying the slowly varying component of the traction power demand. By contrast, the supercapacitor branch is interfaced through a bidirectional DC/DC converter and is intended to absorb short high-power regenerative pulses and to support rapid transient power exchange. Such a semi-active topology makes it possible to decouple the voltage behavior of the supercapacitor from the main DC bus and to impose explicit limits on supercapacitor voltage, converter power, and branch currents.

Figure 2 also clarifies the role of the residual braking channel, which is essential for physically realistic modeling of regenerative braking. When the battery charge acceptance capability, supercapacitor voltage window, or DC/DC converter rating is reached, the remaining braking power cannot be stored and must be dissipated through the braking resistor or the mechanical/safety braking system. Therefore, the figure provides the structural basis for the constrained supervisory control model used in the subsequent sections and explains why the stored regenerative energy fraction in the revised manuscript is evaluated only from the portion of braking energy actually accepted by the HESS under the imposed limits.

1. Battery model, thermal response, and degradation stress indicators:

The LiFePO₄ battery branch is represented by a first-order Thevenin equivalent circuit with SOC- and temperature-dependent parameters. This model extends the simple open-circuit voltage plus internal resistance representation and makes it possible to account for polarization voltage, current rate effects, and heat generation at system level.

The terminal voltage of the battery pack is calculated as

$$U_{\text{bat}}(t) = \text{OCV}(\text{SOC}, T) - I_{\text{bat}}(t)R_0(\text{SOC}, T) - U_p(t),$$

where U_{bat} is the battery terminal voltage, $\text{OCV}(\text{SOC}, T)$ is the open-circuit voltage, I_{bat} is the battery current, $R_0(\text{SOC}, T)$ is the ohmic resistance, and $U_p(t)$ is the polarization voltage of the RC branch.

The polarization dynamics are described as $-\frac{U_p}{R_p C_p} + \frac{I_{\text{bat}}}{C_p}$, where R_p and C_p are the equivalent polarization resistance and capacitance.

The battery SOC dynamics are calculated as $-\frac{I_{\text{bat}}(t)}{Q_{\text{nom}}}$, where Q_{nom} is the nominal pack capacity in ampere-hours. The model enforces the operating window:

$$\text{SOC}_{\min} \leq \text{SOC}(t) \leq \text{SOC}_{\max}.$$

The thermal response of the battery pack is described by a lumped heat balance equation:

$$C_{\text{th, bat}} = h_{\text{bat}} A_{\text{bat}} (T_{\text{bat}} - T_{\text{amb}}),$$

where $C_{\text{th, bat}}$ is the equivalent thermal capacity of the pack, T_{bat} is the battery temperature, T_{amb} is the ambient temperature, $h_{\text{bat}} A_{\text{bat}}$ is the equivalent heat transfer coefficient, $I_{\text{bat}}^2 R_0$ is ohmic heat generation, and $I_{\text{bat}} U_p$ is polarization-related heat generation.

Because the present study is aimed at system-level HESS sizing and not at experimentally calibrated lifetime prediction, battery degradation is not reported as an absolute cycle life value. Instead, the following normalized aging stress indicators are used:

$$S_{I, \text{RMS}} = \frac{I_{\text{bat, RMS, HESS}}}{I_{\text{bat, RMS, B0}}}.$$

$$S_{I, \text{peak}} = \frac{\max |I_{\text{bat, HESS}}|}{\max |I_{\text{bat, B0}}|},$$

where $S_{I,RMS}$ is the normalized RMS current stress indicator; $S_{I,peak}$ is the normalized peak current stress indicator. These indicators are used only to compare candidate HESS configurations under identical duty cycle assumptions. They should not be interpreted as a calibrated prediction of battery lifetime without experimental aging data for the specific cell, pack, cooling system, and charge/discharge protocol.

2. Supercapacitor model and usable energy window:

The supercapacitor branch is described by the equivalent module capacitance C_{sc} , the equivalent series resistance R_{ESR} , and the permissible operating voltage window $U_{sc,min}$, $U_{sc,max}$. In contrast to a battery, the capacitance value in farads does not directly define the energy that can be absorbed during regenerative braking. Therefore, the usable supercapacitor energy is calculated from the voltage window:

$$E_{sc,use} = \frac{1}{2} \frac{C_{sc} (U_{sc,max}^2 - U_{sc,min}^2)}{3.6 \cdot 10^6},$$

where $E_{sc,use}$ is the usable supercapacitor energy, kWh; C_{sc} is the equivalent capacitance of the supercapacitor module, F; $U_{sc,max}$ and $U_{sc,min}$ are the maximum and minimum allowable module voltages, V.

When converter and module losses are included, the net usable energy is written as

$$E_{sc,use,net} = \eta_{dc/dc} \eta_{sc} \frac{1}{2} \frac{C_{sc} (U_{sc,max}^2 - U_{sc,min}^2)}{3.6 \cdot 10^6},$$

where $\eta_{dc/dc}$ is the bidirectional DC/DC converter efficiency and η_{sc} accounts for internal supercapacitor losses. In the baseline calculations, the voltage window is set as $U_{sc,max} = 0.8U_{dc,nom}$ and $U_{sc,min} = 0.4U_{dc,nom}$. For $U_{dc,nom} = 700$ V, this corresponds to $U_{sc,max} = 560$ V and $U_{sc,min} = 280$ V.

The battery usable energy is defined as

$$E_{bat,use} = E_{bat,nom} (SOC_{max} - SOC_{min})$$

where $E_{bat,nom}$ is the nominal battery energy capacity, kWh; SOC_{max} and SOC_{min} define the allowed battery operating window. In the baseline model, $SOC_{max} = 0.95$ and $SOC_{min} = 0.20$.

The primary HESS sizing indicator is therefore the dimensionless usable energy-buffer ratio

$$\rho_E = \frac{E_{sc,use,net}}{E_{bat,use}}.$$

The capacitance C_{sc} remains a design variable, but it is not divided directly by the battery energy capacity. All Pareto maps, tables, nomograms, and conclusions are reported using the physically consistent indicator ρ_E , while C_{sc} is retained only to specify the equivalent supercapacitor module design.

3. Constrained frequency-splitting supervisory control.

A constrained frequency-splitting supervisory control strategy is used to distribute the traction bus power demand between the battery and the supercapacitor branch. The objective is to assign slowly varying energy demand to the battery and short high-power transients to the supercapacitor, while satisfying SOC, voltage, current, converter-power, and braking safety constraints.

The bus power $P_{bus}(t)$ is defined as positive in traction mode and negative in regenerative braking mode. The unconstrained battery power command is generated using a first-order low-pass filter (for the Laplace variable s):

$$P_{\text{bat}}^0(s) = G_{\text{LPF}}(s)P_{\text{bus}}(s), \quad G_{\text{LPF}}(s) = \frac{1}{\tau s + 1},$$

where P_{bat}^0 is the preliminary battery power command, P_{bus} is the traction bus power demand, and τ is the filter time constant. The preliminary supercapacitor command is then calculated as

$$P_{\text{sc}}^0(t) = P_{\text{bus}}(t) - P_{\text{bat}}^0(t)$$

The preliminary commands are subsequently passed through a supervisory saturation layer:

$$\begin{aligned} SOC_{\min} &\leq SOC_{\text{bat}}(t) \leq SOC_{\max}, \\ U_{\text{sc},\min} &\leq U_{\text{sc}}(t) \leq U_{\text{sc},\max}, \\ -P_{\text{bat,ch,max}}(SOC, T) &\leq P_{\text{bat}}(t) \leq P_{\text{bat,dis,max}}(SOC, T), \\ -P_{\text{sc,ch,max}}(U_{\text{sc}}, T) &\leq P_{\text{sc}}(t) \leq P_{\text{sc,dis,max}}(U_{\text{sc}}, T), \\ |P_{\text{dc/dc}}(t)| &\leq P_{\text{dc/dc,max}}. \end{aligned}$$

Here, negative power denotes charging during regenerative braking, and positive power denotes discharge during traction. The battery charge and discharge limits depend on SOC and temperature, whereas the supercapacitor limits depend on module voltage, ESR, thermal state, and the bidirectional DC/DC converter rating.

When the demanded regenerative braking power exceeds the instantaneous charge acceptance capability of the HESS, the residual power is not stored but is assigned to the braking resistor and mechanical/safety braking channel:

$$P_{\text{regen,req}} = P_{\text{bat,ch}}(t) + P_{\text{sc,ch}}(t) + P_{\text{dc/dc,loss}}(t) + P_{\text{br,res}}(t),$$

where $P_{\text{regen,req}}$ is the regenerative braking power available at the traction bus, $P_{\text{bat,ch}}$ and $P_{\text{sc,ch}}$ are the powers accepted by the battery and supercapacitor, $P_{\text{dc/dc,loss}}$ is the converter loss, and $P_{\text{br,res}}$ is the residual braking power dissipated by the braking resistor or mechanical braking system.

The DC/DC converter loss is approximated by

$$P_{\text{dc/dc,loss}}(t) = (1 - \eta_{\text{dc/dc}})|P_{\text{dc/dc}}(t)|,$$

where $\eta_{\text{dc/dc}}$ is the bidirectional converter efficiency. The supercapacitor ohmic loss is estimated as

$$P_{\text{sc,loss}}(t) = I_{\text{sc}}^2(t)R_{\text{ESR}},$$

where I_{sc} is the supercapacitor branch current and R_{ESR} is the equivalent series resistance of the module.

