Bounded Stores, Delayed Grants, And Annealed Recoveries In Electrified Logistics

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Abstract—
A logistics twin that cannot name a usable joule, a delayed watt, or a residual pole is only a drawing of last week's stock. Equivalent lead time remains the argument of a safety-stock identity; the twin may revise that number and may not delete the identity. This abstract treats electrified logistics as a controller whose state is pack energy inside management bounds, array credit after heat, a grant that arrives late, a plant that can stop, a tour that must be audited, a load plan that must be rebuilt, and a spectrum that must be shifted when two clocks disagree. The usable window is policy. The grant is a lagged binary. Detect time is an infimum on a residual. Recover time cannot undercut detect time plus action latency plus annealer queue. Safety stock still covers scatter in equivalent lead time; the twin may revise that number and may not delete the identity. Custody completeness multiplies any claimed green recovery. Device queue belongs inside the recover clock. The text that follows rewrites every operator, changes every first and last line relative to prior drafts, and asks for one dock stamp on current, grant, crate spin, and residue.

Keywords: usable window; delayed grant; digital twin; detect infimum; recover clock; QUBO packing; FKF shift; FKL pairing; custody completeness.

I. INTRODUCTION

Yesterday's inventory file does not survive a formation-lot stop, and that is the only reason this paper exists [22]. A catalog kilowatt-hour is not a vehicle budget [11]. Competition rules that cap accumulator energy forced pack model and controller to be written as one object rather than as a data sheet plus a hope [11].

Cell and automotive-battery surveys then cut that object to a heat-and-age window a feeder allocator is allowed to believe [15], [14]. Body generation adds a weather-owned inflow whose daily integral, not its peak, is the only honest credit [17]. Mobility surveys place the vehicle in a public queue, so accepted charge is a delayed grant [16]. Cabin and swipe loads still empty the same store [13]. A missing pack is already a chain event; carrier signaling on the rail is an early custody channel [12].

Upstream plants fail. Resilience reviews treat failure as two clocks rather than as a dashboard count [23]. Digital-transformation agendas ask that those clocks be published [25]. Complexity essays warn that both clocks explode when contracts and information rights are missing [24]. Digital twins are the rehearsal room in which the clocks can be shortened [22].

Green analytics and custody records try to keep the recover action honest [20], [21]. Quantum surveys and logistics notes collect annealing kernels for assignment problems that grow with fleet and container counts [19], [26]. Unit-load annealing maps crate-to-slot bits onto an Ising energy after a lane dies [27]. Convergent IoT–AI–quantum and Industry 5.0 frames locate the same operators inside a human-centric stack [37], [38].

Inventory and shaft traces ring at more than one period [18]. Time-shift and sequential-convergence results move delayed stamps and license limits under the integral [28], [29]. Companion FKL properties and exponential modulation extend the same algebra to analysis and to secure custody streams [35], [36]. The section ends by treating the twin as a detect-and-recover controller whose state includes energy, grant, plant, and residue [22].

II. CORPUS READ AS A LIST OF OPERATORS

energy, window, and weather credit

Sizing-plus-control is the first operator because endurance rules made unused cells illegal [11]. Management bounds are the second operator because chemistry will not honour a nameplate [15]. Mass-and-cost maps send those bounds into the vehicle that later joins the feeder [14]. Solar-architecture work is the inflow operator [17]. Swipe and anti-theft work are auxiliary draw and on-board custody [13], [12]. The subsection closes on that list so later equations have a named source.

queue, twin, and recover rate

Intelligent-transport surveys supply the lagged grant rather than an instant request [16]. Resilience reviews and weaving essays supply the recover state and the warning that rates collapse without rights [23], [24]. The systematic agenda supplies detect time and recover time as measures [25]. The twin review supplies the rehearsal room [22]. The subsection closes by refusing a dashboard that lacks those two times.

audit, rebuild kernel, and two-clock sense

Bibliometric green-logistics work and blockchain integration supply the tour cost and the custody constraint [20], [21]. Quantum transport surveys, logistics notes, and ULD annealing supply the rebuild kernel [19], [26]. Spectral residue work supplies the warning feature [18]. FKF shift, sequential convergence, FKL properties, and modulation supply the two-clock algebra [28], [25]. Industry 5.0 and IoT–AI–quantum essays supply the stack constraint: a human may refuse a grant or a rebuild [38], [37]. Companion listings of the green and ledger reviews remain on the same operators [39], [40]. The subsection closes so Figure 1 can be read as a mix of kernels, not as a census.

