Journal of Sustainable Development of Energy, Water and Environment Systems

http://www.sdewes.org/jsdewes

Year 2027, Volume 15, Issue 1, 1140797

Original Research Article

Integrated Techno-Economic and External-Cost Assessment of Second-Life Electric Vehicle Batteries in Emerging Economies: A Framework Applied to Azerbaijan

***Fuad M. Mirzayev*[1], *Kovsar Kh. Dadashova*[2], *Arzu D. Abdullayeva*[3*]** National Aviation Academy, Baku, Azerbaijan

[1]e-mail: fmirzayev@naa.edu.az

[2]e-mail: kdadashova@naa.edu.az

[3]e-mail: arzu.abdullayeva@naa.edu.az

Cite as: Mirzayev, F. M., Dadashova, K. K., Abdullayeva, A. D., Integrated Techno-Economic and External-Cost Assessment of Second-Life Electric Vehicle Batteries in Emerging Economies: A Framework Applied to Azerbaijan, J.sustain. dev. energy water environ. syst., 15(1), 1140797, 2027, DOI: https://doi.org/10.13044/j.sdewes.d14.0797

UNCORRECTED PROOF

ABSTRACT

The rapid growth of electric vehicles is expected to generate a substantial volume of end-of-life lithium-ion batteries, particularly in emerging economies where formal waste-management systems are still developing. This study presents an integrated assessment framework combining techno-economic analysis, screening of environmental impact pathways, and an extended environmental and damage cost model. Three pathways are examined: uncontrolled disposal, direct recycling, and second-life use in stationary energy storage. The project model gives a second-life storage-cost base case of 0.110 United States dollars per kilowatt-hour delivered and a cost-side scenario range of 0.110–0.170 United States dollars per kilowatt-hour delivered. On a separate common end-of-life capacity basis, the project-parameterized environmental and societal screening outputs are 0.150, 0.064, and 0.050 United States dollars per kilowatt-hour-equivalent for uncontrolled disposal, recycling, and second-life use, respectively. A conditional displacement credit of 0.020 United States dollars per kilowatt-hour-equivalent gives a base-case net external cost of 0.030 United States dollars per kilowatt-hour-equivalent for the second-life pathway. These are project-model outputs under the stated assumptions, not measured national damage statistics; the results therefore identify second-life use as a potentially favourable transitional pathway rather than a universally dominant option.

KEYWORDS

Second-life lithium-ion batteries, techno-economic analysis, environmental impact pathways, environmental damage cost, energy storage systems, electric vehicles, circular economy, sustainable waste management.

[*] Corresponding author: arzu.abdullayeva@naa.edu.az

Submitted 08.04.2026; Revised 12.10.2026; Accepted 13.11.2026; Available online date (*Dates inserted by the administration at the end of the publishing process*)

Copyright: © 2026 The Author(s). *JSDEWES*, published by SDEWES Centre, Zagreb, Croatia. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution 4.0 International License (CC BY 4.0)

1. INTRODUCTION

This section outlines the global development of electric-vehicle batteries, reviews the recent literature on recycling and second-life applications, and introduces the Azerbaijani context. It then identifies the research gap addressed by the proposed integrated assessment framework.

1.1. Background: global trends

The global shift toward low-carbon mobility has accelerated adoption of electric vehicles and increased demand for lithium-ion batteries. Upadhyay et al. integrated diagnostic, economic, and policy pathways for second-life batteries and framed their deployment as a circular-economy decision [1]. Sisodia and Monteiro proposed a lifecycle-oriented battery-management model, which is relevant to state monitoring rather than damage-cost valuation [2]. Madani et al. reviewed thermal-management and safety mechanisms and therefore support the treatment of thermal runaway as a hazard pathway [3]. Dehury and Samal reviewed smart battery-management controls, highlighting the role of diagnostics and control in safe repurposing [4]. The International Energy Agency documented that more than 20 million electric cars were sold globally in 2025, indicating a growing future stock of retired traction batteries [5].

Battery chemistry and system design materially affect ageing, safety, and recoverability. Salgado et al. reviewed recent battery-chemistry trends and their performance trade-offs [6]. Goyal et al. synthesised recycling and disposal methods, showing that chemistry influences recovery routes and economics [7]. Miao et al. compared current electric-vehicle battery technologies and identified thermal management and battery control as continuing development needs [8]. Sharmili et al. mapped production and reverse-supply-chain research, emphasising supply-chain and recovery constraints rather than second-life system costs [9].

As electric-vehicle deployment expands, end-of-life battery volumes and the consequences of inadequate handling increase. Almahri and An evaluated recycling viability, illustrating how regional conditions affect economic and environmental results [10]. Pang et al. compared recycling technologies through life cycle and economic evidence, while noting process-specific trade-offs [11]. Das et al. critically reviewed techno-economic and socio-environmental effects of recycling, showing that no single process is preferable under all conditions [12]. Zhang et al. focused on life cycle performance of recovery processes and support treating resource recovery separately from use-phase energy delivery [13]. Cui et al. showed that the environmental benefit of second-life use depends on performance degradation, chemistry, and the displaced alternative [14]. Marques et al. demonstrated that capacity fade changes comparative life cycle results and must therefore be represented explicitly [15]. Taken together, these studies support a conditional comparison of recycling and second-life use; they do not justify assuming that one pathway is universally superior.

Existing studies typically emphasise one or two dimensions. Steckel et al. quantified the levelized cost of utility-scale second-life storage and identified strong sensitivity to discount rate, depth of discharge, and repurposing cost [16]. Turan et al. included testing, renovation, transport, replacement, and opportunity costs in an application-specific second-life cost model [17]. Richa et al. compared a battery waste hierarchy using eco-efficiency analysis [18]. Chirumalla et al. examined operational feasibility for remanufacturing, repurposing, and reuse [19]. The present study connects a second-life storage cost model with a screening

UNCORRECTED PROOF

environmental and damage-cost model, while reporting the two monetary bases separately to avoid false arithmetic comparability.

The resulting application is among the first screening studies to combine these dimensions for Azerbaijan. This contribution is methodological and context-specific; it does not replace a full process-based life cycle inventory or measured national damage statistics.

1.2. National context: Azerbaijan's accelerating electric and hybrid vehicle adoption

Azerbaijan reflects global electrification trends, with rapid growth in electric- and hybrid-vehicle imports. During the first six months of 2025, the State Customs Committee recorded 929 electric vehicles and 13,964 hybrid vehicles [20]. In total, more than 6,870 electric vehicles and 80,349 hybrids were imported between 2020 and 2024 [21]. Fragmented market information also indicates that electric and hybrid vehicles entered the country several years before systematic reporting began.

Given an average automotive battery lifespan of 7–10 years, the earliest imported electric- and hybrid-vehicle batteries are already approaching end of life. Azerbaijan may therefore encounter its first substantial wave of end-of-life lithium-ion batteries between 2025 and 2028, followed by a larger accumulation between 2030 and 2036 as the post-2020 import cohorts age. Overlapping end-of-life waves could place pressure on the existing waste-management system in the absence of structured second-life pathways, regulated collection, and domestic or contracted recycling capacity.

Meanwhile, Azerbaijan is expanding renewable generation, increasing interest in affordable stationary storage. Mirzaei Omrani and Jannesari assessed the reuse of electric-vehicle batteries for several load-levelling applications and found that feasibility varies by application [22]. Steckel et al. estimated utility-scale second-life storage costs of 234–278 USD/MWh in their cases, compared with 211 USD/MWh for a new-battery comparator, while reporting substantially lower upfront investment for second-life systems [16]. Turan et al. likewise showed that the usable purchase price of retired batteries is application- and incentive-dependent once testing, renovation, transport, replacement, and opportunity costs are included [17]. These findings justify modelling second-life storage as a conditional option rather than presuming a universal cost advantage.

1.3. Research gap

Steckel et al. quantified second-life storage cost and its main sensitivities [16]. Foster et al. assessed the feasibility of remanufacturing, repurposing, and recycling [23]. Richa et al. compared a battery waste hierarchy using eco-efficiency analysis [18]. Cui et al. showed that second-life environmental benefits depend on degradation, economic value, and the displaced alternative [14]. A remaining gap is a transparent, screening-level approach that reports service cost and end-of-life external costs together without adding values expressed on incompatible functional bases. This study addresses that narrower gap for the Azerbaijani context.

This study addresses the gap by developing and applying an integrated methodology tailored to Azerbaijan. The research aims are to:

1. Develop an integrated framework combining techno-economic analysis, screening of environmental impact pathways, and an environmental and damage cost model.
2. Compare three end-of-life scenarios: uncontrolled disposal, direct recycling, and second-life utilization.

UNCORRECTED PROOF

3. Quantify the project-modelled storage-cost and external-cost indicators and structure the relevant environmental mechanisms without claiming unsupported life-cycle impact reductions.
4. Evaluate the strategic relevance of second-life pathways for Azerbaijan's energy transition.
5. Provide policy recommendations for sustainable battery lifecycle management.

2. METHODS

The methodological approach developed in this study integrates techno-economic analysis (TEA), screening of environmental impact pathways, and an extended environmental and damage cost (EDC) model into one analytical framework for alternative end-of-life pathways. The framework reports two complementary outputs: the levelized cost of storage (LCOS) for the S_2 energy service and the Integrated End-of-Life Cost Metric (IECM) for capacity-normalised net external costs. The IECM combines the environmental and damage cost (EDC) with the avoided-impact credit, whereas LCOS is reported separately because the two indicators use different functional bases. Das et al. reviewed the techno-economic and socio-environmental effects of battery recycling [12]. Martinez-Laserna et al. critically assessed second-life feasibility [24]. Foster et al. evaluated remanufacturing, repurposing, and recycling pathways [23]. Chirumalla et al. examined the operational feasibility of remanufacturing, repurposing, and reuse [19]. A conceptual representation of the framework is provided in Figure 1.