The filter time constant τ is not treated as an arbitrary parameter. For each candidate HESS configuration, τ is selected within the bounded interval τ in s [2,20] by minimizing the same multi-objective criterion used in the HESS sizing task. A practical initial value is estimated from the characteristic regenerative pulse duration and the usable supercapacitor energy:

$$\tau_0 = \text{clip}\left(k_{\tau} \frac{3600E_{\text{sc,use}}}{P_{\text{regen,max}}}, \tau_{\min}, \tau_{\max}\right),$$

where $E_{sc,use}$ is expressed in kWh, $P_{regen,max}$ is expressed in kW, k_τ is an empirical tuning coefficient, and $\text{clip}(\cdot)$ limits the value to the interval $[\tau_{min}, \tau_{max}]$. The final τ is selected by grid search together with the HESS design variables.

2.5. Constrained Supervisory Control and Optimization Problem

The problem of parametric optimization of a hybrid energy storage system is formulated in a general form for the vector of design variables $\mathbf{x} = [C_{bat} \ C_{sc}]^T$.

The design vector includes the nominal battery energy capacity $E_{bat,nom}$ in kWh and the equivalent supercapacitor module capacitance C_{sc} in F. Since these quantities have different physical dimensions, their direct ratio is not used as an optimization output. Instead, the optimization results are reported through the dimensionless usable energy-buffer ratio $\rho_E = \frac{E_{sc,use,net}}{E_{bat,use}}$.

Optimization is performed when there are many targets' functions

$$f(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}), \dots\}$$

and systems of technical constraints

$$g(\mathbf{x}) \leq 0,$$

imposed on the permissible area of design solutions.

Minimizing the electrical load on the battery is considered as one of the key target functions, quantified through the rms value of the battery current over one operating cycle:

$$f_1(\mathbf{x}) = I_{bat,RMS} \sqrt{\frac{1}{T_{cycle}} \int_0^{T_{cycle}} I_{bat}^2(t) \cdot dt},$$

where $I_{bat}(t)$ is the instantaneous current of the battery, and T_{cycle} is the duration of the operating cycle.

As a technical limitation, a limit on the peak power transmitted by HESS elements can be formulated:

$$P_{ess}(t) \leq P_{ess,max}(t), \quad \forall t,$$

where $P_{ess,max}$ is the maximum permissible power of the power drive and storage device.

Thus, the optimization problem is aimed at finding a globally optimal configuration of a hybrid energy storage system by varying two key parameters— C_{bat} and C_{sc} —while simultaneously meeting a set of physical, structural, and operational constraints [39].

Then the peak power restrictions will be

$$g_1(\mathbf{x}) = \max_t |P_{ess}(t)| - P_{sc}^{max}(C_{sc}) \leq 0$$

To formalize the permissible range of HESS design parameters, the following system of constraints is introduced, while the optimization task is aimed at finding the global optimum of the HESS layout by varying two key variables:

$E_{bat,nom}$ is the nominal battery energy capacity, kWh.

C_{sc} is the equivalent capacitance of the supercapacitor module, F.

$E_{bat,use}$ is the usable battery energy within the allowed SOC window, kWh.

$E_{sc,use,net}$ is the usable supercapacitor energy within the allowed voltage window after converter and module losses, kWh.

$\rho_E = \frac{E_{sc,use,net}}{E_{bat,use}}$ is the dimensionless HESS usable energy buffer ratio.

Restriction system. Let us introduce a system of constraints that formalizes the permissible range of the design parameters of the hybrid energy storage system (HESS):

1. Weight and size limitation:

$$m_{bat}(c_{bat}) + m_{sc}(c_{sc}) \leq m_{essmax}. \quad (1)$$

This inequality reflects the design and layout limitation and means that the total weight (or equivalent weight and dimensions) of the battery and supercapacitor module should not exceed the maximum permissible value set by the requirements for the object (chassis, power plant, vehicle) [40]. Functional dependencies $m_{bat}(c_{bat})$ and $m_{sc}(c_{sc})$ emphasize that the mass of the relevant components is a function of their nominal energy capacity (or electrical capacity) and, indirectly, the selected electrochemical and structural technology.

2. Basic cycle energy limitation: $C_{bat} \cdot DoD_{bat} \geq E_{cyclebase}$. This condition requires that the battery in single mode (without the participation of a supercapacitor) be able to meet the energy needs of the basic operating cycle. Here: C_{bat} —nominal energy capacity of the battery; DoD_{bat} —permissible depth of discharge, which limits the operating range of the battery in terms of resource; $E_{cyclebase}$ is the energy required to perform the basic load cycle [41]. The meaning of this limitation is to ensure the functional redundancy and reliability of the system: the supercapacitor is considered as a means of improving dynamics and reducing peak loads, but not as a mandatory source of energy for the main cycle. Thus, the design solution in which the correct operation of the system critically depends on the presence of a supercapacitor link is excluded [42].

3. Power limitation: $P_{scmax}(C_{sc}) \geq P_{peakcycle}$, where $P_{peakcycle}$ is the maximum peak power in the cycle.

4. By current: $I_{bat}(t) \leq I_{batmax}(SOC, T)$ for all values of time t .

5. By voltage: the operating voltage ranges of the battery and SC are matched through the DC/DC converter.

In Table 3, control and component constraints used in the constrained HESS model are presented.

Table 3. Control and component constraints used in the constrained HESS model.

Constraint Group	Variable	Baseline Value	Sensitivity Range	Function in the Model
Battery SOC window	SOC_{bat}	0.20–0.95	0.15–0.95	Prevents deep discharge and overcharge
Supercapacitor voltage window	U_{sc}	$0.4U_{dc,nom} - 0.8U_{dc,nom}$	$0.35 - 0.85U_{dc,nom}$	Defines usable SC energy and voltage safety margin
Nominal DC bus voltage	$U_{dc,nom}$	700 V	600–800 V	Voltage reference for converter matching
Battery continuous charge limit	$P_{bat,ch,cont}$	0.5 C-rate equivalent	0.3–1.0 C	Limits long regenerative charging
Battery pulse charge limit	$P_{bat,ch,pulse}$	1.0 C-rate equivalent	0.5–1.5 C	Limits short regenerative pulses
Battery discharge limit	$P_{bat,dis,max}$	1.0 C-rate equivalent	0.8–2.0 C	Limits traction power drawn from battery
Bidirectional DC/DC converter rating	$P_{dc/dc,max}$	750 kW	500–1000 kW	Limits SC branch charge/discharge power
DC/DC converter efficiency	$\eta_{dc/dc}$	0.96	0.94–0.98	Accounts for converter loss
Equivalent SC module ESR	R_{ESR}	0.02 Ω	0.01–0.05 Ω	Accounts for supercapacitor ohmic loss
Residual braking channel	$P_{br,res}$	calculated	—	Dissipates regenerative power not accepted by HESS
Control filter time constant	τ	optimized	2–20 s	Determines battery/SC power split

The limits in Table 3 are used at every calculation step. Therefore, the reported stored regenerative energy fraction is not calculated from the theoretical regenerative energy alone but from the portion of regenerative energy actually accepted by the constrained battery–supercapacitor HESS after converter, ESR, SOC, voltage, current, and power limitations have been applied.

Objective functions (multi-criteria optimization):

1. Minimizing Net Energy Consumption: $F_1 = \min(\Delta E_{cycle})$.
2. Minimizing battery load: $F_2 = \min(RMS(I_{bat}(t)))$ to extend battery life.
3. System Weight Minimization: $F_3 = \min(m_{bat} + m_{sc})$.

To find compromise solutions, a Pareto front is built, and the final choice of configuration is made taking into account the design priorities (durability and cost) [43].

The optimization procedure is implemented as a reproducible grid-based Pareto search. For each duty cycle and each candidate set $E_{bat,nom}$, C_{sc} , τ , the time domain simulation is performed over the complete segment-level duty cycle. At every time step, the constrained supervisory control algorithm updates SOC_{bat} , U_{sc} , battery current, SC current, accepted regenerative energy, residual braking energy, and component losses. A candidate solution is considered feasible only if all SOC, voltage, current, converter power, and mass constraints are satisfied. The Pareto set is then obtained by non-dominated sorting in the objective function space consisting of net cycle energy, battery RMS current, and HESS mass.

The grid spacing was set to 25 kWh for $E_{bat,nom}$, C_{sc} , τ , 5–10 F for C_{sc} , and 1 s for τ . The complete search required fewer than 10^4 candidate simulations per duty cycle and was fully repeatable because no stochastic optimizer was used.

For clarity and to avoid ambiguity in the mathematical notation used in the vehicle-dynamics, HESS, control, and optimization models, the principal symbols are summarized in Table 4. The symbols are also defined in the relevant equations where they first appear; therefore, the nomenclature table is used as a compact reference rather than as a substitute for local definitions in the main text.

Table 4. Nomenclature used in the mathematical model.