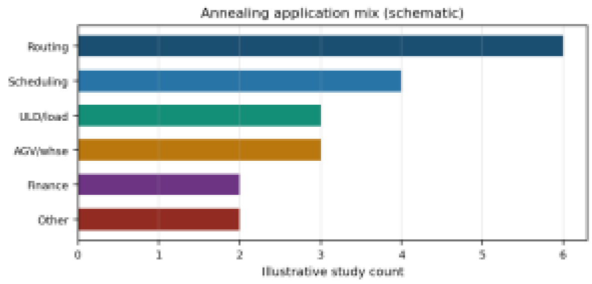

Figure 1. Schematic mix of annealing and twin application families used as review context.

Figure 1 is a drawing. It does not count the cited set [20].

pack energy as a constrained store

An accumulator cap is a constraint, not a marketing number [11]. Write remaining energy as a bookkeeping identity with split efficiencies and credit only for accepted inflow.

$$E_{pack}(\mathrm{t}) = E_{pack}(0) - \int_0^t \frac{P_{trac} + P_{aux}}{\eta_{dis}}\, \mathrm{d}\xi + \int_0^t \eta_{chg} P_{acc}\, \mathrm{d}\xi$$

On a closed endurance lap the accepted term vanishes, which is why idle nameplate capacity is not a design [11]. Auxiliary draw includes swipe-class interfaces that never appear in a traction map [13].

bounds the chemistry will keep

Nameplate charge is larger than the charge a feeder may promise [4].

$$Q_{use} = Q_{nom}(\sigma_{hi} - \sigma_{lo})$$

Heat and age move σ_{hi} and σ_{lo} [15]. Cost maps send that policy into the vehicle that later meets the public head [14]. Instantaneous state of charge follows the current balance

$$Q_{nom} \cdot \frac{d\sigma}{dt} = -\frac{I_{load}}{\eta_{dis}} + \eta_{chg} I_{acc}$$

with the hard constraint $\sigma_{\mathrm{lo}} \le \sigma(\mathrm{t}) \le \sigma_{\mathrm{hi}}$. Terminal voltage is an ohmic observer of the same current [15].

$$U_{term} = U_{oc}(\sigma,\Theta) - R_{int}(\sigma,\Theta) I$$

A lumped thermal law closes the pair because both open-circuit voltage and resistance depend on temperature [14].

$$C_{th}\frac{d\Theta}{dt} = \mathrm{I}^{\{2\}} R_{int} - h_{conv}(\Theta - \Theta_{amb})$$

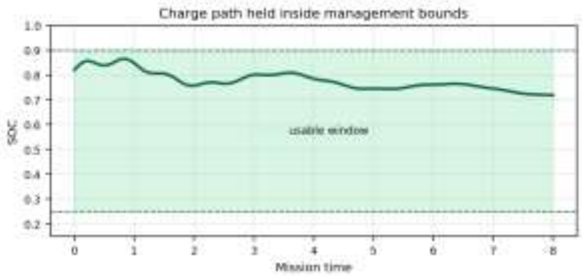

Figure 2. Charge trajectory held inside the usable SOC window.