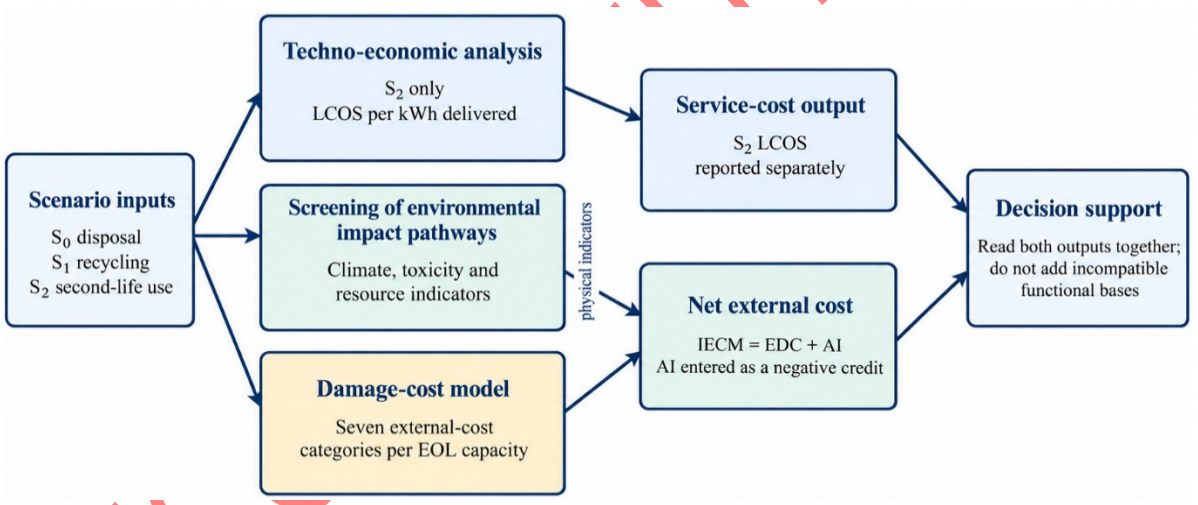


Figure 1. Integrated assessment framework with separate service-cost and net external-cost outputs.

Figure 1 illustrates the analytical framework. LCOS is calculated only for the S_2 energy service, while the screening environmental-pathway indicators and damage-cost model support the net external-cost assessment. The two outputs are interpreted together but are not arithmetically combined.

2.1. Scenario Definition

To systematically compare alternative pathways for managing end-of-life lithium-ion batteries, three scenarios were formulated. These scenarios are intentionally structured to represent progressively more advanced levels of intervention and system organization. They provide a logical framework for distinguishing between unmanaged disposal practices, formal recycling systems, and value-retention strategies such as second-life applications. In this

UNCORRECTED PROOF

context, each scenario reflects a specific stage within the broader waste-management hierarchy, enabling a clearer comparison of environmental and economic trade-offs. The formulation also considers differences in infrastructure readiness, regulatory enforcement, and technological accessibility. Particular attention is given to how these factors influence material flows and risk profiles across the system. Furthermore, the scenarios are aligned with internationally discussed transition pathways toward circular battery management. This structured differentiation ensures consistency with the detailed scenario descriptions presented below.

- S_0 - Uncontrolled disposal. This scenario represents the baseline condition observed in regions lacking formal recycling or battery-waste infrastructure. End-of-life lithium-ion batteries may be stockpiled, abandoned, or discarded in informal waste sites, creating chemical and safety risks. Madani et al. reviewed thermal-management and safety mechanisms relevant to thermal-runaway risk [3]. Miao et al. identified thermal management and battery control as continuing safety needs [8]. Beyond safety concerns, uncontrolled disposal causes the loss of recoverable lithium, nickel, and cobalt. Vega-Muratalla et al. reviewed the strategic supply risks associated with lithium availability [25]. Bailey et al. tracked material and value losses across end-of-life battery flows [26].
- S_1 - Direct recycling. In this scenario, lithium-ion batteries are transported to licensed domestic or international facilities, where hydrometallurgical or pyrometallurgical processes recover critical materials. Goyal et al. reviewed the main recycling and disposal routes [7]. Radomski et al. analysed lithium-ion battery supply-chain dynamics and recovery opportunities [27]. Pang et al. compared recycling technologies using life cycle and economic evidence [11]. Ali et al. showed that effective recycling also depends on logistics, regulation, and market organisation [28]. Salgado et al. documented chemistry-specific performance trade-offs that can affect recycling viability [6].
- S_2 - Second-life utilization. This scenario examines repurposing retired automotive lithium-ion batteries for stationary energy storage systems (ESSs), often with solar photovoltaic systems. Mirzaei Omrani and Jannesari evaluated reuse across residential, industrial, and photovoltaic load-levelling applications [22]. Martinez-Laserna et al. reviewed technical feasibility and remaining performance limitations [24]. Sisodia and Monteiro proposed lifecycle-oriented battery-management evaluation [2]. Dehury and Samal reviewed smart-control algorithms that support reliable battery management [4]. Chirumalla et al. examined the feasibility of remanufacturing, repurposing, and reuse [19].

Figure 2 illustrates the structural differences in value creation, environmental impacts, and risks across the three end-of-life pathways.

UNCORRECTED PROOF

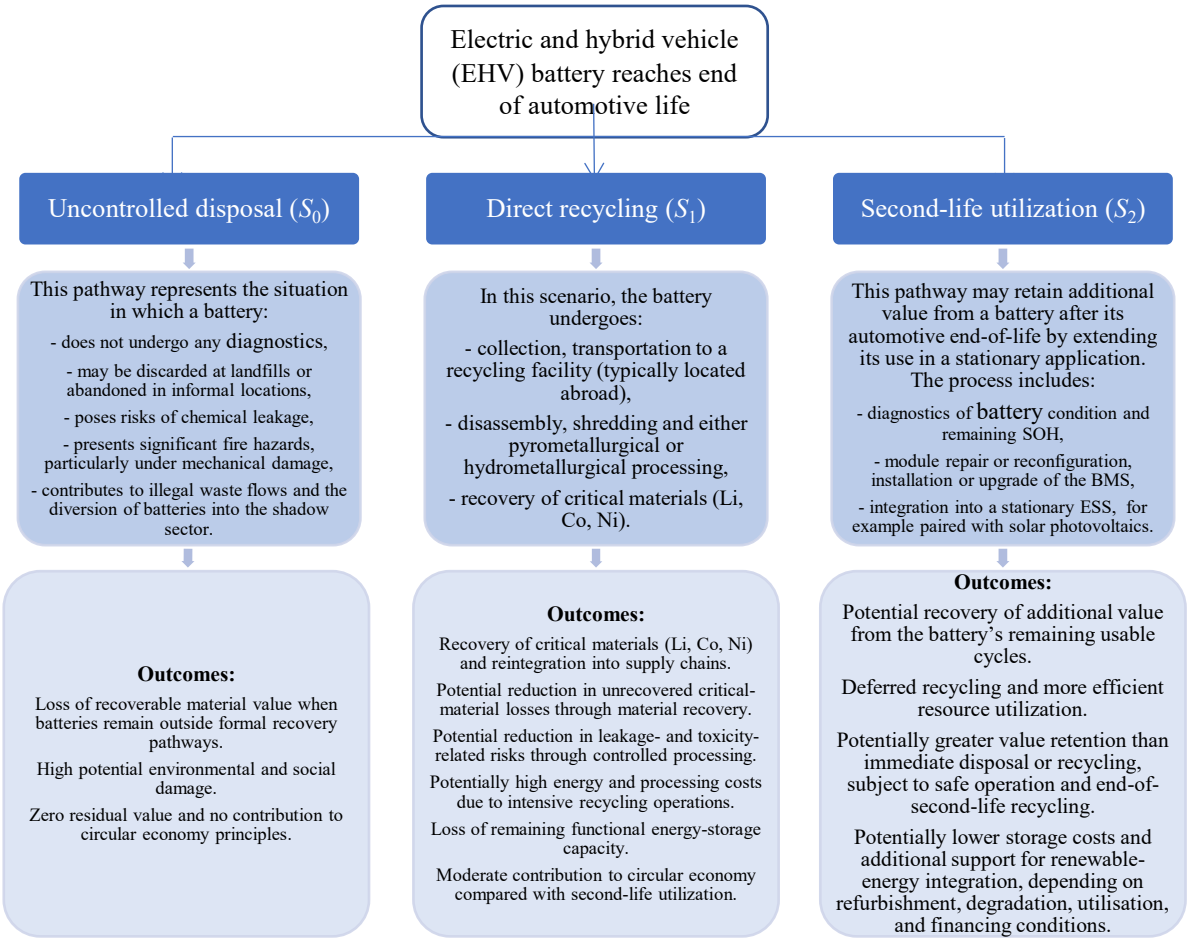


Figure 2. Comparative flowchart of end-of-life pathways for electric-vehicle lithium-ion batteries.

