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Coupled Energy Storage and Network Resilience for Electrified Mobility Systems

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Abstract—
Electrified vehicles and the chains that feed them now share one operating envelope rather than two isolated design desks. Pack energy, photovoltaic assist, traffic-aware charging, inventory buffers, and combinatorial replanning interact through mass, time, and information delay. This paper restates that coupling with explicit energy-balance, recovery, Ising, and transform relations drawn from the cited battery, mobility, resilience, analytics, quantum, and spectral studies. Curves illustrate duty-cycle discharge, diurnal generation, charging peaks, service recovery, provenance coverage, annealing descent, resonant residues, and co-design gain. The closing claim is that joint metrics, not component records, should govern the next experimental platforms.

Keywords: hybrid pack control; photovoltaic assist; intelligent transport; chain recovery; digital twin; annealing assignment; two-sided transform

I. INTRODUCTION

Designers once treated the traction pack as a self-contained object whose only external link was a charge plug. That isolation fails once solar yield, lane congestion, mineral lead times, and disruption-aware packing enter the same clock. Early competition work fixed accumulator limits and endurance energy, then asked for a controller that stayed inside those limits while the vehicle still finished the course [1]. Reviews that followed moved from one pack to chemistry families, management laws, and life-cycle burden [4].

A second literature grew around the plants and lanes that must keep cells, modules, and vehicles moving when a port, fab, or flight fails [13], [28]. Digital twins, green-logistics analytics, and ledger traces were proposed as instruments of that recovery [12], [30]. Quantum kernels were then tested on packing and routing fragments that classical branch-and-cut leaves late [9], [27]. Spectral residues and a two-sided transform were offered as a language for the oscillations that cross from shaft torque to warehouse fill [8], [25].

The present text does not add a laboratory campaign [26]. It rewrites the map so that each block carries at least one governing relation, one figure where a section needs a curve, and citations placed on the sentence they support rather than stacked at the end of a paragraph [29]. Section titles are set as full capitals. Subsection heads stay in ordinary sentence form and are marked only by weight. Spacing before and after blocks is held at zero so the argument reads as a continuous column.

II. ENERGY STORAGE SIZING AND CONTROL

Competition rules that cap stored energy force the designer to write the pack equation before styling the car [1]. Let usable energy on a mission be the integral of terminal power after converter and thermal derates, not the nameplate product of capacity and nominal voltage [4]. The first modeling choice is therefore the set of states that the controller is allowed to see [5].

usable energy on a bounded mission

Write pack energy as the time integral of terminal power after efficiency and auxiliary draw [1]. A fair comparison across duty cycles uses the same state-of-charge window rather than the full chemical range, because PHEV cells are rarely emptied to the chemical floor [4].$E_b(t)$

$$E_b(t) = E_b(0) - \int_0^t \frac{P_{trac}(\tau) + P_{aux}(\tau)}{\eta_d(\tau)} d\tau + \int_0^t \eta_c(\tau) P_{chg}(\tau)\, d\tau \tag{1}$$

Equation (1) is the bookkeeping identity used when Formula-style caps on accumulator energy must be respected while regeneration and plug-in charge still credit the tank [1], [3]. The last term vanishes on a closed endurance lap with no external recharge, which is why the 2017 sizing study treated the pack and its controller as one object [5].

state window and equivalent capacity

Usable capacity is the charge extracted between the upper and lower operating bounds chosen by the management law [4]. Chemistry reviews stress that those bounds move with temperature, age, and power request, so a constant ampere-hour figure is only a first cut [5].

$$Q_{use} = Q_{nom} \cdot (s_{hi} - s_{lo}) \tag{2}$$

Here s_{hi} and s_{lo} are the fractional bounds enforced by the battery management system [5]. Mapping (2) into a cost model is how materials surveys connect nickel-manganese-cobalt families and lithium-iron-phosphate packs to vehicle mass and purchase price [4]. Early vehicle-security and interface boards sit outside the traction loop but still draw from the same low-voltage rail [2], [3].