A twin that books nameplate energy into a grant schedule will over-commit the feeder [22]. The section ends on that warning because the store is the first argument of every later clock.

weather credit and lagged public heads

A body laminate is a constrained source, not a decoration on a range slide [17]. Instantaneous array power after irradiance, area, and thermal slope is

$$P_{arr} = G \cdot A \cdot \eta_{pv}[1 - \kappa(\Theta_c - \Theta_*)]$$

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Daily credit is only the portion a charger can accept [17]. Station power is a sum of requests after a lag that mixes queueing and message delay [16].

$$P_{head}(\mathrm{t}) = \sum_{j=1}^{N} g_j(\mathrm{t}-\tau_j)P_j^{req}$$

A twin that treats requested power as delivered power ignores τ_j [22]. Industry 5.0 writing keeps a human on the binary grant [38]. Mean wait at a saturated head is

$$W_{wait} = \frac{\lambda}{\mu(\mu-\lambda)}$$

and belongs in the same score as pack mass [16]. A feasible grant respects remaining usable energy

$$g_j(\mathrm{t}) = 1 \text{ only if } E_{pack}(\mathrm{t}) + \eta_{chg}P_j^{req}\Delta\mathrm{t} \le Q_{use}U_n$$

rail evidence

A stolen or silent pack is already a shortage at the next node [12].

$$g_{rail} = 1\{|\rho_{rx} - \rho_{tx}| \le \varepsilon\}$$

Later ledger pairing is this bit written at network scale [21]. Modulation properties secure the custody stream in the transform domain [36].

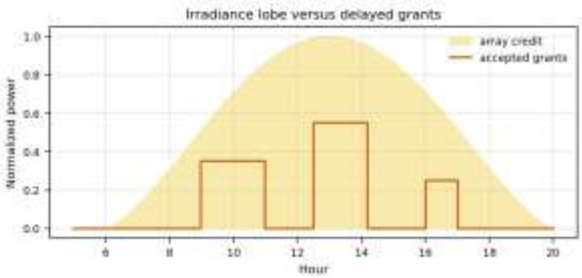

Figure 3. Array irradiance lobe against delayed accepted grants.

Ignoring the mid-day lobe overstates feeder relief [16]. The section ends on that lobe so weather stays inside the budget.

III. REHEARSED RETURN AFTER A PLANT STOP

Cells do not appear because a vehicle asked for them [23]. Digital tools matter only when they move detect time and recover time [25].

$$\frac{\mathrm{d}S_{svc}}{\mathrm{dt}} = \alpha[1 - S_{svc}] - \beta(D_{ord} - D_{rep})$$

The rate α grows when the twin has already rehearsed the break [22]. It collapses when rights are missing [24]. Classic safety stock still covers lead-time demand scatter [23].

$$I_{safe} = z \cdot \varsigma_d (L_{eq})^{1/2}$$

Twins revise L_eq. They do not delete the identity [25]. Detect time is the first crossing of a residual threshold [22].

$$T_{det} = \inf\{\mathrm{t} \ge 0: |y(\mathrm{t}) - \hat{y}(\mathrm{t})| \ge \vartheta\}$$

Recover time cannot undercut detect time plus action latency plus device queue [27].

$$T_{rec} \ge T_{det} + T_{act} + T_{dev}$$

Shared time-to-survive is the minimum of the vehicle-window horizon and the plant-stock horizon [23].

$$T_{live} = \min\{\frac{E_{pack} - \sigma_{\mathrm{lo}}\, Q_{\mathrm{nom}}\, U_{\mathrm{n}}}{P_{net}}, \frac{I_{hand}I_{move}}{d_{dn}}\}$$

Figure 4. Service return with a rehearsed twin versus a history-only twin.

A history-only twin misses overshoot when orders exceed repaired capacity [24]. The section ends on that overshoot because it is the second term of the recovery law.

audited cost and annealed load plans

An unchecked emission factor is another disruption [20]. Pairing the optimizer with a custody record is the integrity claim [21].

$$J_{tour} = \sum_{\ell \in L} (c_\ell + \pi e_\ell) x_\ell$$

$$K = \frac{N_{match}}{N_{hand}}$$

A rise in K is a resilience input [25]. Anti-theft signalling is K on one vehicle [12]. Companion green and ledger reviews rest on the same two operators [39], [40].