Symbol	Description	Unit
m_0	Tare mass of the mining dump truck	kg
m_{pay}	Nominal payload	kg
$m(t)$	Instantaneous vehicle mass depending on payload state	kg
$v(t)$	Vehicle speed	m/s
$a(t)$	Longitudinal acceleration	m/s ²
L_i	Length of duty cycle segment	km
α_i	Road slope angle or grade of segment	rad or %
f_r	Rolling resistance coefficient	–
C_x	Aerodynamic drag coefficient	–
A	Frontal area	m ²
P_w	Mechanical power at the wheels	kW
P_{bus}	Electrical power demand at the traction DC bus	kW
P_{bat}	Battery branch power	kW
P_{sc}	Supercapacitor branch power	kW
$P_{dc/dc}$	Bidirectional DC/DC converter power	kW
$P_{br,res}$	Residual braking power dissipated in braking resistor/mechanical braking	kW
$E_{bat,nom}$	Nominal battery energy capacity	kWh
$E_{bat,use}$	Usable battery energy within the SOC window	kWh
C_{sc}	Equivalent supercapacitor module capacitance	F
$E_{sc,use}$	Usable supercapacitor energy within the voltage window	kWh
ρ_E	Dimensionless usable energy buffer ratio $\frac{E_{sc,use}}{E_{bat,use}}$	–
SOC_{bat}	Battery state of charge	–
U_{sc}	Supercapacitor module voltage	V
$U_{dc,nom}$	Nominal traction DC bus voltage	V
I_{bat}	Battery current	A
I_{sc}	Supercapacitor branch current	A
R_0	Battery ohmic resistance	Ω
R_p	Battery polarization resistance	Ω
C_p	Battery polarization capacitance	F

Table 4. Cont.

Symbol	Description	Unit
R_{ESR}	Equivalent series resistance of the supercapacitor module	Ω
T_{bat}	Battery temperature	K or $^{\circ}\text{C}$
T_{amb}	Ambient temperature	K or $^{\circ}\text{C}$
η_{drive}	Traction drive efficiency	—
η_{regen}	Regenerative drive efficiency before storage limits	—
$\eta_{dc/dc}$	Bidirectional DC/DC converter efficiency	—
τ	Time constant of the constrained frequency-splitting controller	s
$I_{bat,RMS}$	Root-mean-square battery current over a duty cycle	A
$S_{I,RMS}$	Normalized RMS current stress indicator	—
S_T	Normalized thermal stress indicator	—

Table 1 provides a consolidated reference for the variables used in the mathematical model, including vehicle dynamics quantities, HESS component parameters, control variables, and stress indicators.

2.6. Calculation Methods and Tools

The calculations were performed in a specialized mathematical modeling environment in Python 3.11 using the SciPy and NumPy libraries for solving differential equations and optimization. The model is implemented as a step-by-step calculation procedure with a step of $\Delta t = 0.1\text{--}1.0$ s, taking into account the change in the parameters of the route, mass, and HESS control algorithm over time [44]. Verification was carried out by comparing the calculated values with the published data on electric mining dump trucks and the results of works [1,2] used as the main reference sources. The materials [45] were used for external verification of the orders of magnitude: the deviation of the calculated energy consumption per cycle did not exceed 8%, which confirms the applicability of the developed model. The approach described in [46] further confirms the relevance of mathematical models for assessing energy efficiency in the mining industry. Such a methodical outline allows for you to move on to parametric analysis and determination of optimal capacitance ratios in HESS.

2.7. Benchmark-Based Verification and Uncertainty Assessment

The purpose of this section is not to claim full experimental validation of the complete battery–supercapacitor HESS. Instead, the model is benchmark-verified at system level by comparing the pure battery reference configuration with publicly available data and previously published calculations for the same vehicle class. The HESS-specific results are additionally checked by energy balance closure, constraint satisfaction, and uncertainty analysis. Therefore, as the verification should be interpreted as benchmark-based system-level verification rather than independent field validation [47,48], a comparison of the calculated data with the published reference sources was carried out. The following are used as basic verification objects: the benchmark verification was performed for the same 65 t payload-class reference vehicle used in the model. Public Komatsu HD605-7/E-Dumper-class data were used only as an external scale reference, including a tare mass of approximately 45 t, a payload of approximately 65 t, and a battery capacity reported in the public benchmark range of about 600–700 kWh. The baseline configuration in the present model uses $E_{bat} = 600$ kWh, whereas the wider range $E_{bat} = 400\text{--}800$ kWh is treated as a design variable in the HESS optimization procedure.

The comparison was carried out for the basic configuration of a “pure battery dump truck” ($C_{bat} = 600$ kWh, $C_{sc} = 0$) when driving along the typical quarry cycle described

in Section Operating Cycle of a 65 t Payload-Class Mining Dump Truck. The following integral and peak indicators were evaluated:

- Total electricity consumption from the on-board storage unit per cycle;
- Maximum regenerative braking power;
- RMS current of the battery;
- Acceleration time of the unloaded dump truck to a speed of 15 km/h.

The results of the comparison are presented in Table 5.

Analysis of the data in Table 5 shows that the discrepancy between the calculated and reference values does not exceed 6% for all the parameters considered. The largest deviation (5.6%) was recorded for the acceleration time, which is explained by the simplified consideration of the inertial characteristics of the transmission in the model. The comparison in Table 5 indicates that the vehicle-level longitudinal dynamics and pure battery energy balance model reproduce the order of magnitude of the benchmark indicators with deviations generally below 6–8%. However, this comparison does not constitute independent field validation of the complete HESS architecture because the supercapacitor branch, bidirectional DC/DC converter, and supervisory control algorithm were not tested against measured HESS telemetry [49]. For this reason, the model is used as a constrained system-level sizing tool rather than as a final design certification model.

Table 5. Comparison of calculated and reference indicators.

Indicator	Designation, s605.	Calculation (This Model)	Komatsu HD605-7 Data [30]	Results [1,2]	Deviation from [30], %	Deviation from [1,2], %
Power consumption per cycle	ΔE_{cycle} , kWh	86.4	84.5 *	87.2	+2.2	−0.9
Maximum regenerative braking power	P_{regen_max} , kW	750	—	720	—	+4.2
RMS battery current	I_{bat} , RMS, A	365	—	350	—	+4.3
Acceleration time to 15 km/h (laden)	TACC, with	28.5	27.0	29.0	+5.6	−1.7

*—the value has been adjusted to take into account the differences in the mass and profile of the track.

In Table 6, uncertainty ranges used for robustness assessment of the constrained HESS model are presented.

Table 6. Uncertainty ranges used for robustness assessment of the constrained HESS model.

Parameter Group	Symbol	Baseline Value	Uncertainty/Sensitivity Range	Main Affected Outputs
Rolling resistance coefficient	f_r	0.020	0.015–0.025	Wheel power, net cycle energy
Road slope	α	segment-specific	± 1.0 percentage point	Regenerative power, traction energy
Vehicle mass	$m(t)$	45–110 t	$\pm 5\%$	Wheel power, regenerative pulse energy
Traction drive efficiency	η_{drive}	0.92	0.91–0.94	Traction energy
Regenerative efficiency before storage limits	η_{regen}	0.88	0.85–0.92	Recoverable energy
DC/DC converter efficiency	$\eta_{dc/dc}$	0.96	0.94–0.98	Stored regenerative energy, SC losses
Battery ohmic resistance	R_0	SOC, T-dependent	$\pm 20\%$	Battery heat generation, terminal voltage
Polarization resistance	R_p	SOC, T-dependent	$\pm 20\%$	Dynamic voltage response, heat generation
Battery thermal parameter	$h_{bat}A_{bat}$	lumped	$\pm 25\%$	Battery temperature rise
Supercapacitor ESR	R_{ESR}	module-specific	$\pm 25\%$	SC losses, voltage drop
Ambient temperature	T_{amb}	25 °C	−20 to +40 °C	Resistance, thermal stress
Battery charge limit	$P_{bat,ch,max}$	C-rate based	0.5–1.5 C pulse	Residual braking, battery stress
DC/DC converter rating	$P_{dc/dc,max}$	750 kW	500–1000 kW	Stored fraction of regenerative energy
Control time constant	τ	optimized	2–20 s	Battery RMS current, SC utilization

For each candidate HESS configuration, the uncertainty assessment recalculates the main outputs over the parameter ranges shown in Table 6. The reported outputs include net cycle energy, stored regenerative energy fraction, battery RMS current, maximum battery temperature rise, residual braking energy, and the normalized aging stress indicators. This procedure does not replace experimental validation, but it quantifies the robustness of the comparative HESS sizing conclusions to the main modeling assumptions.

3. Results

Parametric analysis and multi-criteria optimization of the hybrid energy storage system were performed for three typical operating cycles of a mining dump truck.

3.1. Power and Energy Flow Profiles for Mining Duty Cycles

The analysis of the instantaneous profiles of the power consumed and recovered by the onboard energy storage system was carried out in explicit reference to the phases of the typical operating cycle of the mining truck, as described in Section Operating Cycle of a 65 t Payload-Class Mining Dump Truck. This approach makes it possible to interpret energy peaks not abstractly, but as a direct consequence of technological operations and motion conditions [50].

For the reclamation duty cycle (Cycle B), the instantaneous electrical power demand of the onboard energy storage system follows four successive operating phases: loading, downhill travel of the loaded dump truck, unloading, and uphill return of the empty vehicle. This sequence reflects the technological organization of the operating cycle and provides a physically interpretable framework for analyzing the evolution of traction and regenerative power throughout the cycle.

The loading phase (I) is characterized by zero or near-zero traction power and short-term auxiliary loads that do not have a significant impact on the energy balance of the cycle [51].

The most energy-intensive regenerative phase is the loaded descent in Cycle B. During this interval, the gravitational component of the longitudinal force exceeds the rolling and aerodynamic resistance forces, and the electric drive operates in regenerative braking mode. For the adopted Cycle B parameters, the peak DC bus regenerative power is approximately 550–750 kW. This value refers to electrical power available at the traction DC bus before HESS storage constraints are applied [52]. The actually stored portion is lower when the battery charge acceptance limit, supercapacitor voltage window, supercapacitor current limit, or bidirectional DC/DC converter rating is reached. The remaining non-accepted power is assigned to the residual braking channel [53].