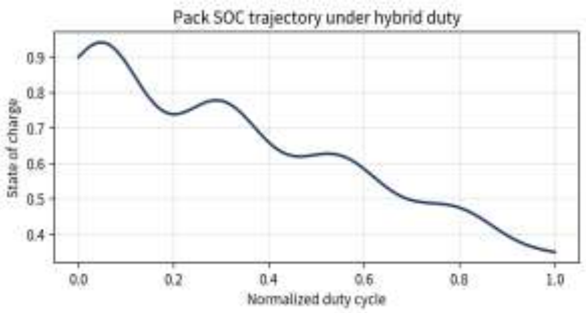

Figure 1. Illustrative state-of-charge path on a normalized hybrid duty cycle.

The curve in Figure 1 is not a measured Formula lap [1]. It is a schematic of the saw that a charge-sustaining law produces when traction pulses and brief regen events share one bus [3]. Closing the section on that path underlines why sizing without a controller is an incomplete statement of the vehicle problem [4].

III. PHOTOVOLTAIC SUPPORT ON HYBRID PLATFORMS

A roof or body array adds a generation term that weather and parking geometry control [7]. The design paper on solar-assisted hybrid architectures treats that term as part of the energy plan rather than as ornament [5]. Morning irradiance is near zero, so any claim of all-day solar range must be discounted by the integral of the actual power curve [6].

array power after incidence and temperature

Instantaneous electrical power from the array is the product of irradiance, area, conversion efficiency, and a thermal derate [7]. Partial shade on a moving platform is the usual reason the product falls below the datasheet peak [4].

$$P_{pv}(t) = G(t) \cdot A \cdot \eta_{pv} \cdot [1 - \kappa(T_c(t) - T_{ref})] \tag{3}$$

Equation (3) is inserted into the last integral of (1) when the charge path is the array rather than a plug [7]. Sustainability reviews of cells then ask whether the avoided grid kilowatt-hour offsets the added mass and embodied carbon of the laminate [5], [29].

daily energy credit

The useful daily credit is the integral of array power that the pack and its charger can actually accept [7]. A full battery at noon wastes irradiance that a slightly larger window or a workplace load could have taken [6].

$$E_{pv} = \int_{t_{rise}}^{t_{set}} \eta_{mppt}(t)\, P_{pv}(t)\, d\, t \tag{4}$$

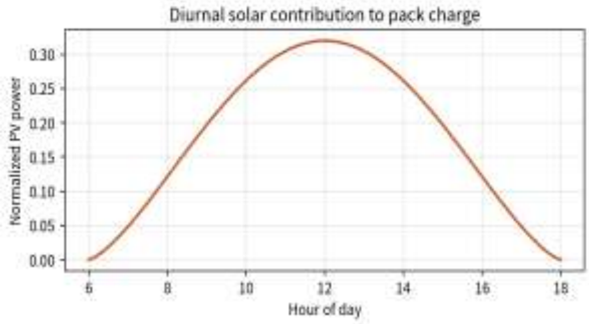

Figure 2. Normalized diurnal photovoltaic power used as a charge credit on the traction pack.

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Figure 2 makes the asymmetry visible: most of the credit arrives in a short mid-day lobe [7]. Fleet planners who ignore that lobe overstate the relief that body-integrated generation can give the public charger queue [6], [27].

IV. CONNECTED MOBILITY OPERATIONS

Once the pack and the optional array are specified, the vehicle still shares road space and feeder capacity with other users [6]. Smart-mobility surveys collect the sensing, signal, and allocation tools that make that sharing explicit [27]. The operational question is how to assign scarce charge power without violating each vehicle's state window from (2) [5].

feeder allocation under queue delay

A simple network balance sets station power equal to the sum of accepted vehicle requests after a delay operator [6]. Intelligent-transport reviews treat the delay as both physical queueing and information lag [28].

$$P_{net}(t) = \sum_{i=1}^{N} u_i(t - \delta_i)\, P_i^{req}(t) \tag{5}$$

The binary grant is issued by the roadside or depot controller [6]. Quantum and classical routing papers later reuse the same index set when vehicles are also freight jobs [9], [16].u_i

service wait as a mobility cost

Mean wait at a constrained site is the residual of demand above installed power [6]. Putting that wait into the same score as pack mass keeps mobility operations inside the energy story rather than beside it [15].