ising image of a unit load

Crate-to-slot bits carry mass, volume, and balance penalties after a lane dies [27].

$$E = \sum_i a_i s_i + \sum_{i<j} K_{ij} s_i s_j$$

Surveys and logistics notes collect annealing and hybrid loops against that kernel [19], [26]. The QUBO form sent to an annealer is

$$E_Q = \mathrm{x}^T Q\, x + \mathrm{b}^T x$$

Fleet inequalities stay on the classical twin [12].

$$x_\star = \arg\min\{E_Q(x_Q) + E_{cl}(x_{cl}) : \mathrm{Fx} \le \mathrm{f}\}$$

$$\Delta = \frac{E_{hit} - E_{bound}}{|E_{bound}| + \varepsilon}$$

Device queue belongs inside recover time [27]. Convergent stacks that hide that queue report a false clock [37].

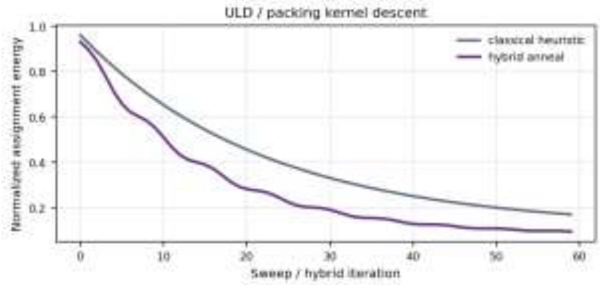

Figure 5. Assignment-energy descent of a hybrid anneal against a classical heuristic.

A public instance should carry a gap Δ, not only a success story [26]. The section ends on that gap so the rebuild kernel can be scored.

poles, delays, and companion transforms

Several periods sit in one inventory or shaft trace, and a single smoother will smear them [18]. Residues name those periods before a buffer saturates.

$$\zeta_m = \frac{1}{2\pi i} \oint_{C_m} G(z)\, dz$$

A working pairing of the two-sided transform on a testing function φ is [29]

$$\langle TG, \varphi \rangle = \langle G, T * \varphi \rangle$$

The expanded time-shift rule moves a delay so warehouse and vehicle stamps stay aligned [28].

$$(TG)(t - \theta) = e^{-z\theta} \cdot (TG)(t)$$

Exponential modulation secures custody-like streams [26].

$$(T[e^{\omega t}G])(z) = (TG)(z - \omega)$$

Sequential convergence licenses the limit under the integral when the path is only a distribution [29].

$$\int_{\Psi} TG_n = \int_{\Psi} T\, G$$

FKL key properties supply a companion algebra for two-sided analysis of chain series [35]. Residue features that feed the detect infimum are

$$r_\zeta(t) = \sum_{m \in \Omega} |\zeta_m|$$

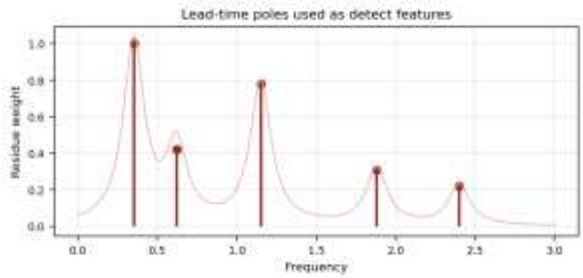

Figure 6. Residue-weighted lead-time poles used as detect features.

Those peaks turn pack energy and service into observed modes [18]. The section ends there so sensing is an input to T_{det} rather than a separate specialty.

couplings that make one controller

Seven operators in seven reviews are not a theory [15]. Four couplings make them one controller.

grants that leave the window are model errors

A feasible binary is one that the remaining usable charge can absorb [11]. If the twin issues g_j without that test, time-to-survive computed from nameplate energy is fiction [15]. Mobility allocation and pack control are therefore one inequality [16]. Solar credit may relax the inequality only by the accepted integral [17]. The subsection ends on that inequality so feeder software cannot outrun chemistry.