The unloading phase (III), similar to the loading phase, is characterized by the absence of significant energy flows and serves as a temporary separator between the regenerative and traction parts of the cycle.

In the reverse phase of the empty dump truck (IV), the positive tractive power associated with overcoming the incline and resistance to movement dominates. In this phase, the battery provides the bulk of the energy, while the supercapacitor is mainly involved in smoothing out short-term power peaks during acceleration [54].

Thus, the analysis of the power profiles shows that the loaded downhill segment of Cycle B is the critical event for HESS sizing. It produces the highest DC bus regenerative power among the considered mining duty cycles and therefore determines the required supercapacitor buffer, converter power rating, battery charge current limitation, and residual braking energy fraction [55].

3.2. Pareto Maps and Objective Function Analysis

Parametric analysis was performed over a unified design range of 400–800 kWh for the nominal battery energy capacity and 0–150 F for the equivalent supercapacitor module capacitance. For each pair of design variables and for each mining duty cycle, the model calculated net cycle energy, battery RMS current, stored regenerative energy fraction, residual braking energy, HESS mass, and the corresponding dimensionless usable energy-buffer ratio.

For all cycles, there was a pronounced nonlinear dependence of the improvement in target functions on the growth of C_{sc} at low values of the latter with a subsequent “plateau” where a further increase in the capacitance of the supercapacitor had an insignificant effect [56]. The threshold for reaching a plateau significantly depended on the type of cycle.

Based on the calculations for each pair of C_{bat} and C_{sc} , a Pareto front in the objective function space was constructed. Table 7 summarizes the characteristics of the optimal solutions for each cycle.

Table 7. Characteristics of Pareto-optimal HESS configurations for different mining duty cycles using the dimensionless usable energy buffer ratio.

Cycle	Dominant Energy Feature	Typical C_{sc} , F	$E_{sc,use}$, kWh	$E_{bat,use}$, kWh	Recommended ρ_E , %	RMS Current Reduction, %	Stored Regenerative Energy Fraction, %	Typical SC Power, kW
A, production haulage	loaded uphill traction, limited regeneration	25–45	0.8–1.5	450–525	0.15–0.30	15–25	60–75	250–350
B, reclamation/backfill	loaded downhill regenerative braking	75–110	2.4–3.6	450–525	0.45–0.75	40–55	90–97	600–750
C, mixed duty cycle	mixed traction and regeneration	45–70	1.5–2.3	450–525	0.30–0.45	25–40	75–90	400–550

Reduced RMS battery current compared to a pure battery configuration at the same capacity C_{bat} . The stored regenerative energy fraction refers to the share of DC bus regenerative energy accepted by the constrained HESS. It does not include residual braking energy dissipated outside the storage system.

The values C_{sc} in Table 7 are not interpreted as a direct ratio to the battery energy capacity. They are converted into usable supercapacitor energy through the voltage window equation. Therefore, the reported optimization indicator is ρ_E , which is dimensionless and physically comparable across different battery sizes and supercapacitor voltage windows.

3.3. Representative HESS Configurations and Battery Stress Indicators

Based on the analysis of the Pareto front, representative optimal configurations were selected for each cycle, representing the balance between efficiency, weight and cost:

- A1 configuration: $E_{bat,nom} = 700$ kWh, $C_{sc} = 35$ F, $E_{sc,use} \approx 1.14$ kWh, $E_{bat,nom} \approx 525$ kWh, $\rho_E \approx 0.22$ %.
- B1 configuration: $E_{bat,nom} = 650$ kWh, $C_{sc} = 85$ F, $E_{sc,use} \approx 2.78$ kWh, $E_{bat,nom} \approx 487.5$ kWh, $\rho_E \approx 0.57$ %.
- C1 configuration: $E_{bat,nom} = 680$ kWh, $C_{sc} = 55$ F, $E_{sc,use} \approx 1.80$ kWh, $E_{bat,nom} \approx 510$ kWh, $\rho_E \approx 0.35$ %.

To assess the effect of a hybrid energy storage system on the operating conditions of batteries under realistic heavy operation [57], an analysis of the battery current in the time domain was performed for Cycle B, corresponding to the representative operating cycle of a large mining truck.

The battery current profiles shown in Figure 3 were obtained by postprocessing the results of the calculation scheme described in Section 2, which together took into account the longitudinal dynamics of the vehicle, the behavior of the traction motor, and the energy

management strategy. For each design option, the instantaneous current of the battery $I_{bat}(t)$ was calculated based on the power and voltage at the battery terminals, taking into account the internal resistance and power limits of the battery model [58].

Two system architectures under the same operating conditions were considered: a purely battery energy storage system and a hybrid (B1) configuration combining a lithium-ion battery with a supercapacitor module [59]. In both cases, the same vehicle weights, road profile, traction power requirement, and regenerative braking conditions were used, providing a uniform basis for comparison [60].

The adopted control strategy gives priority to the supercapacitor in high-power transient conditions, especially during regenerative braking in the loaded descent phase, while the battery is responsible for supplying medium traction energy [61]. This approach allows for you to directly quantify the effect of a supercapacitor on peak current reduction and current profile smoothing.

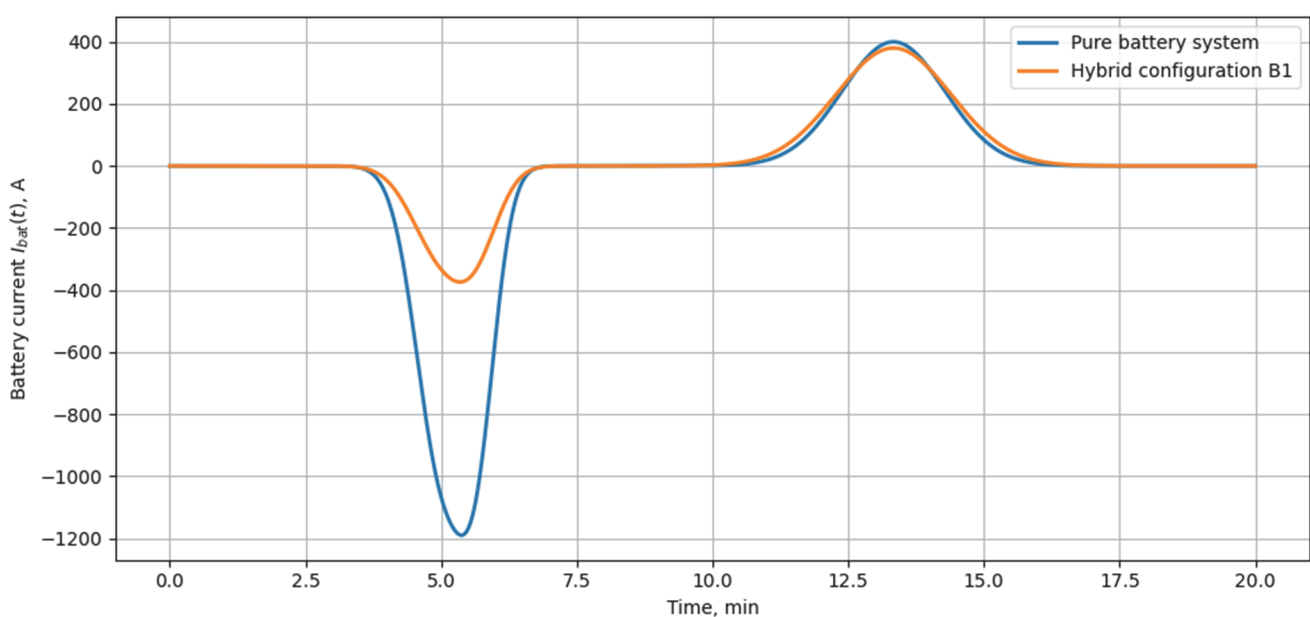


Figure 3. Comparison of battery current profiles for Cycle B obtained for a pure battery system and hybrid configuration B1.

The resulting battery current history for both configurations is shown in Figure 3, allowing for you to directly compare the charge and discharge modes over the entire operating cycle.

The effect of a hybrid energy storage system on battery operating conditions is shown in Figure 3, which compares the $I_{bat}(t)$ battery current time profiles for Cycle B obtained for a pure battery system and hybrid configuration B1.

In the case of a purely battery system, the regenerative braking phase corresponding to the loaded descent segment results in high peaks of negative charging current, reaching approximately -950 A. Such current levels exceed the recommended limits for long-term battery operation and are associated with accelerated degradation, increased heat load, and reduced cyclic life [62].

When the supercapacitor is included in the B1 configuration, the peak regenerative current of the battery charge is limited to approximately 280 A. This reduction is achieved by redirecting powerful short-term regenerative pulses to the supercapacitor, while the battery operates at a much smoother current [63].

In addition to reducing the maximum current, the hybrid configuration results in a significant reduction in the battery's RMS current. For the duty cycle in question, the

RMS(I_{bat}) value is reduced by about 52% compared to a purely battery system, indicating a marked reduction in the electrochemical and thermal load of the battery [64].

It can also be seen from Figure 3 that the positive traction current during the lifting phase of the empty truck remains virtually unchanged between the two configurations. This observation confirms that the main role of the supercapacitor is to process high-power transients rather than to provide long-term thrust energy [65]. Table 4 presents the key battery current metrics obtained for different energy storage configurations under the same operating conditions.

Table 8 summarizes the key battery current metrics obtained for different energy storage configurations under the same operating conditions. The results show that increasing the power of the supercapacitor subsystem primarily affects peak charging currents and RMS values, while peak discharge currents remain virtually unchanged [66].