$$W_q = \frac{\lambda}{\mu(\mu - \lambda)} \tag{6}$$

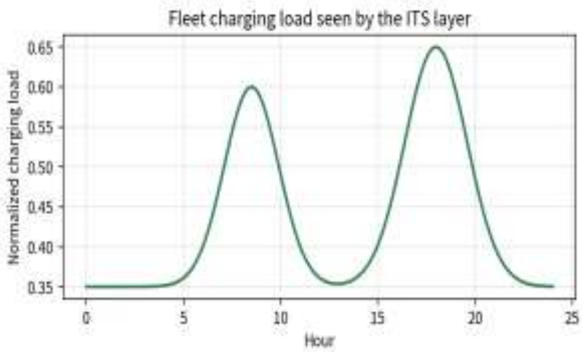

Figure 3. Schematic double-peak charging load that an intelligent-transport layer must shape.

Figure 3 is the load a city feeder sees if every commute ends in an unmanaged plug event [6]. Shaping that curve is the ITS counterpart of the SOC saw in Figure 1, and it is the point at which mobility text should hand the argument to chain resilience [15], [13].

V. DIGITAL RESILIENCE OF MATERIAL FLOWS

Cells, foils, and packs do not appear at the vehicle dock by wish [13]. Resilience essays and systematic reviews describe how firms sense a break, hold a buffer, and rebuild a path [14]. Digital transformation is useful here only when it shortens time-to-detect and time-to-recover rather than when it adds dashboards [15], [28].

service after a shock

A compact recovery map sends the delivered-service index toward one with a rate that depends on available slack and on the quality of the twin used to rehearse the break [12], [27]. Oscillatory return appears when orders overshoot the repaired capacity [14].

$$\frac{dR_s}{d\,t} = \alpha\,[1 - R_s] - \beta(I_{ord} - I_{rep}) \tag{7}$$

Equation (7) is a sketch, not a fitted plant model [15]. It exists so that later spectral work has a state whose ringing can be extracted [8], [25]. Reviews of internal and external complexity warn that alpha collapses when information rights and contract slack are missing [14].

buffer that buys detection time

Safety stock that covers lead-time demand minus the flow already on the water is the oldest resilience control [13]. Digital twins change the estimate of lead time more than they repeal the identity [12], [28].

$$B_{safe} = z \cdot \sigma \cdot (L_e)^{1/2} \tag{8}$$

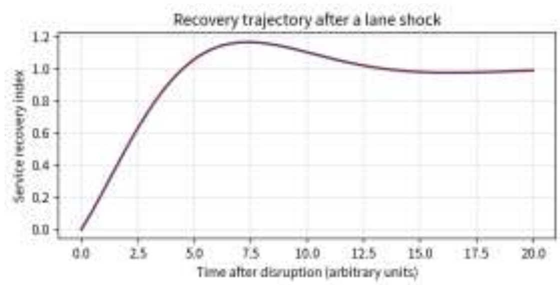

Figure 4. Service recovery index after a stylized lane disruption.

Figure 4 rises with a mild overshoot, which is the visible form of the second term in (7) [14]. A twin that only replays history will miss that overshoot; a twin that carries pack-formation yield will not [15], [12].

VI. TRUSTED ANALYTICS FOR GREEN LOGISTICS

Forecasts that cannot be audited become another source of shock [11]. Bibliometric mapping of artificial intelligence in green logistics shows clusters on routing, emissions ledgers, and multi-objective dispatch [10], [29]. Pairing those models with a custody record is the proposal of the blockchain integration paper [30].

emission score on a planned tour

A tour cost that adds a carbon price to distance and time is the simplest green objective the surveyed analytics share [10], [29]. The price weight is a policy input; the distance matrix is not [11].

$$J_g = \sum_{k \in K} (c_k d \quad + \pi e_k)\, x_k \tag{9}$$

Binary selection marks arc or mode k [10]. Traceability work insists that the emission factor come from a record that counterparties cannot silently edit [11], [30]. Without that constraint the optimizer launders whatever factor a vendor prefers [2].