UNCORRECTED

2.2. Functional Unit and System Boundaries

Two reporting bases are used because the scenarios do not provide the same function. For the cross-scenario environmental and damage-cost comparison, the reference flow is 1 kWh-equivalent of nominal end-of-life battery capacity entering the post-vehicle management system. This capacity-based basis applies to uncontrolled disposal (S_0), direct recycling (S_1), and second-life use (S_2) and does not imply that S_0 or S_1 delivers electricity. For the techno-economic assessment of S_2 only, the functional unit is 1 kWh of electricity delivered by the stationary second-life system over its operating life. The levelized cost of storage is therefore not calculated for S_0 or S_1 and is not added to their external-cost values. Each result is labelled with its corresponding basis.

The service-based unit captures state-of-health decline, usable depth of discharge, efficiency, cycle frequency, and service life in S_2. The capacity-based reference flow provides a common denominator for screening the external consequences of sending the same retired battery stock to S_0, S_1, or S_2. This distinction prevents the absence of energy delivery in S_0 and S_1 from being treated as zero techno-economic cost or from being forced into an energy-service denominator.

System boundaries encompass the full post-vehicle stage of the lithium-ion battery life cycle, including:

– collection and transport after automotive use;

- diagnostic assessment and refurbishment (state of health (SOH) testing, module balancing, battery management system (BMS) adjustments);
- integration into stationary energy storage systems. Sisodia and Monteiro described lifecycle-oriented battery-management evaluation [2]. Dehury and Samal reviewed smart-control optimisation [4];
- operational performance, including degradation, thermal behaviour, and safety. Madani et al. reviewed thermal-management and safety mechanisms [3]. Salgado et al. documented chemistry-dependent performance trade-offs [6];
- end-of-second-life recycling. Goyal et al. reviewed recovery routes [7]. Sharmili et al. examined reverse-supply-chain constraints [9];
- environmental and societal impacts of uncontrolled disposal. Bailey et al. tracked end-of-life material and value flows [26]. Radomski et al. analysed supply-chain vulnerability [27].

The common post-vehicle assessment horizon starts when a battery leaves automotive service and ends at final material treatment. It includes collection and transport for all scenarios; unmanaged disposal and associated releases for S_0; transport and controlled recovery of critical raw materials (CRMs) through recycling for S_1; and diagnostics, sorting, refurbishment, module reconfiguration, battery-management-system integration, stationary second-life operation, followed by recycling at the end of the second-life service period for S_2. The external-cost model is a static screening comparison on incoming capacity and is not an annual discounted cash-flow model. The delayed recovery of materials in S_2 is represented in its loss-of-critical-minerals term. Production burdens displaced by second-life service are reported only through the separate avoided-impact credit.

To quantify the potential scale of the end-of-life battery stream, this study converts the vehicle import data presented in Section 1.2 into cumulative energy capacity.

For the inventory analysis, the following average battery capacities were assumed based on the dominant electric and hybrid models currently operating in the Azerbaijani market (e.g., BYD, Tesla, Toyota Prius):

Battery Electric Vehicles (BEVs): 55 kWh

Hybrid Electric Vehicles (HEVs): 1.5 kWh

The total potential end-of-life (EOL) capacity stock (E_{total}) expected to enter the waste stream is calculated as:

$$E_{total} = (N_{BEV} \times C_{BEV}) + (N_{HEV} \times C_{HEV}) \quad (1)$$

where N represents the cumulative number of imported vehicles and C denotes the average battery capacity. Applying this calculation to the 2020-2024 import volumes yields a total estimated capacity of approximately 378 MWh from BEVs and 120 MWh from HEVs.

For internal consistency, the cross-scenario EDC and IECM calculations for S_0, S_1, and S_2 all use the same 378 MWh BEV reference stock. The estimated 120 MWh HEV stock is reported only as inventory context and is excluded from the numerical scenario comparison because its smaller, high-power batteries require a separate suitability and service-life model.

2.3. Techno-Economic Analysis

The techno-economic assessment applies only to S_2 because S_0 and S_1 do not deliver an electricity-storage service. The project LCOS boundary includes receipt inspection, state-of-health testing, sorting, refurbishment, module reconfiguration, battery-management-system upgrades, inverter integration, installation, monitoring, module replacement, and terminal

UNCORRECTED PROOF

decommissioning. Purchased charging energy is excluded from the reported storage-service LCOS numerator and treated as a scenario-specific pass-through; comparisons with other storage systems must use the same boundary. Steckel et al. showed that second-life system upfront cost can be lower than that of a new-battery system while LCOS remains sensitive to discount rate, depth of discharge, and repurposing cost [16]. Turan et al. included testing, renovation, transport, replacement, and opportunity costs and found the viable retired-battery price to be application- and incentive-dependent [17]. Foster et al. likewise treated repurposing feasibility as conditional on processing and market assumptions [23]. The project application gives a 0.110 USD/kWh-delivered base case and a 0.110–0.170 USD/kWh-delivered cost-side scenario range; these are project-derived model results under the documented assumptions, not a claim of universal cost advantage.

- Capital expenditure (CAPEX). Receipt inspection, state-of-health testing, sorting, diagnostics, repackaging, battery-management-system upgrades, inverter integration, module configuration, installation, and commissioning.
- Operating expenditure (OPEX). Routine maintenance, monitoring, insurance, performance management, and terminal decommissioning in the final project year. Purchased charging energy is outside the reported storage-service LCOS numerator.
- Battery degradation modelling. Estimation of capacity fade and round-trip efficiency losses throughout the second-life operational period using empirical data and degradation parameters reported in prior lithium-ion battery (LIB) ageing studies.
- Levelized Cost of Storage (LCOS). A standardized cost metric expressing total discounted lifecycle expenditures per unit of energy delivered by the second-life system:

$$LCOS = \frac{CAPEX_0 + \sum_{t=1}^{n} \frac{OPEX_t + Repl_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_{out,t}}{(1+r)^t}} \quad (2)$$

where:

- $CAPEX_0$: represents the upfront capital expenditure incurred at the commissioning stage, including diagnostic testing, module reconfiguration, and power conversion system (PCS) integration.
- $OPEX_t$: annual operating expenditures in year t, covering routine maintenance, monitoring, and insurance; the terminal-year value also includes final decommissioning.
- $Repl_t$: mid-cycle replacement costs for specific battery modules or components that reach their end-of-service limit before the overall system's decommissioning.
- $E_{out,t}$: the total annual energy delivered by the ESS to the grid or load in year t (kWh).
- r: the discount rate, reflecting the cost of capital and investment risk in the Azerbaijani energy sector.
- n: the total expected operational lifespan of the second-life system (years).

For the reported project calculation, annual energy output $(E_{out,t})$ is modelled as a function of incoming nominal end-of-life energy, usable depth of discharge, round-trip efficiency, annual state of health, and the number of cycles completed in year t:

$$E_{out,t} = E_{nom} \cdot DOD \cdot \eta_{sys} \cdot SOH_t \cdot N_{cycles,t} \quad (1)$$

here $N_{cycles,t}$ is the annual cycle count. In the base case, the five-year schedule is 400 cycles per year, giving 2,000 cumulative cycles. State of health declines linearly from 0.75 to 0.60 over the five years. The reported LCOS is a project-scenario result rather than an audited investment quotation; site-specific sizing, duty cycle, degradation, refurbishment yield, logistics, financing, and market conditions must be updated for an individual deployment.

UNCORRECTED PROOF

The reproducible base case is normalised to 1 kWh of incoming nominal end-of-life capacity and represented by a 100-kWh battery block with a 15-kW inverter. The inputs are n = 5 years, DOD = 0.90, η_{sys} = 0.85, r = 0.08, $N_{cycles,t}$ = 400, and SOH_t = (0.75, 0.7125, 0.6750, 0.6375, 0.6000). The annual delivered-energy vector is therefore (229.500, 218.025, 206.550, 195.075, 183.600) kWh per incoming nominal kWh, and its discounted sum is 831.728 kWh.

Upfront capital expenditure is 32.5 + 185/100 + (210 × 15)/100 + 7.5 = 73.350 USD per incoming nominal kWh. The discounted routine operating expenditure is 8.786 USD/kWh, the year-3 replacement allowance of 10% of CAPEX has a present value of 5.823 USD/kWh, and the year-5 decommissioning allowance of 5 USD/kWh has a present value of 3.403 USD/kWh. The discounted numerator is therefore 91.362 USD/kWh and LCOS = 91.362/831.728 = 0.10985, which rounds to the reported 0.110 USD/kWh delivered.

The upper cost-side case holds the energy-service assumptions and discount rate constant but uses refurbishment cost = 45 USD/kWh, battery-management-system cost = 250 USD per 100-kWh block, inverter cost = 300 USD/kW, installation = 10 USD/kWh, annual operating expenditure = 4% of CAPEX, a year-3 replacement allowance of 20% of CAPEX, and year-5 decommissioning = 9 USD/kWh. This gives CAPEX = 102.500 USD/kWh, a discounted numerator of 141.269 USD/kWh, and LCOS = 141.269/831.728 = 0.16985, which rounds to 0.170 USD/kWh delivered. The 0.110–0.170 interval is therefore a defined cost-side scenario range, not the global minimum and maximum obtained by simultaneously combining every literature bound in Table 1.

The techno-economic parameters in Table 1 apply only to S_2. S_0 and S_1 are not assigned a zero levelized cost; the metric is not applicable because they have no delivered-energy denominator. Cross-scenario comparison is instead made using the external-cost model on the common end-of-life capacity basis defined in Section 2.2.