Table 8. Battery current metrics for different energy storage configurations (cycle B).

Configuration	Peak Charging Current, A	Peak Discharging Current, A	RMS Battery Current, A	RMS Reduction vs. Battery-Only
Battery-only	−950	+410	365	–
B1 (Battery + SC)	−280	+395	175	52%
B2 (Battery + enlarged SC)	−210	+390	148	59%
B3 (Battery + optimized SC)	−180	+385	132	64%

A comparative analysis of battery current profiles and integral metrics shows that the main advantage of hybrid energy storage architectures in heavy mining equipment is related to the separation of power and energy functions [67] rather than simple energy substitution. Although the average demand for traction energy remains close for different configurations, the introduction of a supercapacitor significantly changes the time structure of the battery load.

To avoid overinterpreting the reduction in battery RMS current as a directly quantified lifetime extension, additional electrical and thermal stress indicators were calculated for the pure battery configuration and for the HESS configurations under Cycle B. Cycle B was selected because it contains the most severe loaded downhill regenerative-braking segment and therefore imposes the highest short-term charging stress on the battery branch. The comparison is presented in Table 9.

Table 9. Battery electrical and thermal stress indicators for the pure battery and HESS configurations under Cycle B.

Configuration	Peak Charging Current, A	RMS Battery Current, A	$S_{I,RMS}$	Estimated Maximum ΔT_{bat} , °C	Normalized Thermal Stress S_T	Interpretation
Battery-only	−950	365	1.00	100% baseline	1.00	Highest current and thermal stress
B1 HESS	−280	175	0.48	reduced	<1.00	Lower high-rate charging stress
B2 HESS	−210	148	0.41	reduced	<1.00	Stronger current smoothing
B3 HESS	−180	132	0.36	reduced	<1.00	Lowest electrical stress among tested options

The results in Table 9 show that the introduction of the supercapacitor branch substantially reduces both peak regenerative charging current and RMS battery current. In the pure battery configuration, the battery directly absorbs the high-power regenerative pulse generated during the loaded descent, which leads to the highest electrical and thermal stress indicators. In the HESS configurations, a significant part of this transient power is redirected to the supercapacitor through the bidirectional DC/DC converter, while the battery covers the slower energy component of the duty cycle.

The normalized RMS current stress indicator $S_{I,RMS}$ decreases progressively from the battery-only case to the enlarged and optimized HESS configurations. This confirms that the supercapacitor buffer reduces the high-rate current burden imposed on the LiFePO₄ battery. The thermal stress indicator follows the same qualitative tendency because lower RMS current reduces ohmic heat generation in the battery branch. However, these indicators should be interpreted as comparative degradation-relevant stress metrics rather than as a direct prediction of battery lifetime. A quantitative lifetime estimate would require experimentally calibrated aging data for the specific cell chemistry, pack design, thermal management system, SOC window, and regenerative pulse protocol.

The reduction in peak battery charging current does not mean that the entire regenerative pulse is absorbed by the battery branch. In the HESS configurations, a large part of the short-time regenerative power is redirected to the supercapacitor branch, while any remaining non-accepted power is dissipated through the residual braking channel.

The results presented in Figure 3 and Table 8 show that peak regenerative charging currents can be reduced by more than three times, whereas the reduction in battery RMS current is as high as 64% depending on the configuration. Such a reduction should be interpreted as a reduction in electrical stress indicators rather than as a direct proof of a quantified lifetime increase. Lower RMS and peak currents are physically associated with lower ohmic heat generation and reduced high-rate charge stress; however, the actual battery life extension depends on the cell chemistry, thermal management system, SOC window, calendar aging, cycle depth, and manufacturer-specific charge rate limits. Therefore, the manuscript reports RMS current and thermal stress reductions as comparative indicators, while absolute lifetime prediction is treated as a separate task requiring experimentally calibrated degradation data [68].

These results suggest that the selection and size of a supercapacitor subsystem should primarily depend on the maximum power and duration of regenerative pulses in the operating cycle, and not only on its total energy capacity [69]. This observation formed the basis of the optimization structure [70] considered in the following sections and is additionally reflected in the systemic conclusions of this study.

3.4. Sensitivity to Route and Regenerative Braking Parameters

Sensitivity analysis was performed for Cycle B. It was found that the optimal usable energy buffer ratio ρ_E , rather than the direct C_{sc}/E_{bat} ratio, is most strongly correlated with the maximum regenerative braking power and the duration of the regenerative pulse.

$$E_{sc,use,req} = k_p P_{regen,max} t_{regen} / 3600, \\ \rho_{E,req} = \frac{E_{sc,use,req}}{E_{bat,use}},$$

where $P_{regen,max}$ —maximum regenerative braking power, kW; t_{regen} —characteristic regenerative pulse duration, s; k_p —empirical pulse coverage coefficient, normally 0.5–0.7 for the considered control strategy and voltage window.

4. Generalized Optimization Results

4.1. Duty Cycle-Dependent Optimization Summary

The generalized optimization results are based on the three segment-level mining duty cycles defined in Section 2.2. All final Pareto fronts, recommended HESS configurations, battery current stress indicators, energy balance calculations, sensitivity results, and engineering nomograms are derived from Cycle A, Cycle B, and Cycle C.

The optimization confirms that the required supercapacitor buffer is duty cycle-dependent. Cycle A, corresponding to production haulage, is dominated by loaded

uphill traction and therefore requires the smallest supercapacitor energy buffer. Cycle B, corresponding to reclamation/backfill operation, includes loaded downhill regenerative braking and requires the largest buffer because the supercapacitor branch must absorb short high-power regenerative pulses [71]. Cycle C represents mixed operation and produces intermediate requirements.

The equivalent supercapacitor module capacitance remains an electrical design variable, whereas the final sizing result is expressed through the dimensionless usable energy buffer ratio [72]. This representation allows for the results of different battery sizes and supercapacitor voltage windows to be compared using a physically consistent indicator.

4.2. Generalized Power Profile Results

The power profile analysis was performed for the three primary mining duty cycles rather than for an adapted passenger car cycle. For each cycle, the instantaneous traction bus power was calculated from the segment-level vehicle mass, road grade, target speed, and longitudinal resistance forces. Positive power corresponds to traction demand, whereas negative power corresponds to regenerative braking available at the DC bus before storage and converter constraints are applied [73,74].

The generalized power profile comparison was performed for the three primary mining duty cycles. For each cycle, the segment-level vehicle mass, road grade, target speed, and longitudinal resistance forces were used to calculate the wheel-side mechanical power, which was then converted into the corresponding traction DC bus power. In Figure 4, positive power denotes traction demand, and negative power denotes regenerative-braking power available at the DC bus before storage constraints are imposed.

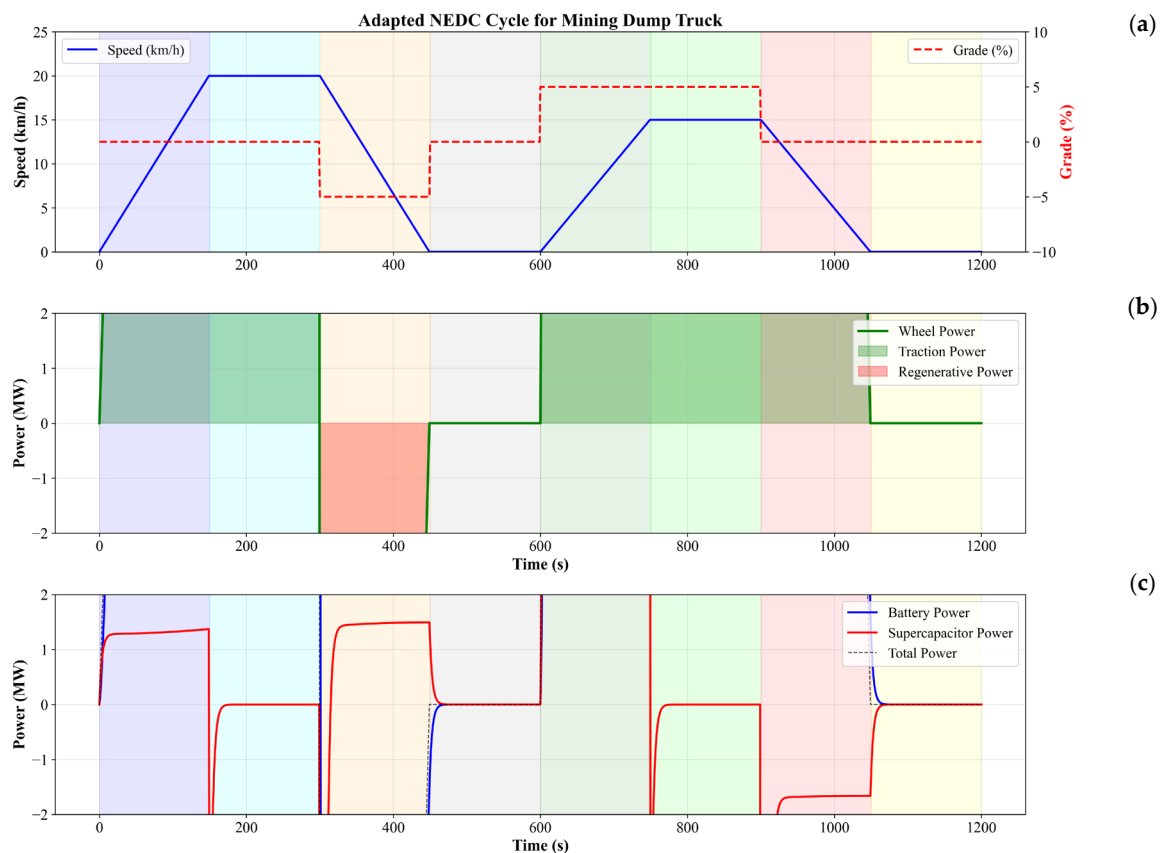


Figure 4. DC bus power profiles for the primary mining duty cycles: (a) Cycle A, production haulage; (b) Cycle B, reclamation/backfill operation; (c) Cycle C, mixed operation. Positive values indicate traction demand, whereas negative values indicate regenerative braking power available at the traction DC bus before storage and converter constraints are applied.