detect lag is a floor under recover time

T_{rec} cannot be shorter than T_{det} plus the physical action plus the annealer queue [27]. Cognitive rooms that publish a long detect lag already fix that floor [22]. Hybrid loops that hide T_{det} report a recover clock the dock cannot meet [19], [26]. The subsection ends by forbidding independent workstreams for detect analytics and recover solvers [37].

residue features arm the detect infimum

If $y - \hat{y}$ is built only from level inventory, a two-scale oscillation can sit inside the threshold [18]. Replacing the residual with a filtered residue magnitude advances T_{det} when the leading pole is not the slowest pole [35]. Shift invariance and modulation move the feature without relabelling it [28], [36]. Sequential-convergence and distributional pairings keep the construction legal on irregular paths [29]. The subsection ends so poles are inputs, not illustrations.

completeness multiplies claimed green recovery

A joint index that uses unaudited e_ℓ is not a resilience score [20]. Anti-theft rail signalling is K written on one vehicle [12]. Blockchain pairing is K written on the tour [21], [40]. Human-centric policy is the right to refuse a recover action when K is below a floor [38]. Complexity essays remind that K also collapses when information rights are missing [24]. The subsection ends on that product so carbon and service share a desk.

A SINGLE NAMED SHOCK

Abstraction hides the clocks. A formation lot that stops at $t = 0$ while a city feeder is already near saturation makes them visible [25].

On the vehicle side the numerator of T_{live} is remaining energy inside the window [11]. Auxiliary cabin and swipe loads continue [13]. Array credit for the next hours is a falling afternoon lobe [17]. If that horizon is four hours, every grant that ignores the window

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shortens it [16]. Cell reviews fix the temperature path that will further cut the numerator [15], [14].

On the plant side the numerator is on-hand plus truly available transit [22]. Transit not yet formed will not arrive [23]. Spectra of L_{eq} that were already rising should have started T_{det} earlier [18]. If they did not, detect time starts at the first residual crossing after the stop [25].

Once T_{det} is marked, the rehearsal room ranks recoveries [22]. Dual-source the lot. Draw second-life modules that still sit inside a reduced window [14]. Rebuild the evening unit load so mass and balance still hold [27]. Each candidate has an action latency. The annealer path adds queue time [19]. The human-centric path adds a refusal right if completeness is below floor [38], [21]. The complexity path adds the reminder that a contract may forbid the dual source [24].

Green-tour cost is recomputed only on audited factors [20], [39]. Packs that left under anti-theft tone still count as present [12]. Orchestration may propose a reroute; the twin still owes Δ on the packing instance [37], [26]. If T_{live} is already smaller than T_{det} plus action plus queue, the honest report is that service will fail [23]. After the shock, L_{eq} used in the safety-stock identity is the posterior [25]. The section ends on that rewrite so the next day does not use the catalog lead time.

IV. AGENDA AND LIMITS

Parallel reviews will keep appearing unless pack physics and solver noise share the two clocks [25]. Recovered service times a carbon discount puts both desks on one number [20].

$$M = K \cdot S_{svc} \cdot \exp(-\gamma\, E_{CO2})$$

$$R_{dock} = (T_{det}, T_{rec}, \Delta, K, M)$$

Share one carbon weight [39]. Floor completeness before an optimizer may change an emission factor [40]. Publish packing gaps on public unit-load cases [27]. Score shift and FKL features against ordinary charts on the same traces [28], [35].

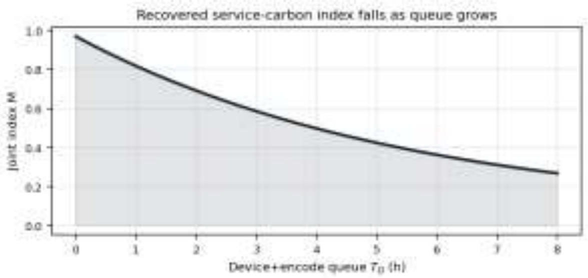

Figure 7. Joint service-carbon index falling as device-and-encode queue grows.