Table 1. Project-model parameters and literature-bounded ranges for the S_2 storage-cost assessment

Parameter	Unit	Value Range / Assumption	Project base-case value	Source / basis
Initial SOH of EOL battery	%	60-80% depending on age and prior use	75%	Martinez-Laserna et al. review second-life state-of-health limits [24]
Refurbishment cost (diagnostics + repacking)	USD/kWh	20-45	32.5	Turan et al. include testing and renovation costs [17]
BMS upgrade	USD per unit	120-250	185.0	Blümke et al. identify second-life battery-management-system building blocks [29]
Inverter cost for ESS integration	USD/kW	120-300	210.0	Turan et al. include integration costs in application-specific modelling [17]
Installation and commissioning costs	USD/kWh	5-10	7.5	Project-model input; tested in sensitivity analysis
Annual O&M cost	% of CAPEX	2-4%	3%	Turan et al. include operating and replacement costs [17]
Total second-life cycle limit	cycles	1500-3000	2000	Marques et al. model capacity fade over battery life [15]
Round-trip efficiency in second-life ESS	%	80-90%	85%	Turan et al. report efficiency-sensitive second-life performance [17]
Discount rate (r)	%	3-10%	8%	Project base-case financing assumption; tested in sensitivity analysis

CORRECTED PROOF

Parameter	Unit	Value Range / Assumption	Project base-case value	Source / basis
Charging electricity price (context only)	USD/kWh	0.05-0.12	0.07	Project comparison parameter; excluded from the storage-service LCOS numerator
Calculation basis	kWh	Per kWh of incoming nominal EOL capacity	1	Common project normalisation for the LCOS reconstruction
Representative battery / inverter block	kWh / kW	100 kWh / 15 kW	100 / 15	Project scaling assumption used to allocate unit and power costs
Project service life	years	5	5	Project duty-cycle assumption
Usable depth of discharge	%	90%	90%	Project base-case service assumption
Annual cycle schedule	cycles/year	400 in each of five years	400	Gives the 2,000-cycle base limit over the project life
End-of-project state of health	%	60% after linear decline from 75%	60%	Project degradation endpoint; local trajectory tested in Figure 4
Component-replacement allowance	% of CAPEX	0–20% in year 3	10% in year 3	Project scenario assumption.
Terminal decommissioning allowance	USD/kWh	5–9 in year 5	5 in year 5	Project scenario assumption.

Notes:

1. *The base-case values and the additional duty-cycle rows provide the complete numerical chain needed to reproduce 0.110 USD/kWh delivered.*
2. *The 0.170 upper value is the defined cost-side case described above; it is not a full-factor worst-case envelope.*
3. *Figure 4 is a local one-at-a-time diagnostic: the favourable/adverse state-of-health trajectories are 80→77% and 60→53%; refurbishment cost is 26.4/38.8 USD/kWh; and allocated logistics or integration cost is 33.6/44.7 USD/kWh. Other base-case inputs are held constant.*

The economic interpretation is therefore two-part: the levelized cost indicates whether S_2 can provide a potentially competitive storage service, while the net end-of-life external-cost metric compares the damage consequences of S_0, S_1, and S_2. These outputs are reported side by side but are not arithmetically combined because their denominators represent different functions.

Table 1 documents the project-model inputs and literature-bounded ranges used for the S_2 cost assessment. Figure 4 provides a separate one-at-a-time local sensitivity diagnostic around the 0.110 USD/kWh-delivered base case. The broader 0.110–0.170 range reflects the defined cost-side case and is not replaced by the local diagnostic.

The S_2 base-case LCOS and the defined cost-side scenario range are reported separately from the net end-of-life external cost in Table 3.

UNCORRECTED PROOF

2.4. Screening of Environmental Mechanisms and Impact Pathways

This section identifies environmental flows and potential impact pathways associated with the three end-of-life scenarios. It does not construct a process-based life-cycle inventory or calculate characterised impacts for climate change, human toxicity, ecotoxicity, or resource depletion. Greenhouse-gas flows are considered as climate-related mechanisms; electrolyte and metal releases are associated with human-toxicity and ecotoxicity pathways; and unrecovered critical materials are associated with resource-depletion potential. Thermal-runaway releases are treated as hazard flows contributing to toxicity and fire damage rather than as a separate impact category. Fire-related greenhouse-gas emissions are not quantified in the present screening analysis.

The screening procedure maps only the operational indicators in Table 2 to the damage-cost categories in Section 2.5. Its sole consequential element is the separately reported, conditional S_2 displacement credit.

- Attributional indicators describe direct post-vehicle burdens; the consequential element is limited to an explicitly reported substitution credit for S_2.
- All cross-scenario externality indicators are normalised per kWh-equivalent of end-of-life capacity entering the management system.
- The avoided-burden credit for S_2 is scenario-dependent and is shown as a negative monetary value after monetisation.

Only the operational indicators defined in Table 2 are monetised in the environmental and damage cost model. Greenhouse-gas flows are discussed qualitatively and are not included in the ecological damage (ECO) component.

2.5. Extended Environmental and Damage Cost Model

The extended environmental and damage cost model reports seven monetary-equivalent external-cost components. In this application, EDC is a project-parameterized screening indicator rather than a bottom-up estimate of national environmental or social damage. The numerical coefficients are therefore interpreted as project-model parameters, not observed national damage values.

$$EDC_{total} = ECO + HB + FIRE + SOC + GOV + LCM + CRIM \quad (2)$$

For the applied numerical screening case, category i in scenario s is calculated as:

$$EDC_{i,s} = b_i \times m_{i,s} \quad (3)$$

where b_i is the project-defined S_0 component coefficient in USD per kWh-equivalent of the common BEV end-of-life capacity, and $m_{i,s}$ is the dimensionless project scenario multiplier. By definition $m_{i,0} = 1$. The m values encode the modelled relative effect of controlled handling, recovery, delayed recovery, and final recycling. Neither b nor m is presented as a nationally measured damage factor or causal effect size.

- ECO in this framework is limited to soil and groundwater contamination caused by battery leakage. Its operational indicators are leaked pollutant mass and affected soil or water area, while monetisation is based on pollutant-specific remediation costs and an area-sensitivity factor. Greenhouse-gas emissions are treated separately and are not included in the ECO component.
- HB (Health burden) uses one selected exposure or disability-adjusted life year (DALY) valuation route in any application of the framework. Disability-adjusted life-year, value of statistical life (VSL), and cost-of-illness methods are alternatives and are not summed.
- FIRE (Fire-related damage) represents expected property damage and emergency response associated with thermal runaway. The governmental expenditure (GOV) term excludes the same emergency-response expenditure, and fire-related greenhouse-gas emissions are not estimated.
- SOC (Social degradation) uses affected land area and a proxy for the change in land value or productivity adjacent to unmanaged sites.
- GOV represents administration and formal waste-management oversight only. It excludes soil remediation counted in ECO, emergency response counted in FIRE, and enforcement expenditure counted in illegal trade and shadow activity (CRIM).

UNCORRECTED PROOF

- LCM (Loss of critical minerals) multiplies the unrecovered mass of lithium, cobalt, and nickel by scenario-consistent market-price factors. Delayed recovery in S_2 is represented separately from immediate recovery in S_1.
- CRIM represents indicative tax loss and enforcement expenditure; enforcement is recorded here and not again in GOV. Because observed informal-flow data are unavailable, this component is an order-of-magnitude screening assumption rather than a measured fiscal loss.

Table 2 separates the coefficients actually used in the project model from prospective bottom-up calibration routes and clarifies the specific role of each external-cost component within the screening framework. For each component, the table identifies the corresponding operational indicators, the prospective quantity-by-unit-factor valuation route, and the empirical data source that would be required for future calibration. This structure makes it possible to distinguish clearly between the parameters that are actively used in the current project calculation and the physical or monetary data that would be needed for a fully bottom-up assessment. The cited external sources support remediation-cost estimation, mortality-risk valuation, fire-data analysis, and mineral-price calibration; however, they do not generate the reported b or m values used in the present model. No external coefficient is retrofitted to the project outputs solely to reproduce the retained totals. Instead, the table documents how future applications could progressively replace the present screening assumptions with locally observed quantities, unit-cost factors, recovery efficiencies, exposure data, incident probabilities, and market information. This distinction is important for maintaining transparency between the current project-defined screening application and a future empirically calibrated assessment. Accordingly, Table 2 should be interpreted as a methodological bridge between the present screening-level application and a more data-intensive, empirically calibrated assessment framework.

Table 2. Screening components, prospective bottom-up valuation routes, and calibration status

Component	Description	Operational indicators	Prospective bottom-up quantity × unit factor	Prospective calibration source and status
ECO	Soil and groundwater contamination from chemical leakage	kg of leaked pollutant; m² of affected soil/water	Pollutant-specific remediation cost; regional sensitivity factor	Future calibration: local site-remediation and environmental cost records; no external unit rate transferred.
HB	Health burden from toxic exposure (hydrogen fluoride (HF), volatile organic compounds (VOCs), and heavy metals)	DALYs; exposed population; concentration/exposure levels	One mutually exclusive valuation route: cost per DALY, adjusted VSL, or cost-of-illness per case	Organisation for Economic Co-operation and Development (OECD) mortality-risk valuation guidance [30]; no local VSL or DALY coefficient transferred.
FIRE	Fire-related damage and emergency response	Frequency of thermal runaway events; affected area; incident severity	Fire probability $\boldsymbol{P_{fire}}$; emergency response cost $\boldsymbol{C_{emer}}$; average property damage cost per event	National Institute of Standards and Technology (NIST) lithium-ion battery fire-data analysis [31]; no U.S. incident probability transferred.
SOC	Social degradation and land/property value loss	Decline in adjacent property values; affected land area (m²)	Land value delta ($\boldsymbol{V_{pre} - V_{post}}$); USD per m² land value loss; social cost indices	Future calibration: local affected-area and land-value records; no external coefficient transferred.