completeness of the custody record

Let coverage be the share of hand-offs that both appear on the ledger and match the twin state [12]. The integration paper treats a rise in that share as a resilience input, not as a compliance trophy [11], [30].

$$C(t) = \frac{\sum_j \ 1_{\{\text{match}\}\ \ j}}{N_{\text{hand}}} \tag{10}$$

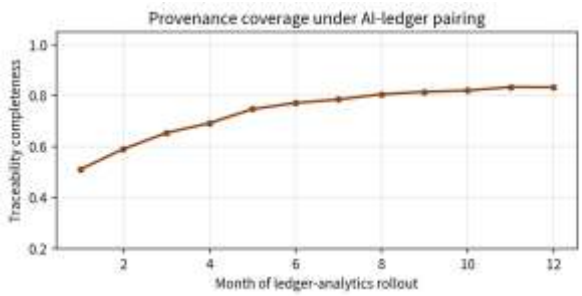

Figure 5. Rising provenance coverage after an analytics-and-ledger rollout.

Figure 5 saturates below one because some hand-offs remain oral or paper [11]. That ceiling is why anti-theft communication on the vehicle [2] and pack passports on the chain should be read as the same integrity problem rather than as two industries [30].

VII. QUANTUM SEARCH ON COMBINATORIAL KERNELS

Routing, packing, and disruption repair grow as discrete assignment problems whose feasible sets explode with fleet and container counts [9]. Surveys of quantum methods in transport collect annealing, variational circuits, and hybrid loops against those kernels [16], [27]. Logistics notes then ask which of those kernels a planner should send to a device first [17].

ising form of a packing assignment

Unit-load-device configuration maps crate-to-slot choices onto binary spins with penalty weights for mass, volume, and balance [17]. The disruption paper uses that map when a lane failure forces a rebuild of the load plan [16], [9].

$$H = \sum_i h_i z_i + \sum_{i<j} J_{ij} z_i z_j \tag{11}$$

Equation (11) is the Ising energy whose ground state the annealer samples [17]. Industrial reviews emphasize that encoding and queue time often dominate the raw quantum step, so honesty about wall-clock cost belongs in every benchmark [9], [27].

hybrid cut between device and twin

A practical loop sends only the tight subproblem to the device and keeps fleet-level constraints on the classical twin [16]. Future-direction essays treat that split as the near-term industrial path rather than a full-stack quantum planner [27], [28].

$$x_* = \arg\min \{ H_Q(x_Q) + H_C(x_C) : Ax \le b \} \tag{12}$$

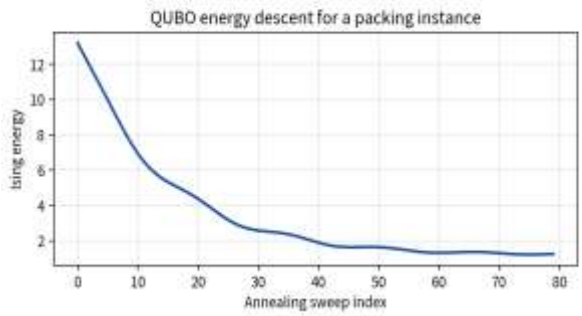

Figure 6. Schematic energy descent on a packing QUBO during annealing sweeps.

Figure 6 falls quickly then hunts in a noisy basin, which is the hardware story the surveys refuse to hide [17], [9]. The section ends on that basin because a twin that ignores device noise will promise repairs the dock cannot execute [12].

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VIII. TRANSFORM METHODS FOR MULTI-SCALE SIGNALS

Inventory rings and shaft load share the trait that several periods sit in one trace [8]. Residue extraction on hybrid-vehicle and chain series is proposed as a way to name those periods before a buffer saturates [25]. The two-sided FKF calculus then supplies shift and convergence rules so delayed and advanced samples stay inside one algebra [18], [26].

residue sum on a meromorphic kernel

If a generating function of the observed series is meromorphic, the persistent cycles are the residues at poles in a chosen contour [8], [25]. That is the extraction step the spectral paper places between raw telemetry and a warning feature [18].