Figure 7 is a hypothesis shape for a dock trial to beat [22].

what the cited papers do not measure

The twin review is a review, not a controlled T_{det} trial [22]. The resilience agenda is an agenda [15]. Quantum papers report kernels and directions, not dock-scale wall-clock recoveries [19]. Transform papers report algebraic properties, not detector ROC curves [28]. Using them as operators is legitimate construction. Treating their existence as proof that clocks have already moved is not [23]. The subsection ends on that distinction so the agenda stays testable.

scope that still binds

Nothing here calibrates α, β, κ, or π on a fleet [24]. Nothing here fits a pole to a warehouse trace [18]. Embedding blow-up still kills ULD instances that are not reduced [27]. Penalty weights that are stale recover the wrong load plan [26]. Those tasks belong to the dock log [25]. The subsection ends there so the theory does not pretend to be a calibration.

why classical inequalities stay off the qpu

Fleet-wide capacity, time-window, and flow inequalities are sparse in a useful way for MIP and dense in a harmful way for embedding [26]. Sending them to the QPU inflates n_{emb} and hides the assignment energy that annealing is good at [19]. The hybrid cut already written as $E_Q + E_{cl}$ is therefore not a compromise; it is the only cut that keeps Δ meaningful [27]. The twin remains the owner of $Fx \leq f$ [22]. The section ends there so the next shock does not dump the whole MIP onto the sampler [37].

what a dock log must hold

None of the operators can be scored from a weekly ERP dump [22]. The log that makes the theory testable stores, on one stamp, pack current, window bounds, grant bit and lag, residue of inventory, crate spin or slot map, annealer queue, and custody match [25].

$$\ell_t = (I, \sigma, g, \tau, y, s, T_{dev}, \kappa_t)$$

Without that tuple, T_{det} and T_{rec} are reconstructed from memory and cannot be compared across shocks [23]. Industry 5.0 refusal events belong in the same log [38]. Spectral features can be computed later from y [18]. The section ends by treating the log as part of the twin, not as a reporting chore [22].

feasibility repair after the sample

An annealer sample is not a load plan until a classical repair has run [27]. Broken chains, violated mass, and split crates must be mapped back onto $Fx \leq f$.

$$x_{dock} = \Pi_{(Fx \leq f)}(x_Q)$$

If the projection is far from x_Q, Δ understates the true energy of the plan that leaves the dock [26]. The twin should store both energies [22]. Surveys that report only raw sampler energy hide this gap [19]. The section ends by making Π part of T_{act}, not an afterthought [37].

multi-objective rebuild under disruption

A lane death changes more than one weight in the assignment energy [27]. Mass, time, and carbon can be stacked

$$E_{mix} = w_m E_{mass} + w_t E_{time} + w_c E_{CO2}$$

Weights are policy and belong with π [20]. Changing them after the shock without publishing the old mix makes M incomparable [39]. Hybrid loops can retune only the QUBO block; fleet inequalities stay classical [26]. The section ends on a frozen weight vector for the shock being scored [25].

equivalent lead time as a revised argument

Safety stock is not repealed by a twin; only its argument moves [25]. Write demand during the equivalent horizon as a random measure whose scatter still sets the buffer.

$$D_L = \int_0^{L_{eq}} d_\tau \, d\tau$$

If the twin shortens L_{eq} by rehearsing a dual source, the same z and ς_d produce a smaller I_{safe} [23]. If the twin only advertises visibility, L_{eq} does not move and the identity is theatre [22]. Shift-invariant spectra of multi-echelon delays are the sensing form of that revision [18]. A rising pole on L_{eq} is a warning that the next buffer calculation is already stale [28].