CORRECTED PROOF

Component	Description	Operational indicators	Prospective bottom-up quantity × unit factor	Prospective calibration source and status
GOV	Administration and formal waste-management oversight; excludes remediation, emergency response, and enforcement counted elsewhere	Hazardous-waste tonnage; formal treatment capacity; administrative workload	Administrative overhead per unit; hazardous-waste treatment cost (USD/tonne)	Future calibration: public budgets and waste-agency cost records; no external coefficient transferred.
LCM	Economic loss of critical raw materials (Li, Co, Ni, etc.)	Mass of each unrecovered metal per battery	Global market price of each metal P_j(USD/kg); value of unrecovered materials	Bailey et al. provide a material and value-flow framework [26]. Future empirical calibration requires battery-specific material quantities and contemporaneous market prices; no external price series is embedded in the current b vector.
CRIM	Illegal trade and shadow-market externalities	Estimated volume of informal waste flows; number of enforcement actions	Estimated tax loss and enforcement cost; enforcement excluded from GOV	Future calibration: Customs and enforcement records; no external coefficient transferred.

Note: The b vector and m multipliers are project-defined coefficients used to produce the retained project outputs. The operational indicators, prospective valuation factors, and external sources in Table 2 *show how a future bottom-up valuation could be calibrated; they should not be interpreted as the numerical basis from which the current b or m values were derived.*

UNCORRECTED PROOF

With categories ordered as (ECO, HB, FIRE, SOC, GOV, LCM, CRIM), the project retains an S_0 screening envelope $B_0 = 0.150$ USD/kWh-equivalent and allocates it using the project weights:

$$w = (0.2667, 0.1667, 0.1000, 0.0667, 0.1333, 0.2000, 0.0667)$$

where $\Sigma w_i = 1$ and $b_i = B_0 w_i$. This gives

$$b = (0.040, 0.025, 0.015, 0.010, 0.020, 0.030, 0.010)$$

The scenario multipliers are

$$m_0 = (1, 1, 1, 1, 1, 1, 1),$$

$$m_1 = (0.50, 0.40, 0.3333, 0.40, 0.60, 0.3333, 0.30),$$

and

$$m_2 = (0.30, 0.24, 0.2667, 0.30, 0.40, 0.50, 0.20).$$

Component-level rounding gives

$$S_0 = (0.040, 0.025, 0.015, 0.010, 0.020, 0.030, 0.010),$$

$$S_1 = (0.020, 0.010, 0.005, 0.004, 0.012, 0.010, 0.003),$$

and

$$S_2 = (0.012, 0.006, 0.004, 0.003, 0.008, 0.015, 0.002),$$

with unchanged totals of 0.150, 0.064, and 0.050 USD/kWh-equivalent.

The baseline envelope, component weights, and scenario multipliers are transparent project-defined assumptions rather than empirically estimated national coefficients. Their relative ordering reflects the expected direction of change under controlled handling, material recovery, delayed recovery, and final recycling. Lower multipliers were assigned to scenarios

with controlled handling and immediate risk reduction, whereas higher residual multipliers were retained where material recovery is delayed or where operational and enforcement risks remain. Because local observations are not yet available to estimate component-specific reduction factors, the numerical values should be interpreted as scenario parameters used for comparative screening. Future applications should replace them with locally observed quantities, unit-cost factors, recovery efficiencies, incident probabilities, or formally elicited expert ranges.

To examine the sensitivity of the comparative results to parameter uncertainty, a uniform arithmetic stress-test range was applied to the scenario outputs. This test is intended as a screening diagnostic and should not be interpreted as an empirically estimated confidence interval.

The project calculation is arithmetically reproducible from B_0, w, b, and m, the common capacity denominator, and $EDC_{i,s} = b_i \times m_{i,s}$ (3). Regulatory damage valuation or investment appraisal would require locally measured inventory, exposure, incident, remediation, health, land-value, governance, recovery, enforcement, and market-price data.

2.6. Integrated End-of-Life Cost Metric

The IECM is used in this manuscript as a label for a net external-cost indicator expressed on a common end-of-life capacity basis. It is treated separately from the TEA and EDC components. IECM combines the screening damage cost with any separately stated avoided-impact credit. LCOS remains a distinct S_2 service-cost indicator and is not added to IECM.

For scenario s, the net external-cost indicator is:

$$IECM_s = EDC_s + AI_s \quad (4)$$

where:

- EDC_s is the sum of the seven environmental and societal damage categories in Section 2.5, expressed in USD per kWh-equivalent of end-of-life capacity;
- AI_s is a benefit on the same capacity basis and therefore has a negative sign. It can be written as $AI_s = -d_s c_s$, where d_s is the displacement fraction and c_s is the monetised avoided burden per unit of incoming capacity. The project application uses the combined coefficient $d_2c_2 = 0.020$ USD/kWh-equivalent for S_2, giving $AI_2 = -0.020$; $AI_0 = AI_1 = 0$. If displacement is not demonstrated, AI_2 is set to zero. S_1 receives no separate credit because its recovery benefit is already represented by the lower LCM component, which prevents double counting.
- $LCOS_2$ is reported separately in USD per kWh delivered. It is not a term in the IECM equation because adding a service cost to a capacity-normalised external cost would mix functional bases.

Worked project calculation for S_2:

$EDC_2 = 0.012 + 0.006 + 0.004 + 0.003 + 0.008 + 0.015 + 0.002 = 0.050$;

$IECM_2 = 0.050 + (-0.020) = 0.030$ USD per kWh-equivalent of end-of-life capacity.

This formulation enables a consistent external-cost comparison across S_0, S_1, and S_2 while preserving the distinct energy-service interpretation of LCOS for S_2.

The two outputs answer different decisions: IECM compares end-of-life externalities for the same incoming capacity, whereas LCOS tests whether the S_2 storage service may be economically feasible.

UNCORRECTED PROOF

Generative AI use statement.

Generative AI tools were used only to support language editing, grammar correction, stylistic refinement, and improvement of textual clarity. All scientific content, calculations, interpretations, results, and conclusions were developed, verified, and approved by the authors. No generative AI tool was used to generate or alter research data, numerical results, figures, or scientific conclusions.

3. RESULTS

This section presents the environmental and societal damage-cost results, the net end-of-life external-cost comparison, and the techno-economic sensitivity findings for the three scenarios. The results are reported according to their respective functional bases.

3.1. Comparison of Environmental and Societal Damage Costs

On the common capacity basis, the project-parameterized EDC screening totals are 0.150 USD/kWh-equivalent for S_0, 0.064 for S_1, and 0.050 for S_2. These values reconcile with the seven component coefficients in Section 2.5 and Figure 3. They are retained project-model outputs under the stated envelope, weights, and multipliers, not measured national damage costs.

Analysis of damage components:

- Baseline burden (S_0): ECO (0.040) and HB (0.025 USD/kWh-equivalent) are the largest leakage- and exposure-related project-model components. They represent the documented baseline parameterisation for unmanaged handling and should not be interpreted as an observed Caspian remediation bill.
- Direct recycling (S_1): the project-modelled total is 57.3% below S_0 because the scenario multipliers represent controlled handling and material recovery. Transport and recycling-process burdens are not separately quantified because a process-specific inventory is unavailable.
- Second-life pathway (S_2): the EDC total is 0.050 USD/kWh-equivalent. LCM remains slightly above S_1 because material recovery is deferred, while the scenario multipliers represent controlled handling for the other external-cost terms. This result is conditional on safe diagnostics, refurbishment, operation, and final recycling.
- Interpretation: relative to S_0, the base-case difference in modelled external cost is 0.100 USD/kWh-equivalent before the avoided-impact credit. This is a project-model result whose transfer to policy or investment decisions requires validation with local monitoring data.

As shown in Figure 3, the component sums reconcile exactly with the scenario totals.

UNCORRECTED PROOF

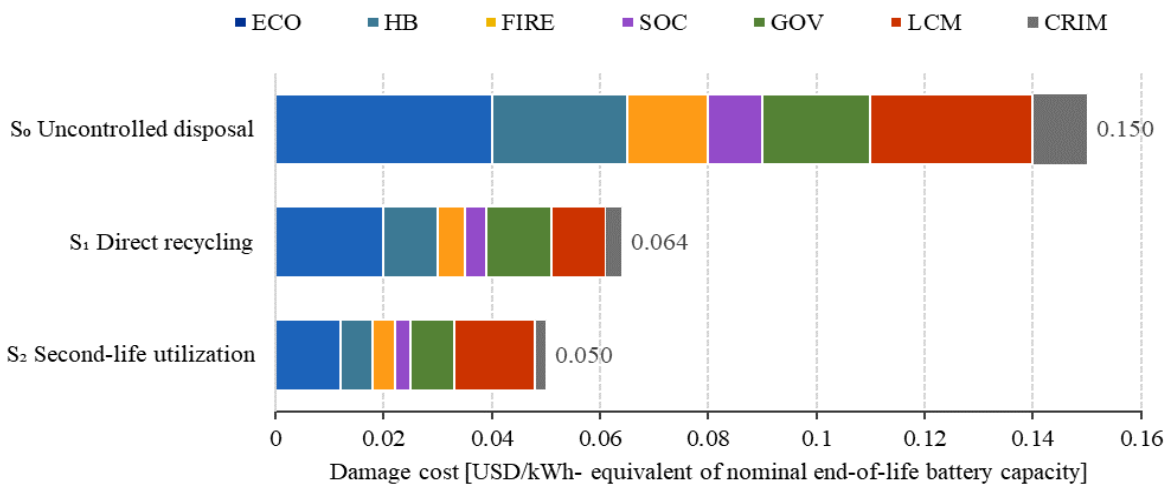


Figure 3. Composition of environmental and damage cost components across S_0, S_1, and S_2.