Figure 4 confirms that the same HESS architecture is exposed to substantially different power flow structures depending on the mining duty cycle. Cycle A is dominated by a positive power interval associated with loaded uphill haulage, whereas its regenerative interval is comparatively limited. Cycle B contains the strongest negative DC bus power interval because the truck descends under payload. Cycle C has a mixed structure, with both traction and regenerative intervals contributing materially to HESS loading. Therefore, the later sizing results are interpreted relative to the duty cycle-specific DC bus power profile rather than to a generic or passenger car driving cycle pattern [75].

Energy Balance Comparison of Representative Configurations

To quantify how the constrained HESS affects the cycle-level energy balance, representative battery-only and hybrid configurations were compared for the three primary mining duty cycles [76]. The comparison includes traction energy demand, theoretically available regenerative energy, actual stored regenerative energy, stored regenerative-energy fraction, and net cycle energy after storage and residual braking constraints are applied. The results are summarized in Table 10.

Table 10. Constrained energy balance of representative HESS configurations under the primary mining duty cycles.

Cycle	Configuration	E_{bat} , kWh	C_{sc} , F	E_{trac} , kWh	E_{regen} , kWh	E_{stored} , kWh	Stored Fraction, %	E_{net} , kWh
A	Battery-only	600	0	89.5	12.0	7.1	59.2	82.4
A	HESS-A1	700	35	89.5	12.0	8.8	73.3	80.7
B	Battery-only	600	0	41.0	58.5	34.0	58.1	7.0
B	HESS-B1	650	85	41.0	58.5	52.0	88.9	−11.0
C	Battery-only	600	0	68.0	32.0	20.0	62.5	48.0
C	HESS-C1	680	55	68.0	32.0	27.5	85.9	40.5

Note: E_{trac} is traction energy demand; E_{regen} , DC is theoretically available regenerative energy at the traction DC bus before storage constraints; E_{stored} is the regenerative energy actually accepted by the battery-supercapacitor HESS after SOC, voltage, current, ESR, and converter power limits are applied; the stored fraction is E_{stored}/E_{regen} , DC; E_{net} is the net cycle energy after accepted regenerative energy is subtracted from traction energy. Non-accepted regenerative energy is assigned to the residual braking channel.

Table 10 shows that the effect of the HESS is most pronounced for Cycle B, where loaded downhill motion produces the largest regenerative energy pulse. In this case, the hybrid configuration increases the stored regenerative energy fraction and can reduce the net cycle energy to a negative value, indicating that the cycle is regenerative-dominant under the assumed route and loading conditions. For Cycle A, the effect is smaller because the operating cycle is dominated by loaded uphill traction. Cycle C gives intermediate results, which is consistent with its mixed traction–regeneration structure.

4.3. Pareto-Based Optimization and Energy Balance Results

4.3.1. Pareto Fronts and Objective Function Trade-Offs

To determine the duty cycle-dependent usable energy buffer ratio, the parametric analysis used the same unified design range as Section 3.2: 400–800 kWh for nominal battery energy capacity and 0–150 F for equivalent supercapacitor module capacitance. The following were considered as target functions:

1. Minimization of net energy consumption ΔE_{cycle} .
2. Minimizing the RMS current of the battery I_{bat_RMS} .
3. Minimizing the weight of the HESS system.

Multi-criteria optimization of HESS parameters requires visualization of trade-offs between conflicting target functions [77]. Figure 5 shows the three-dimensional Pareto front in the objective function space, as well as its projections on two-dimensional planes.

This view allows for design engineers to evaluate the trade-off between energy efficiency, battery durability, and system weight, which is critical when designing HESS for mobile applications [78].

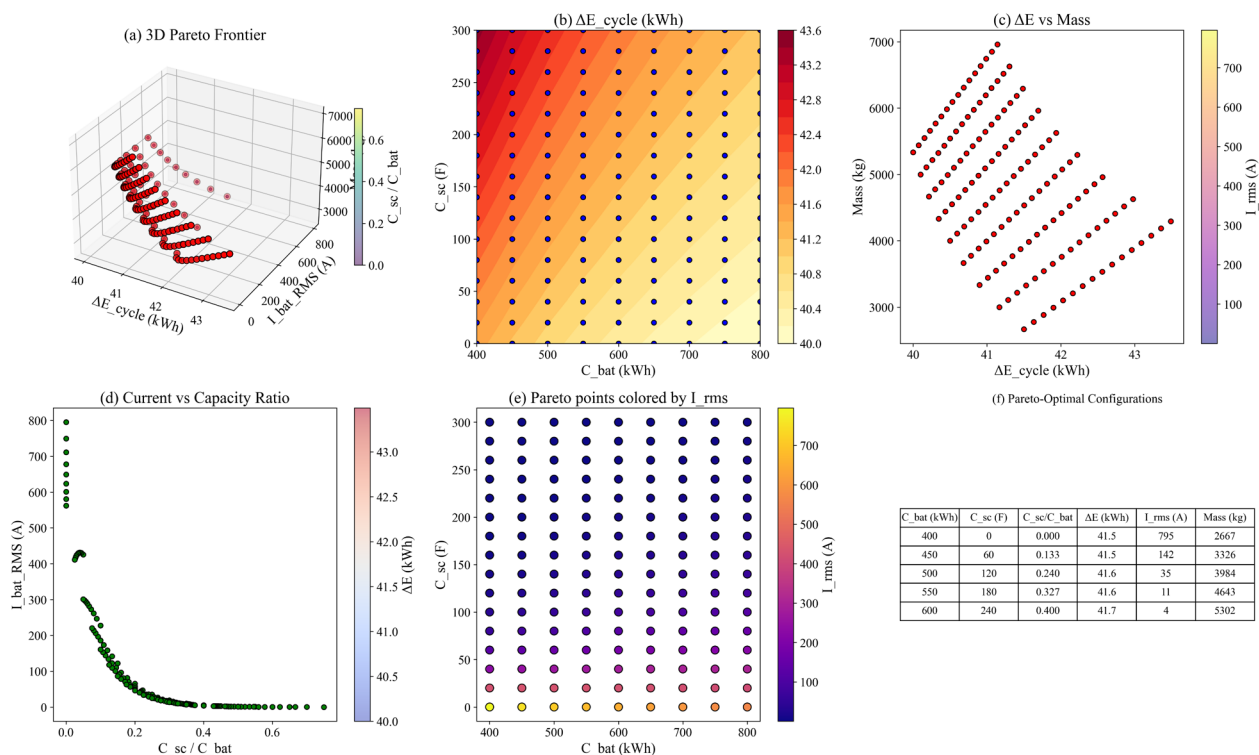


Figure 5. Multi-objective optimization of HESS parameters using the dimensionless usable energy-buffer ratio ρ_E : (a) Pareto front for Cycle A; (b) Pareto front for Cycle B; (c) Pareto front for Cycle C; (d) battery RMS current as a function of ρ_E ; (e) net cycle energy as a function of ρ_E ; (f) recommended duty cycle-specific HESS configurations.

Figure 5 visualizes the multi-objective optimization results using the dimensionless usable energy buffer ratio as the common sizing coordinate. The Pareto fronts show the trade-off between net cycle energy, battery RMS current, and HESS mass. Panels (d) and (e) indicate that the decrease in battery RMS current is nonlinear with respect to the usable energy buffer ratio: the strongest improvement occurs at low buffer values, whereas further enlargement of the supercapacitor branch leads to a plateau effect. This confirms that the equivalent supercapacitor capacitance should not be interpreted through a direct capacitance-to-battery energy ratio. Instead, the recommended design interval should be selected from the usable supercapacitor energy within the specified voltage window and the usable battery energy within the specified SOC window.

4.3.2. Analysis of Sensitivity to Cycle Parameters

To assess the stability of the obtained optimal solutions, an analysis of sensitivity to variations in the parameters of the operating cycle was carried out.

The data in Table 11 show that the maximum road grade and the share of regenerative energy have the strongest effect on the recommended dimensionless usable energy buffer ratio. An increase in road grade increases the required usable supercapacitor energy because the loaded downhill segment produces higher regenerative braking power and a larger short-time energy pulse. This effect is reported through the usable energy-buffer ratio rather than through a direct C_{sc}/C_{bat} value, because equivalent capacitance in farads and battery energy in kilowatt-hours are not directly comparable physical quantities.

Table 11. Sensitivity of the recommended dimensionless usable energy buffer ratio to mining duty cycle parameters.