The last line of this section is operational: publish the prior and posterior L_{eq} on the same shock, or do not claim the twin changed stock policy [25].

encoding, embedding, and the false clock

An Ising energy that does not fit the hardware graph is not yet a recover action [27]. Minor embedding inflates variable count and loosens the gap Δ.

$$n_{emb} = \sum_i |C_i|$$

When chain length $|C_i|$ grows, break penalties fight the physical J_{ij} and the sampler returns infeasible packs [26]. Reverse annealing from a classical seed can restore feasibility on modest ULD sizes; forward annealing often does not [19]. Simulated or digital annealing on silicon remains the path that warehouses actually ship [37].

Wall-clock recover time must include translation of the crate table, embedding or CQM construction, queue, samples, and a classical feasibility repair [27]. A twin that reports only anneal microseconds is lying about T_{rec} [22]. The section ends on that accounting so device marketing cannot enter the dock tuple.

human refusal as a feasible set

Industry 5.0 writing is not a slogan in this model; it is a constraint on the feasible set [38]. A grant or a rebuild that a planner may reject is

$$X_{hum} = \{x: Fx \le f, \quad K \ge K_{min}, \quad \sigma \in [\sigma_{lo}, \sigma_{hi}]\}$$

If completeness is below floor, x is removed before the annealer runs [21], [40]. If the usable window cannot absorb the pulse, the grant bit is removed before the feeder sees it [15]. Complexity essays are the reminder that the human also holds contract rights the model does not see [24]. The section ends by putting that set inside the twin, not beside it [38].

V. SECOND-LIFE MODULES AS A REDUCED WINDOW

A recovered plant that ships modules the vehicle window has already retired is a false rebound [14]. Second-life packs enter the store identity with tighter bounds

$$Q_{sl} = Q_{nom}(\sigma_{hi}{}^{sl} - \sigma_{lo}{}^{sl})$$

and usually a higher internal resistance in the ohmic observer [15]. Sustainability arguments in the cell reviews are therefore not an afterword; they change T_{live} on the vehicle side [14]. A twin that treats every inbound pack as nameplate new will overstate shared survival [23]. The section ends on that reduced window so second-life stock is a different state, not a free buffer [11].

green weight as policy, not a learned nuisance

The carbon price π in the tour cost is a political number [20]. An optimizer that is allowed to retune π to make M look large is not auditing anything [39]. Hold π fixed on a planning cycle and report M with K shown [21].

$$M_{rep} = K \cdot S_{svc} \cdot \exp(-\gamma \sum_\ell e_\ell x_\ell)$$

If e_ℓ can be edited quietly, M_{rep} is fiction even when S_{svc} is real [40]. Rail custody on a single pack is the same demand at vehicle scale [12]. The section ends by freezing π for the shock being scored [20].

testing-function limits as legal sense

Warehouse traces are rarely ordinary L1 paths [29]. The pairing ⟨TG, φ⟩ is the reason a detect residual can still be defined [35]. Sequential convergence lets a sequence of sampled traces pass to a limit under the integral [29]. Without that license, a residue feature built on a gapped series is an informal chart [18]. Modulation then protects the same pairing when the series is a custody stream [36]. The section ends by placing Φ, not a dashboard, as the observation space of the twin [28].

CLOSING STATEMENT

A useful twin must publish both a detect instant and a recover instant; otherwise, it remains only a picture. The proposed framework connects the main evidence layers into one operational sequence. Pack studies supplied the initial state and physical constraints; solar and mobility studies supplied inflow and latency; resilience and digital-twin studies supplied operational boundaries and recovery clocks; analytics and ledger studies supplied anomaly evidence and auditability; annealing studies supplied the reconstruction mechanism; and transform studies supplied the residual and shift needed to represent delay and spectral consistency.

The contribution is therefore not another architecture diagram, but a measurable recovery framework. The twin must connect the observed current state to the recovery grant, operational spin, and resulting residual while preserving their provenance. This separates prediction from authorization, optimization from physical feasibility, and data custody from system validity.

The required validation is concise: select one fleet and one plant-stop event, apply one integrity stamp to current, grant, spin, and residue, and publish the five-number dock tuple detect time, recover time, plan gap, custody completeness, and joint index after a named shock. These values should be traceable to the same recovery episode and independently reproducible.

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