Note: values are project-derived screening outputs in USD per kWh-equivalent of nominal BEV end-of-life capacity; they are not measured national damage costs. Greenhouse-gas emissions are not included in ECO.

UNCORRECTED PROOF

3.2. Net End-of-Life External Cost Analysis

Table 3 reports two non-additive outputs: LCOS for the S_2 energy service and IECM for cross-scenario net external costs. Avoided impacts are shown as a negative value, and the calculation gives $IECM_2$ = 0.030 USD/kWh-equivalent.

Analysis of integrated results:

- Uncontrolled disposal (S_0): net external cost is 0.150 USD/kWh-equivalent, entirely attributable to modelled damage categories.
- Direct recycling (S_1): net external cost is 0.064 USD/kWh-equivalent. This value does not represent the financial cost of operating a recycling facility.
- Second-life use (S_2): project-modelled EDC of 0.050 and a conditional avoided-impact credit of -0.020 produce a base-case IECM of 0.030 USD/kWh-equivalent. Separately, the project LCOS base case is 0.110 USD/kWh delivered and the defined cost-side scenario range is 0.110–0.170.
- Key finding: S_2 has the lowest net external cost in the project base case and may provide a viable storage service. The result is conditional on safe operation, recycling at the end of the second-life service period, actual displacement of new storage, refurbishment yield, degradation, financing, utilisation, and the new-battery comparator.

Table 3. Separate service-cost and net external-cost results by scenario

Scenario	LCOS (USD/kWh delivered)	EDC (USD/kWh-equivalent EOL capacity)	Avoided impacts (same basis; benefit < 0)	IECM: net external cost (same basis)
S_0 – Uncontrolled disposal	Not applicable	0.150	0.000	0.150
S_1 – Direct recycling	Not applicable	0.064	0.000	0.064
S_2 – Second-life use	0.110 base; 0.110-0.170 project scenario range	0.050	-0.020	0.030

Note: LCOS is not applicable to S_0 or S_1. EDC, avoided impacts, and IECM use USD per kWh-equivalent of nominal BEV end-of-life capacity; LCOS uses USD per kWh delivered, so the indicators are not added. A uniform ±20% arithmetic stress-test envelope - not an empirically estimated confidence interval - gives S_0 = 0.120-0.180, S_1 = 0.051-0.077, and S_2 EDC = 0.040-0.060. Combining the S_2 EDC envelope with AI_2 from -0.024 to 0.000 gives $IECM_2$ = 0.016-0.060. The base case ranks S_2 lowest, but the S_1 and S_2 arithmetic stress-test ranges overlap when no displacement credit is assumed; the ranking is therefore conditional rather than universal.

3.3. Comparative Synthesis and Discussion

The integrated framework was applied to three end-of-life pathways in Azerbaijan: uncontrolled disposal (S_0), direct recycling (S_1), and second-life utilization (S_2). The project results differ across the service-cost and external-cost dimensions and must be interpreted on their stated functional bases. Martinez-Laserna et al. critically assessed second-life feasibility [24]. Chirumalla et al. examined remanufacturing, repurposing, and reuse in practice [19]. These studies support a conditional comparison rather than a universal ranking.

From a techno-economic perspective, the project gives an S_2 LCOS base case of 0.110 USD/kWh delivered and a defined cost-side scenario range of 0.110–0.170. This is not an automatic advantage over new systems. Steckel et al. found that second-life LCOS could exceed their new-battery comparator even when upfront investment was lower [16]. Turan et al. likewise showed that testing, renovation, transport, replacement, and opportunity costs materially affect the viable purchase price [17]. Site-specific validation is therefore required before investment.

The screening analysis of environmental impact pathways indicates that S_0 has the highest potential for toxicity-related releases and unrecovered-resource loss. Fire-related greenhouse-gas emissions are not quantified because event-specific inventory data are unavailable. S_1's recovery benefit is represented through its lower LCM term. S_2 receives the separate -0.020 USD/kWh-equivalent credit only when second-life service demonstrably displaces new storage; otherwise that credit is zero. Its magnitude depends on chemistry, state of health, service life, replacement ratio, and the displaced technology [14].

The EDC comparison is a project-derived output of the documented screening model. S_0 has the largest modelled leakage, health, fire, governance, and material-loss burden. S_2 has the lowest base-case net value under the stated assumptions regarding controlled diagnostics, safe operation, end-of-second-life recycling, and displacement credit. However, the overlap of the stated arithmetic stress-test ranges, particularly when the displacement credit is not demonstrated, indicates that this ordering should not be interpreted as universal. To assess the robustness of the project results to selected parameter uncertainties, a one-at-a-time sensitivity analysis was conducted. As shown in Figure 4, the S_2 LCOS is sensitive to changes in the principal project parameters around the 0.110 USD/kWh-delivered base case.

UNCORRECTED PROOF

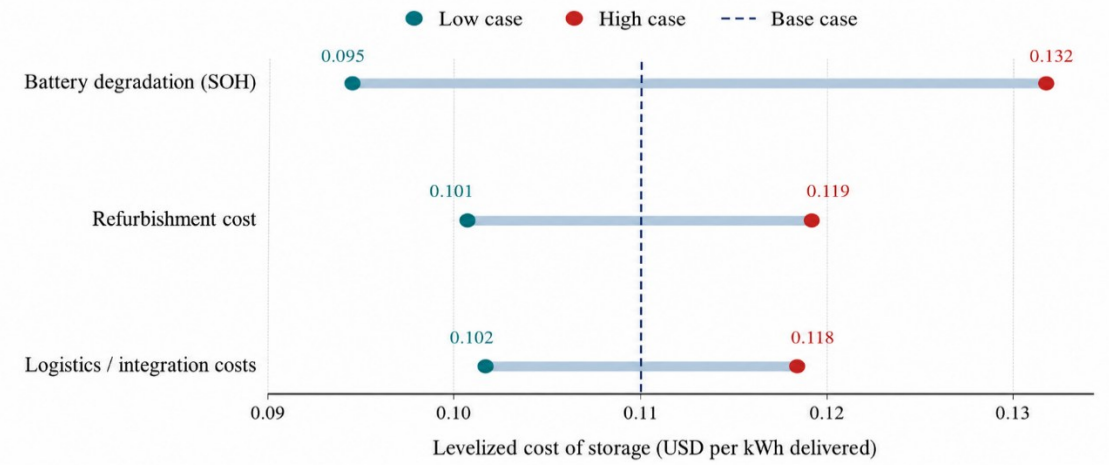


Figure 4. One-at-a-time local sensitivity of the S_2 project LCOS around the 0.110 USD/kWh-delivered base case.

Figure 4 reports a one-at-a-time local sensitivity diagnostic around the project base case. The low/high LCOS values are 0.095/0.132 for the favourable/adverse state-of-health trajectories 80→77% and 60→53%, 0.101/0.119 for refurbishment cost at 26.4/38.8 USD/kWh, and 0.102/0.118 USD/kWh delivered for allocated logistics or integration cost at 33.6/44.7 USD/kWh. All other base inputs are held constant. This local diagnostic is distinct from the 0.110–0.170 defined cost-side scenario range and is not compared with the capacity-normalised IECM values.

4. DISCUSSION

The findings show that policy assessment should consider the types of societal damage represented in the screening model. The assumed health and fire-related terms for S_0 motivate preventive attention to informal battery-waste flows but are not observations of national damage.

The integrated assessment provides a multidimensional comparison of end-of-life strategies for lithium-ion batteries. On the common external-cost basis, S_2 has the lowest base-case value; however, its techno-economic performance remains application- and assumption-dependent. The contribution of this study is to monetise a broader set of screening-level societal externalities while keeping service cost and capacity-normalised external cost separate.

A central insight is that purely financial assessments do not represent the external costs associated with uncontrolled disposal. In the screening model, S_0 has the highest leakage, health, fire-related, governance, and material-loss terms. These modelled differences support structured end-of-life governance, but they should not be interpreted as measured national damages.

On the common external-cost basis, direct recycling (S_1) has a lower modelled value than uncontrolled disposal because it retains materials and uses controlled processing. The study does not estimate the financial cost of operating a recycling facility, and therefore does not make a techno-economic ranking between S_1 and S_2.

Second-life use (S_2) is a potentially favourable transitional pathway under the base assumptions because it has the lowest modelled net external cost and can provide an additional storage service. The economic screen does not establish an unconditional cost advantage over new stationary storage. The screening framework represents three distinct mechanisms:

UNCORRECTED PROOF

potential avoidance of new battery production through second-life substitution, toxicity-related risks from electrolyte and metal releases, and losses associated with unrecovered critical materials. These mechanisms are used to support the external-cost comparison; the study does not calculate characterised reductions in greenhouse-gas emissions, human toxicity, ecotoxicity, or resource depletion.