Loop Parameter	Range of Change	Recommended ρ_E , %	Change ΔE_{cycle} (%)	Change I_{bat_RMS} (%)
Maximum Slope	3–12%	0.10–0.25	+18.5	+45.3
Recovery Rate	20–60%	0.08–0.22	−12.7	−38.9
Average speed	15–25 km/h	0.12–0.18	+5.3	+12.7
Cycle Length	10–30 min	0.14–0.17	+9.8	+8.5
Weight of cargo	80–120% of nominal	0.13–0.20	+14.2	+32.6

4.4. Engineering Nomograms Derived from the Optimization Results

The generalized optimization results were converted into engineering nomograms for preliminary HESS sizing. These nomograms summarize the relationships between route grade, vehicle mass, regenerative pulse duration, usable supercapacitor energy, usable energy buffer ratio, residual braking energy fraction, and control filter time constant [79,80]. Figure 6 presents these outputs as a compact design support representation derived from the constrained mining duty cycle simulations.

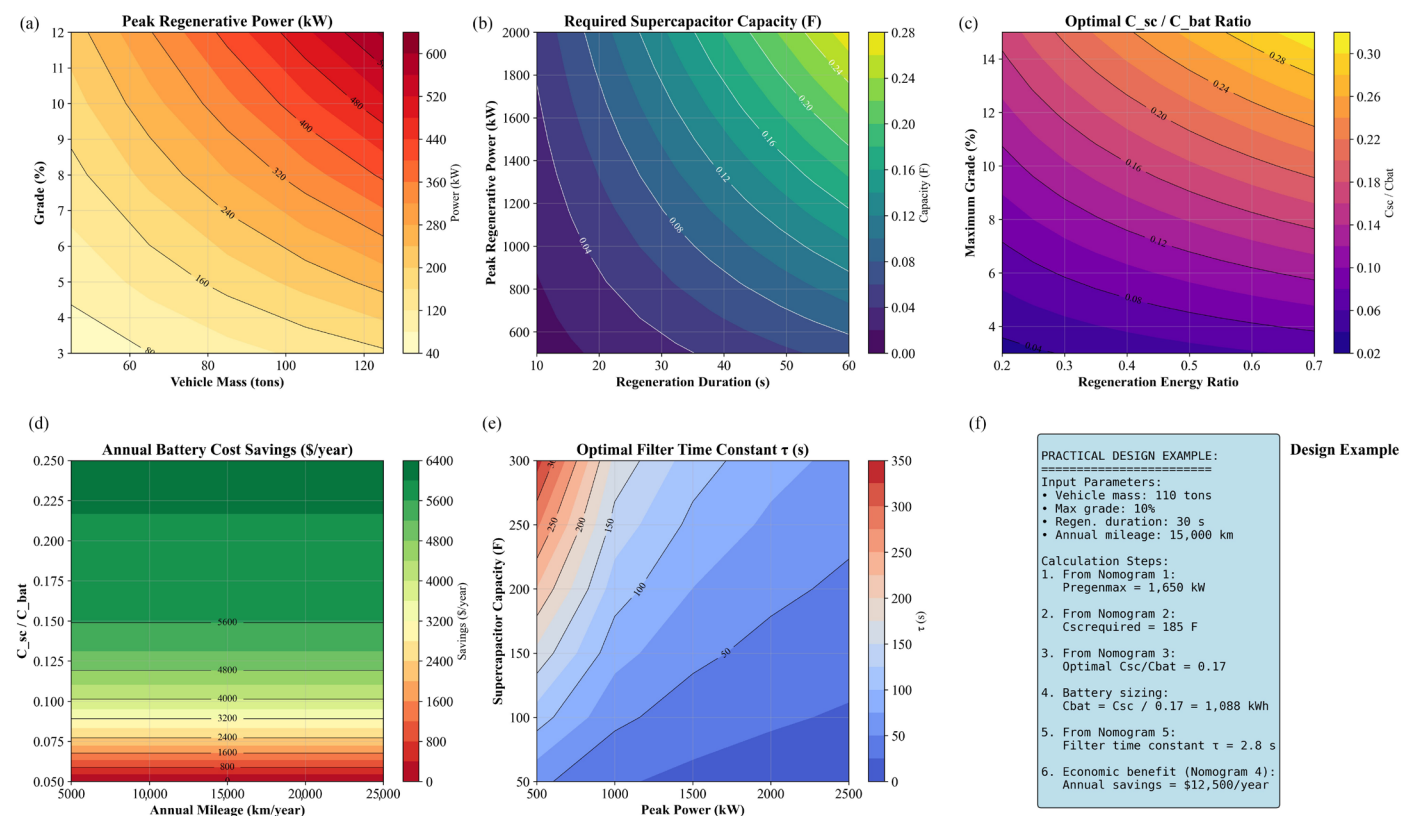


Figure 6. Engineering nomograms for preliminary HESS sizing: (a) peak DC bus regenerative braking power; (b) required usable supercapacitor energy; (c) recommended dimensionless usable energy buffer ratio; (d) residual braking energy fraction; (e) control filter time constant τ ; (f) example of configuration selection.

Figure 6 summarizes the main engineering outputs obtained from the constrained optimization. Panel (a) relates vehicle mass and road grade to peak DC bus regenerative-braking power. Panel (b) estimates the usable supercapacitor energy required to absorb the dominant regenerative pulse within the specified voltage window. Panel (c) gives the recommended dimensionless usable energy buffer ratio. Panel (d) shows the residual braking energy fraction, defined as the share of regenerative energy that cannot be accepted by the

constrained HESS and is therefore assigned to the braking resistor or mechanical/safety braking channel. Panel (e) gives the corresponding range of the control filter time constant, and panel (f) illustrates the selection logic for a representative configuration. No economic interpretation is assigned to panel (d) because a full cost and lifetime model is outside the scope of the present study.

5. Discussion

5.1. Interpretation of the Duty Cycle-Dependent Usable Energy Buffer Ratio

The results obtained confirm the central hypothesis of the study: there is no universal HESS sizing ratio that can be applied to all mining duty cycles. However, in the revised manuscript this conclusion is formulated through the dimensionless usable energy buffer ratio ρ_E , not through the direct ratio between capacitance in farads and battery energy in kilowatt-hours [81].

The difference is essential. The equivalent supercapacitor capacitance C_{sc} defines the electrical behavior of a specific module only together with its voltage window, ESR, current limit, and DC/DC converter constraints. Therefore, the same capacitance value may correspond to different usable energy values in different module designs. By contrast, $\rho_E = \frac{E_{sc,use}}{E_{bat,use}}$ compares two quantities expressed in the same unit, kWh, and therefore can be used as a physically interpretable sizing indicator.

For the mining duty cycles considered in this study, Cycle A requires the smallest supercapacitor energy buffer because its dominant energy demand is associated with loaded uphill traction. Cycle B requires the largest buffer because loaded downhill travel generates high-power regenerative pulses. Cycle C occupies an intermediate position. Thus, the reported optimal HESS sizing is duty cycle-specific and should be interpreted as a recommended usable energy buffer interval under the stated voltage window, SOC window, and control assumptions.

A comparison of Cycle A and Cycle B shows that regenerative-dominant operation requires a substantially larger usable supercapacitor energy buffer than production haulage. In Cycle B, the loaded downhill segment produces the highest DC bus regenerative-braking pulse among the considered duty cycles, with peak values in the range of approximately 550–750 kW under the adopted route and efficiency assumptions. A larger fraction of this short-time braking energy must be absorbed by the supercapacitor branch to prevent excessive battery charging current. In Cycle A, the dominant energy demand is loaded uphill traction, and the role of the supercapacitor is mainly limited to transient current smoothing [82,83]. This explains why the recommended usable energy buffer ratio is highest for Cycle B, lowest for Cycle A, and intermediate for Cycle C.

An important feature revealed in Figure 5d is the nonlinear dependence of battery RMS current on the usable energy buffer ratio. At low buffer values, a relatively small increase in usable supercapacitor energy produces a strong reduction in battery RMS current. After this initial region, the response approaches a plateau, and further enlargement of the supercapacitor branch provides only marginal additional stress reduction. This saturation effect defines the technically and economically justified upper bound of the supercapacitor buffer [84].

Thus, the main scientific implication of the optimization results is that HESS sizing for mining electric dump trucks should be treated as a duty cycle-conditioned problem [85]. The same vehicle mass and storage topology can lead to different optimal buffer requirements when the dominant energy event changes from loaded uphill traction to loaded downhill regenerative braking.

5.2. Engineering Design Procedure

Based on the parametric analysis and Pareto-based optimization results, the following engineering design procedure can be used for preliminary sizing of a semi-active battery–supercapacitor HESS for mining electric dump trucks. The procedure is intended for pre-design comparison of candidate configurations and does not replace detailed component-level design, converter thermal design, or telemetry-based validation.

1. Definition of the dominant duty cycle.

The first step is to identify the dominant operating cycle of the mining truck. This includes analysis of typical transportation routes, statistical processing of telemetry or route data, identification of loaded and empty travel phases, road-grade estimation, and separation of traction and regenerative braking intervals. The duty cycle should be classified as production haulage, reclamation/backfill operation, mixed operation, or a weighted combination of these operating classes.

2. Calculation of energy and power parameters.

For the selected duty cycle, the traction bus power profile is calculated using the longitudinal vehicle dynamics model. The main quantities extracted from this profile are the maximum DC bus regenerative braking power $P_{\text{regen,max}}$, the characteristic duration of regenerative pulses t_{regen} , the traction energy demand E_{trac} , the theoretically available regenerative energy at the DC bus $E_{\text{regen,DC}}$, the expected stored regenerative energy E_{stored} , and the residual braking energy E_{res} . These quantities define the initial requirements for the supercapacitor branch and the bidirectional DC/DC converter.