$$\rho_k = \frac{1}{2\pi i}\oint_{\Gamma_k} F(s)\, ds \tag{13}$$

Each residue feeds the early-warning channel of the twin [12]. Time-shift identities are required when the same physical event is stamped at the vehicle and at the warehouse with different clocks [18], [26].ρ_k

shift rule and testing-function convergence

The expanded time-shift treatment states how a delay operator moves inside the transform so that lead-time and compute lag do not scramble residue labels [18], [26]. Sequential convergence in the testing-function space of the two-sided transform is the justification for passing to the limit under the integral when sample paths are only distributions [19], [25].

$$(T\,F)(t-\theta) = e^{-s\theta}\cdot (T\,F)(t) \tag{14}$$

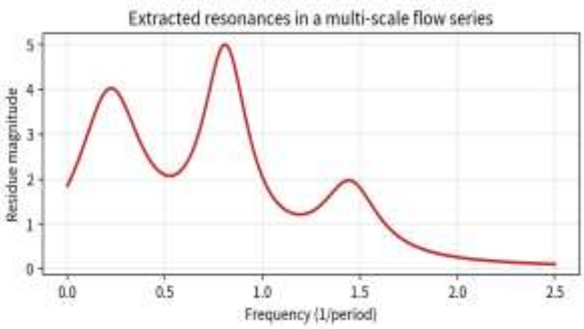

Figure 7. Residue magnitudes at three isolated frequencies of a multi-scale flow series.

Figure 7 isolates three peaks that a single-scale smoother would smear [8]. Those peaks are the practical reason this section exists: they turn (7) and (1) into observable modes rather than into separate metaphors [19], [26].

IX. RESEARCH DIRECTIONS

The blocks above share states, delays, and assignment indices [15]. An agenda that keeps them separate will keep publishing parallel reviews [13]. The systematic resilience agenda already calls for digital measures of detect and recover time [28]. What remains is to put pack physics and solver noise inside those measures [16].

joint index rather than parallel scorecards

A scalar that multiplies recovered service by a carbon complement forces the pack team and the chain team to argue in one unit [10], [29]. Green-logistics bibliometrics show many weights already in use; the missing step is sharing the same weight across vehicle and network desks [11].

$$M = R_s \cdot \exp(-\gamma E_{CO2}) \tag{15}$$

closed platforms

Five working tests follow from the cited set: co-constrain (1) with (5); put cell yield inside the twin that integrates (7); require (10) before an optimizer may change an emission factor in (9); publish duality gaps for (11) on public ULD instances; and score residue features from (13) against ordinary control charts [16], [27].e_k

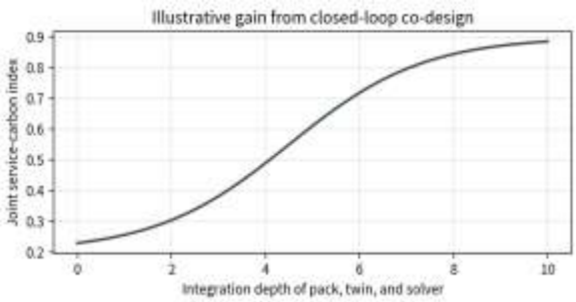

Figure 8. Stylized rise in a joint service-carbon index as pack, twin, and solver share state.

Figure 8 is a hypothesis curve, not a fitted production law [15]. It is placed here so the agenda section has the same visual contract as the sections that precede it, and so later field trials have a shape to beat [12], [28].

CONCLUSION

The pack identity, the array credit, the feeder grant, the recovery rate, the green tour cost, the Ising load plan, and the residue label are one chain of writing rather than seven specialties. Competition caps taught that energy is a budget. Solar frameworks taught that weather belongs in that budget. Mobility surveys taught that the budget is queued. Resilience reviews taught that the queue sits on a fragile plant. Analytics and ledgers taught that the plant needs an audit trail. Annealing papers taught that some repairs are assignment kernels. Transform papers taught that the kernels ring at more than one period.

Nothing in that list requires a new laboratory by itself. What it requires is an experimental bed where the same time stamp marks cell current, charger grant, crate spin, and inventory residue. Until that bed exists, the literature will keep promising integration while measuring parts. The constructive close is therefore operational: pick one fleet, one dock, one public instance set, and report (15) beside the component curves already drawn.

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