Overall, the framework places the S_2 service-cost result and the cross-scenario external-cost result in one decision context without combining their different functional bases. This provides a broader screening basis for regions with emerging electric-vehicle markets and limited end-of-life infrastructure. The results support considering second-life utilization as a conditional transitional strategy alongside formal collection and future recycling capacity.

5. POLICY IMPLICATIONS

The base-case screening results have implications for energy policy, waste-management regulation, and long-term planning in Azerbaijan. The policy directions below are conditional on local validation and effective safety, traceability, and end-of-second-life requirements.

First, a formal system for end-of-life battery collection, classification, and diagnostics would address the leakage, fire, and health pathways represented in the screening model. These are preventive risk categories, not measured EDC outcomes. Tracking and reporting would provide the evidence needed for future national calibration.

Second, Azerbaijan could consider a monitored second-life pilot within renewable-energy planning. The project LCOS result supports testing potential feasibility, but a pilot should validate duty cycle, degradation, refurbishment yield, logistics, safety, charging-energy allocation, and final-recycling performance before investment or incentive decisions.

Third, a phased recycling roadmap is required. Because domestic process data are unavailable, the study does not compare local recycling investment with second-life deployment. Second-life use may be tested as a transitional option only alongside collection, safety standards, traceability, and guaranteed end-of-second-life recycling.

Fourth, the screening framework identifies illegal waste flows as a policy risk, while the CRIM value itself is not empirically validated. Enforcement, import-export controls, and reporting can both reduce that risk and generate the data needed to estimate it more credibly.

Finally, institutional coordination is necessary to ensure cohesive policy implementation. The government may consider designating a lead competent authority or establishing an inter-ministerial task force, operating within a public-private partnership (PPP) framework, to coordinate battery lifecycle regulation, infrastructure planning, the design of market-based incentives, and structured engagement with private-sector stakeholders, technology providers, and investors. Such institutional clarity would support the development of a circular-economy framework for electric-vehicle batteries and align Azerbaijan with emerging international sustainability standards.

Collectively, these policy actions could mitigate near-term risks associated with uncontrolled disposal while supporting the development of formal battery management. The framework provides a screening decision-support basis; national monitoring and process-specific data are still required before investment decisions.

From a regulatory perspective, the findings support formal battery collection and clear institutional responsibility for electric-vehicle battery waste. Without these mechanisms, the leakage, fire, health, and material-loss risks represented in the screening model may grow as electric-vehicle adoption increases.

UNCORRECTED PROOF

6. LIMITATIONS AND DIRECTIONS FOR FUTURE RESEARCH

The screening framework provides a structured basis for comparing end-of-life pathways, but several limitations must be acknowledged. These limitations arise from Azerbaijan's early electric-vehicle and waste-management data environment and from the deliberately simplified screening design.

Reliance on project-model assumptions remains the central limitation. The LCOS sensitivities and external-cost envelope quantify parameter dependence but do not eliminate structural uncertainty. When the avoided-impact credit is allowed to fall to zero, the S_1 and S_2 net-external-cost arithmetic stress-test ranges overlap. No standalone fire-related greenhouse-gas inventory is claimed.

First, Azerbaijan currently lacks systematic data on end-of-life battery flows, informal disposal, fire incidents, leakage, health outcomes, and operating second-life projects. The reported LCOS and EDC values are project-derived model outputs under explicit assumptions, not measured national statistics or an investment quotation. Future applications should recalibrate the model with monitoring and pilot-project data.

Second, the absence of domestic battery-recycling facilities prevents a process-specific estimate of recovery efficiency, energy use, emissions, and cost in Azerbaijan. These burdens are not quantified in the present screening case. Future work should model defined local and export-recycling routes using technology, scale, transport, and electricity-mix data.

Third, the EDC application uses a project-parameterized screening envelope, weights, and scenario multipliers. These parameters reproduce the project outputs but are not bottom-up physical-inventory or nationally estimated monetisation factors. The ±20% ranges are arithmetic stress tests rather than statistical confidence intervals. Future work should estimate region-specific damage functions while retaining the stated exclusions that prevent double counting across ECO, HB, FIRE, GOV, and CRIM.

Fourth, the present framework does not incorporate macroeconomic and system-wide feedback effects, such as labour market impacts, trade ramifications of critical mineral supply chains or long-term innovation spillovers from adopting second-life technologies. Integrating input-output modelling or computable general equilibrium (CGE) frameworks could provide additional insight into how battery end-of-life strategies interact with the broader national economy.

Finally, future research should explore optimisation strategies for national ESS deployment using second-life batteries, including spatial modelling, storage placement algorithms, and resilience assessments for grid planning. Experimental validation through pilot projects, laboratory measurements of ageing patterns and real-world performance monitoring would further enhance the empirical strength of the integrated techno-economic and external-cost screening framework.

Despite these limitations, the framework and its project application provide a transparent starting point for end-of-life decisions in a data-limited setting. The numerical results are retained as model outputs under the reported assumptions and should be recalibrated as national evidence becomes available.

Azerbaijan's limited end-of-life battery monitoring explains why the project application uses an explicit screening envelope, component weights, and scenario multipliers. The values are reproducible project-model coefficients but are not validated regional damage factors; the exact external sources added in Table 2 describe future calibration routes rather than the numerical origin of the retained outputs.

UNCORRECTED PROOF

The project application supports methodological and policy screening, but not an unconditional ranking. The base-case net IECM is lowest for S_2; under the conservative no-displacement case, the S_1 and S_2 arithmetic stress-test ranges overlap.

7. CONCLUSION

This study developed and applied a framework that reports a reproducible project-modelled second-life storage cost alongside project-parameterized end-of-life external-cost screening outputs for Azerbaijan. The delivered-energy basis used for S_2 LCOS is kept separate from the incoming-capacity basis used for the cross-scenario screening comparison.

Under the project base-case assumptions, S_2 has a net external cost of 0.030 USD per kWh-equivalent of BEV end-of-life capacity, compared with 0.064 for S_1 and 0.150 for S_0. Separately, the project S_2 LCOS base case is 0.110 USD per kWh delivered and the defined cost-side scenario range is 0.110–0.170. These indicators are not added because they answer different questions and use different denominators.

Under the stated project-model assumptions, controlled second-life use is associated with lower modelled leakage, health, fire, governance, and material-loss external-cost components than uncontrolled disposal, provided that diagnostics, refurbishment, operation, and final recycling are properly managed. The analysis does not calculate characterised reductions in greenhouse-gas emissions, human toxicity, ecotoxicity, or resource depletion.

For Azerbaijan, a standards-based second-life pilot can be considered as a transitional measure alongside formal collection and future recycling capacity. The recommendation is conditional on local validation of cost, degradation, safety, substitution, and damage factors.

Future research should recalibrate the project model with measured national data, build a process-level life-cycle inventory, validate refurbishment yields and service profiles, and test wider uncertainty ranges. The present result therefore identifies S_2 as a potentially favourable pathway under the stated conditions rather than a universally superior solution.

ACKNOWLEDGEMENT

This work was funded by the Scientific Development Fund of the State Oil Company of the Republic of Azerbaijan (SOCAR), grant No. 012LR – ETF/2025-12

UNCORRECTED PROOF

NOMENCLATURE

AI	Avoided impact
BEV	Battery electric vehicle
BMS	Battery management system
CAPEX	Capital expenditure
CGE	Computable general equilibrium
CRIM	Illegal trade and shadow activity
CRM	Critical raw material
DALY	Disability-adjusted life year
DOD	Depth of discharge
ECO	Ecological damage
EDC	Environmental damage cost
EHV	Electric and hybrid vehicle
EOL	End of life
ESS	Energy storage system
FIRE	Fire-related damage
GOV	Governmental expenditure
HB	Health burden
HEV	Hybrid electric vehicle
HF	Hydrogen fluoride
IECM	Integrated End-of-Life Cost Metric
LCM	Loss of critical minerals
LCOS	Levelized cost of storage
LIB	Lithium-ion battery
NIST	National Institute of Standards and Technology
OECD	Organisation for Economic Co-operation and Development
O&M	Operation and maintenance
OPEX	Operating expenditure
PCS	Power conversion system
PPP	Public-private partnership
SOC	Social degradation
SOH	State of health
TEA	Techno-economic analysis
VOC_S	Volatile organic compounds
VSL	Value of statistical life

UNCORRECTED PROOF

REFERENCES

1. R. K. Upadhyay, R. Kumari, S. Mondal, A. Jena, and S. Pandey, “Advancing Second-Life Lithium-Ion Batteries for a Circular Energy Economy through Diagnostic Economic and Policy Pathways,” *Circular Economy and Sustainability*, vol. 6, no. 3, p. 289, Jun. 2026, https://doi.org/10.1007/s43615-026-01012-z.

2. A. Sisodia and J. Monteiro, “Lithium-Ion Battery Management System: A Lifecycle Evaluation Model for the Use in the Development of Electric Vehicles,” *MATEC Web of Conferences*, vol. 144, p. 04020, Jan. 2018, https://doi.org/10.1051/matecconf/201714404020.

3. S. S. Madani, M. J. Swierczynski, and S. K. Kaer, “A review of thermal management and safety for lithium ion batteries,” in *2017 Twelfth International Conference on*

Ecological Vehicles and Renewable Energies (EVER), Apr. 2017, pp. 1–20, https://doi.org/10.1109/EVER.2017.7935914.