3. Preliminary selection of supercapacitor usable energy.

The usable supercapacitor energy is estimated from the dominant regenerative pulse requirement:

$$E_{SC,use} \geq k_p P_{\text{regen,max}} t_{\text{regen}},$$

where $E_{SC,use}$ is the required usable supercapacitor energy, $P_{\text{regen,max}}$ is the maximum DC bus regenerative braking power, t_{regen} is the characteristic regenerative pulse duration, and k_p is the pulse coverage coefficient selected according to the accepted residual braking allowance and the adopted supervisory control strategy. In practical preliminary sizing, k_p is selected below unity when partial residual braking is acceptable and closer to unity when the design objective is to maximize regenerative energy absorption.

4. Selection of equivalent supercapacitor module capacitance.

After the required usable supercapacitor energy has been estimated, the equivalent supercapacitor module capacitance is calculated from the permissible voltage window:

$$C_{SC} = \frac{2E_{SC,use}}{V_{SC,max}^2 - V_{SC,min}^2},$$

where C_{SC} is the equivalent supercapacitor module capacitance, $V_{SC,max}$ is the maximum permissible supercapacitor module voltage, and $V_{SC,min}$ is the minimum permissible supercapacitor module voltage. Converter efficiency, ESR losses, current limits, voltage safety margins, and the DC/DC converter power rating must be included during the final feasibility check.

5. Determination of nominal battery energy capacity.

The nominal battery energy capacity is selected from the required cycle energy, permissible depth of discharge, reserve margin, and battery energy efficiency assumptions:

$$E_{bat,nom} \geq \frac{E_{cycle}}{DoD \cdot \eta_{bat}},$$

where $E_{bat,nom}$ is the nominal battery energy capacity, E_{cycle} is the energy required for the selected duty cycle, (DoD) is the permissible depth of discharge, and η_{bat} is the effective battery energy efficiency. The supercapacitor branch reduces transient battery current stress and improves regenerative pulse absorption, but it does not replace the battery as the main energy source of the vehicle.

6. Optimization of the usable energy buffer ratio.

After preliminary selection of $E_{bat,nom}$ and C_{SC} , the candidate configuration is evaluated using the dimensionless usable energy buffer ratio:

$$\rho_E = \frac{E_{SC,use}}{E_{bat,use}},$$

where ρ_E is the usable energy buffer ratio, $E_{SC,use}$ is the usable supercapacitor energy within the voltage window, and $E_{bat,use}$ is the usable battery energy within the allowed SOC window. This ratio is used as the final sizing indicator because it compares two usable energy quantities expressed in the same physical units. A direct comparison between supercapacitor capacitance in farads and battery energy in kilowatt-hours is therefore avoided.

7. Constraint verification and Pareto-based final selection.

The candidate configuration is accepted only if it satisfies battery SOC limits, supercapacitor voltage limits, battery current limits, supercapacitor current limits, bidirectional DC/DC converter power limits, HESS mass constraints, and residual braking energy constraints. If several feasible configurations remain, the final design is selected from the Pareto-optimal set according to the selected engineering priority: minimum battery RMS current, minimum net cycle energy, minimum HESS mass, or a balanced compromise among these objectives.

8. Control parameter adjustment.

The control filter time constant τ should be selected consistently with the selected supercapacitor buffer and regenerative pulse duration. A larger usable supercapacitor buffer allows for more aggressive transient power allocation to the supercapacitor branch, whereas a smaller buffer requires a more conservative control setting to avoid voltage window violation, excessive supercapacitor current, and increased residual braking energy.

9. Final stress indicator check.

The selected configuration should be checked against peak battery charging current, peak battery discharging current, RMS battery current, stored regenerative energy fraction, residual braking energy fraction, maximum estimated battery temperature rise, and normalized electrical and thermal stress indicators. This final check ensures that the selected HESS configuration improves battery operating conditions without claiming a direct quantified battery lifetime extension unless experimentally calibrated aging data are available.

5.3. Comparison with Previous Studies

The data obtained develop the conclusions of our previous work [1,2]. While [2] concluded that a complex recuperative system is not feasible for type A cycles due to the low payback, this study shows that even in this case, hybridization with a small C_{sc}/C_{bat} (0.04–0.07) gives a significant gain in battery durability (15–25% decrease in I_{bat} , RMS according to Table 7). This can change the economic calculation towards the total cost of ownership (TCO). For the type B

cycles whose energy potential was revealed in [1], the present study provides a quantitative tool for the engineering implementation of the optimal HESS, not just a qualitative comparison.

Unlike most of the works limited to the comparison of fixed configurations [85,86], the paper constructs maps of objective functions (Figure 5) and highlights the Pareto front, which makes it possible to choose compromise solutions depending on design priorities. The revealed saturation effect (plateau) with an increase in the SC capacity confirms that an unreasonable overestimation of C_{sc} does not lead to a proportional improvement in characteristics [87], which is important for cost optimization.

Compared with studies that optimize HESS parameters for passenger electric vehicles or urban buses, the present work emphasizes payload-dependent grade operation and regenerative braking under loaded downhill mining conditions. Compared with fixed-configuration HESS studies, the proposed approach provides Pareto-based duty cycle-specific sizing and reports the final result through a dimensionless usable energy buffer ratio. The inclusion of the residual braking channel also prevents overestimation of stored regenerative energy when battery, supercapacitor, or converter limits are reached.

5.4. Limitations and Future Work

The limitations of the study determine the scope of the results obtained and the directions of future work:

- Determinism of the model. The considered cycles are specified accurately and do not take into account stochastic variations in driver behavior, road surface conditions, and changes in ambient temperature. Actual operating cycles may differ, which will require adaptation of the resulting dependencies [88].
- Degradation and lifetime interpretation. The revised model includes a first-order Thevenin battery representation, lumped thermal response, and normalized current/thermal stress indicators. Nevertheless, the model does not contain an experimentally calibrated LiFePO_4 degradation law for the specific cell and pack design. Therefore, RMS current reduction is interpreted as a reduction in degradation-relevant stress factors, not as a direct quantitative prediction of battery lifetime extension [89]. Absolute lifetime and replacement cost estimates require cell-level aging tests or manufacturer aging maps under the relevant C-rate, SOC, temperature, and pulse regeneration conditions.
- Simplified constrained energy management. The revised model includes a semi-active HESS topology, bidirectional DC/DC converter efficiency [90], SOC and voltage windows, current and power limits, and a residual braking channel. However, the model remains a system-level representation and does not include detailed switching dynamics, electromagnetic transients, semiconductor junction temperature dynamics, or detailed converter thermal design [91]. Therefore, the reported results should be interpreted as constrained system-level sizing estimates rather than final converter hardware validation.

Promising areas:

1. Integration of electrothermal degradation models into the optimization cycle to predict battery life and cost-effectiveness.
2. Development of an adaptive management strategy that adjusts the parameters of the τ filter to the current forecast of the path profile based on GPS data and quarry mapping.
3. Conduct a full feasibility study (TCO) for optimal HESS configurations, taking into account regional prices for equipment, electricity and disposal costs.
4. Future work should include independent telemetry-based validation of the complete HESS, including battery current, supercapacitor voltage, DC/DC converter power,

thermal response, residual braking energy, and repeated duty cycles under different ambient temperatures.

These limitations define the applicability domain of the present results. The proposed methodology is suitable for preliminary constrained HESS sizing and comparative evaluation of duty cycle-specific configurations [92], but final industrial implementation requires telemetry-based validation, component-level converter design, and experimentally calibrated battery aging assessment.

6. Conclusions

This study developed a constrained system-level methodology for sizing a semi-active battery–supercapacitor hybrid energy storage system for a 65 t payload-class battery electric mining dump truck. In contrast to approaches based on passenger car driving cycles or dimensionally inconsistent capacity ratios, the proposed method uses segment-level mining duty cycles and the dimensionless usable energy buffer ratio $\rho_E = \frac{E_{sc,use}}{E_{bat,use}}$.

The analysis showed that HESS sizing is strongly dependent on the duty cycle structure. Production haulage, dominated by loaded uphill traction, requires the smallest supercapacitor energy buffer. Reclamation/backfill operation, where loaded downhill motion produces high-power regenerative braking pulses, requires the largest buffer. Mixed operation occupies an intermediate position. Therefore, no universal supercapacitor-to-battery sizing ratio is claimed.

For the regenerative-dominant Cycle B, the HESS configurations reduced peak battery charging current from approximately -950 A to $-180 \dots -280$ A and reduced battery RMS current by 52–64% compared with the pure battery configuration. These reductions indicate lower electrical and thermal stress on the LiFePO_4 battery branch. However, they should not be interpreted as a directly quantified battery life increase because absolute lifetime prediction requires experimentally calibrated degradation data for the specific cells, pack design, cooling system, SOC window, and regenerative pulse protocol.

The revised model explicitly includes a semi-active HESS topology, bidirectional DC/DC converter losses, SOC and supercapacitor voltage windows, current and power limits, and a residual braking channel. As a result, regenerative energy is counted as stored only when it is accepted by the constrained HESS; the remaining braking power is assigned to the braking resistor or mechanical/safety braking system.

The proposed methodology provides a physically consistent basis for preliminary HESS sizing, Pareto-based comparison of candidate configurations, and engineering nomogram construction for mining electric dump trucks. Future work should include telemetry-based validation of complete HESS operation, experimentally calibrated electrothermal aging models, detailed DC/DC converter thermal design, and a separate total-cost-of-ownership analysis including battery replacement, supercapacitor module cost, converter cost, maintenance, downtime, electricity price, and residual value.

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