4. P. K. Dehury and S. K. Samal, "Smart Algorithms and Controls for Electric Vehicle Battery Management Systems: A State-of-the-Art Review," *Journal of The Institution of Engineers (India): Series B*, vol. 107, no. 2, pp. 461–480, Apr. 2026, https://doi.org/10.1007/s40031-025-01247-8.

5. International Energy Agency (IEA), "Global EV Outlook 2026," Paris, France, 2026. Accessed: Aug. 05, 2026. [Online]. Available: https://www.iea.org/reports/global-ev-outlook-2026.

6. R. M. Salgado, F. Danzi, J. E. Oliveira, A. El-Azab, P. P. Camanho, and M. H. Braga, "The Latest Trends in Electric Vehicles Batteries," *Molecules*, vol. 26, no. 11, p. 3188, May 2021, https://doi.org/10.3390/molecules26113188.

7. R. Goyal, P. D. Kusalkar, A. Paul, D. Yadav, A. Goyal, and A. D. Oza, "Recycling and Disposal of Lithium-Ion Batteries Utilized in Electric Vehicles: A Review," *Micro and Nanosystems*, vol. 17, May 2025, https://doi.org/10.2174/0118764029369243250325084413.

8. Y. Miao, P. Hynan, A. von Jouanne, and A. Yokochi, "Current Li-Ion Battery Technologies in Electric Vehicles and Opportunities for Advancements," *Energies (Basel).*, vol. 12, no. 6, p. 1074, Mar. 2019, https://doi.org/10.3390/en12061074.

9. N. Sharmili, R. Nagi, and P. Wang, "A review of research in the Li-ion battery production and reverse supply chains," *J. Energy Storage*, vol. 68, p. 107622, Sep. 2023, https://doi.org/10.1016/j.est.2023.107622.

10. R. Almahri and H. An, "Evaluating economic and environmental viability of recycling lithium-ion battery for electric vehicles in the middle east: a case study in the UAE," *Humanit. Soc. Sci. Commun.*, vol. 12, no. 1, p. 508, Apr. 2025, https://doi.org/10.1057/s41599-025-04629-x.

11. D. Pang, H. Wang, Y. Zeng, X. Han, and Y. Zheng, "Sustainable Recycling of Lithium-Ion Battery Cathodes: Life Cycle Assessment, Technologies, and Economic Insights," *Nanomaterials*, vol. 15, no. 16, p. 1283, Aug. 2025, https://doi.org/10.3390/nano15161283.

12. P. Das, K. Hewage, R. Kotagodahetti, S. Wanniarachchi, and R. Sadiq, "Lithium-ion battery recycling: a critical review of techno-economical and socio-environmental impacts," *Sep. Purif. Technol.*, vol. 382, p. 135847, Feb. 2026, https://doi.org/10.1016/j.seppur.2025.135847.

13. L. Zhang, G. Hu, X. Mu, Y. Wu, and H. Wang, "Sustainable recovery: Life cycle assessment for lithium-ion battery recycling," *J. Environ. Manage.*, vol. 395, p. 127879, Dec. 2025, https://doi.org/10.1016/j.jenvman.2025.127879.

14. J. Cui, Q. Tan, L. Liu, and J. Li, "Environmental Benefit Assessment of Second-Life Use of Electric Vehicle Lithium-Ion Batteries in Multiple Scenarios Considering Performance Degradation and Economic Value," *Environ. Sci. Technol.*, vol. 57, no. 23, pp. 8559–8567, Jun. 2023, https://doi.org/10.1021/acs.est.3c00506.

UNCORRECTED PROOF

15. P. Marques, R. Garcia, L. Kulay, and F. Freire, "Comparative life cycle assessment of lithium-ion batteries for electric vehicles addressing capacity fade," *J. Clean. Prod.*, vol. 229, pp. 787–794, Aug. 2019, https://doi.org/10.1016/j.jclepro.2019.05.026.

16. T. Steckel, A. Kendall, and H. Ambrose, "Applying levelized cost of storage methodology to utility-scale second-life lithium-ion battery energy storage systems," *Appl. Energy*, vol. 300, p. 117309, Oct. 2021, https://doi.org/10.1016/j.apenergy.2021.117309.

17. F. Turan, A. R. Boynuegri, and T. Durmaz, "Comprehensive technical and economic evaluations of using second-life batteries as energy storage in off-grid applications: A customized cost analysis," *J. Energy Storage*, vol. 120, p. 116379, Jun. 2025, https://doi.org/10.1016/j.est.2025.116379.

18. K. Richa, C. W. Babbitt, and G. Gaustad, "Eco-Efficiency Analysis of a Lithium-Ion Battery Waste Hierarchy Inspired by Circular Economy," *J. Ind. Ecol.*, vol. 21, no. 3, pp. 715–730, Jun. 2017, https://doi.org/10.1111/jiec.12607.

19. K. Chirumalla, I. Kulkov, F. Vu, and M. Rahic, "Second life use of Li-ion batteries in the heavy-duty vehicle industry: Feasibilities of remanufacturing, repurposing, and reusing approaches," *Sustain. Prod. Consum.*, vol. 42, pp. 351–366, Nov. 2023, https://doi.org/10.1016/j.spc.2023.10.007.

20. The State Customs Committee of the Republic of Azerbaijan, "Customs Statistics of Foreign Trade of the Republic of Azerbaijan (in Azerbaijani; original title: Azərbaycan Respublikası Xarici Ticarətinin Gömrük Statistikası)," Baku, 2025. Accessed: Aug. 05, 2026. [Online]. Available: https://customs.gov.az/uploads/foreign/2025/2025_8.pdf?v=1757938366.

21. State Statistical Committee of the Republic of Azerbaijan, "Transport in Azerbaijan: Statistical Yearbook (in Azerbaijani; original title: Azərbaycanda nəqliyyat: Statistik məcmuə)," Baku, 2025. Accessed: Aug. 05, 2026. [Online]. Available: https://www.stat.gov.az/source/transport/.

22. M. Mirzaei Omrani and H. Jannesari, "Economic and environmental assessment of reusing electric vehicle lithium-ion batteries for load leveling in the residential, industrial and photovoltaic power plants sectors," *Renewable and Sustainable Energy Reviews*, vol. 116, p. 109413, Dec. 2019, https://doi.org/10.1016/j.rser.2019.109413.

23. M. Foster, P. Isely, C. R. Standridge, and M. M. Hasan, "Feasibility assessment of remanufacturing, repurposing, and recycling of end of vehicle application lithium-ion batteries," *Journal of Industrial Engineering and Management*, vol. 7, no. 3, pp. 698–715, Jun. 2014, https://doi.org/10.3926/jiem.939.

24. E. Martinez-Laserna, I. Gandiaga, E. Sarasketa-Zabala, J. Badeda, D.-I. Stroe, M. Swierczynski, and A. Goikoetxea, "Battery second life: Hype, hope or reality? A critical review of the state of the art," *Renewable and Sustainable Energy Reviews*, vol. 93, pp. 701–718, Oct. 2018, https://doi.org/10.1016/j.rser.2018.04.035.

25. V. O. Vega-Muratalla, C. Ramírez-Márquez, L. F. Lira-Barragán, and J. M. Ponce-Ortega, "Review of Lithium as a Strategic Resource for Electric Vehicle Battery Production: Availability, Extraction, and Future Prospects," *Resources*, vol. 13, no. 11, p. 148, Oct. 2024, https://doi.org/10.3390/resources13110148.

UNCORRECTED PROOF

26. C. Bailey, C. Babbitt, and G. Gaustad, "Tracking the material, energy, and value flow for end-of-life lithium ion batteries in the US," in *Proceedings of the 2011 IEEE International Symposium on Sustainable Systems and Technology*, May 2011, pp. 1–1, https://doi.org/10.1109/ISSST.2011.5936856.

27. D. Radomski, K. Jezierski, T. Nelson, and R. Kibler, "NextEnergy Center's Highlights on Global Lithium Ion Battery Supply Chain Dynamics and Domestic Opportunities," *World Electric Vehicle Journal*, vol. 6, no. 4, pp. 909–920, Dec. 2013, https://doi.org/10.3390/wevj6040909.

28. A. Ali, M. Al Bahrani, S. Ahmed, M. T. Islam, S. A. Qadir, and M. Shahid, "Sustainable Recycling of End-of-Life Electric Vehicle Batteries: EV Battery Recycling Frameworks in China and the USA," *Recycling*, vol. 10, no. 2, p. 68, Apr. 2025, https://doi.org/10.3390/recycling10020068.

29. J. Blümke, C. Laves, and H.-J. Hof, "Identifying Building Blocks for Second-Life-Enabled Battery Management Systems," in *2025 IEEE International Conference on Environment and Electrical Engineering and 2025 IEEE Industrial and Commercial Power Systems Europe (EEEIC / I&CPS Europe)*, Jul. 2025, pp. 1–5, https://doi.org/10.1109/EEEIC/ICPSEurope64998.2025.11169196.

30. Organisation for Economic Co-operation and Development (OECD), "Mortality Risk Valuation in Policy Assessment: A Global Meta-Analysis of Value of Statistical Life Studies," OECD Publishing, Paris, France, Oct. 2025. https://doi.org/10.1787/76ca89a2-en.

31. S. W. Gilbert, H. Fang, D. T. Butry, W. C. Tam, M. Donnelly, and J. F. Fung, "Understanding the Risk of Lithium-Ion Battery Fires - multi-source data analysis," Gaithersburg, MD, USA, Mar. 2026. https://doi.org/10.6028/NIST.TN.2365.

UNCORRECTED PROOF