# **Triadic Framework Technology for BMS improvements**

You’re right—this deserves its own paper. Here’s a tight scaffold with the market picture, the TFT-to-BMS principles, and a clear before/after on effective Wh that we can defend and iterate.

## **Purpose and scope**

* **Aim:** Establish Triadic Framework Technology (TFT) as a minimal, composable enhancement layer for battery management systems (BMS) that upgrades signal hygiene, controls, and coordination—yielding measurable gains in usable energy (Wh), round‑trip efficiency, and life.
* **Focus:** Main chemistries in market use; baseline market context; a defensible, chemistry‑specific “effective Wh” uplift model; and a reproducible BMS integration pattern.

## **Market snapshot**

* **Global scale:** The battery market was about USD 122B in 2023 and is projected to grow rapidly, with Asia‑Pacific holding roughly half the market and lithium‑ion as the leading chemistry2.
* **Li‑ion dominance:** Lithium‑ion is the largest material segment (share >44% in 2024), driven by EVs, consumer electronics, and stationary storage.
* **Regional dynamics and players:** Asia‑based firms (CATL, BYD) lead globally; Korean makers (LG Energy Solution, SK On, Samsung SDI) are strong in the U.S., with localization policies shaping supply chains.
* **EV pull‑through:** EV penetration continues to rise globally and in the U.S., sustaining demand for high‑energy‑density chemistries and advanced BMS features.

Sources: 1

## **Battery types and baseline performance**

This quick reference uses typical, defendable ranges at the cell/pack level. Values are representative; exact designs vary by vendor and use case.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Type (chemistry)** | **Typical applications** | **Typical specific energy (Wh/kg)** | **Typical cycle life (cycles)** | **Notes/constraints** |
| Lead‑acid (flooded/VRLA) | Starter, backup, forklifts | 30–50 | 300–1,000 | Low cost, low energy density, shallow DoD for life |
| NiMH | HEVs, tools | 60–120 | 1,000–2,000 | Robust, moderate density, higher self‑discharge |
| Li‑ion LFP | EVs, ESS, buses | 120–180 | 2,000–6,000 | Long life, good safety, lower cold performance |
| Li‑ion NMC/NCA | EVs, electronics | 180–260 | 1,000–2,500 | High energy density, tighter safety margins |
| Sodium‑ion | ESS, low‑cost mobility (emerging) | 90–160 | 1,000–3,000 | Lower cost materials, improving density |
| Flow batteries | Stationary long‑duration | 10–50 (system) | 10,000+ | Power/energy decoupled, lower RTE, excellent longevity |

## **TFT principles applied to BMS**

TFT slots in as a very small control/signal layer that reinforces three pillars—Signal, Structure, Scheduling—inside the BMS loop.

#### **Signal (clean, synchronized, observable)**

* **Noise‑aware sensing:** Synchronized sampling and digital filtering to reduce measurement jitter; improves SOC/SOH estimation fidelity and reduces conservative buffers.
* **Harmonics‑aware actuation:** Coordinated switching to cut ripple/THD, trimming conversion losses and heat (supports higher RTE and stability).
* **Secure, low‑latency telemetry:** Deterministic frames over CAN/SMBus; optional wireless BMS with robust crypto where architecture permits.

#### **Structure (cell‑to‑pack coherence)**

* **Adaptive balancing:** Prefer active or hybrid balancing under dynamic thresholds (temp, impedance), cutting delta‑V and recovering usable capacity without thermal penalty5.
* **Health‑aware limits:** Narrower, individualized charge/discharge windows as confidence grows in per‑cell state models (less blanket derating).
* **Protection precision:** Faster, more selective trips using better sensing and hysteresis design to avoid unnecessary energy cut‑outs5.

#### **Scheduling (context‑aware timing)**

* **Load/charge orchestration:** Align high‑current events with thermal headroom; schedule balance during low‑stress windows to minimize aging.
* **Predictive control:** Short‑horizon forecasts (temp, load) to pre‑empt excursions and reduce safety buffers; supports gentler, more efficient CC‑CV transitions.
* **Fleet coordination:** For ESS, staggered charge/power set‑points to minimize aggregate losses and pump overhead (flow/thermal systems).

BMS core functions—cell monitoring, protection, balancing (passive/active), SOC/SOH estimation, and comms—are the substrate TFT enhances5. Wireless BMS architectures are emerging in EV platforms and benefit from TFT’s telemetry discipline.

## **TFT‑enabled effective Wh comparison**

We model “effective Wh” as: Effective\_Wh = Nameplate\_Wh × Usable\_SOC\_window × Round‑trip\_efficiency

Below are illustrative, conservative uplifts for a 60 kWh pack, assuming TFT enables tighter estimation, cleaner actuation, and smarter scheduling. Baselines reflect common practice; deltas reflect what a minimal, well‑implemented TFT layer can plausibly unlock without hardware changes.

##### **Assumption deltas by chemistry**

* **Lead‑acid:** +5 percentage points usable window, +2 points RTE (better charge staging, temperature‑aware control).
* **NiMH:** +3 pp usable, +1 pp RTE (more accurate SOC at high C‑rates).
* **Li‑ion LFP:** +4 pp usable, +2 pp RTE (active balancing + synchronized switching).
* **Li‑ion NMC/NCA:** +3 pp usable, +1.5 pp RTE (tighter safety margins with high‑fidelity sensing).
* **Sodium‑ion:** +4 pp usable, +2 pp RTE (similar to LFP behavior).
* **Flow battery:** +0 pp usable, +2 pp RTE (pumps/valves optimization, harmonics).

##### **Results (per 60 kWh nameplate)**

|  |  |  |  |
| --- | --- | --- | --- |
| **Chemistry** | **Baseline effective Wh (kWh)** | **TFT effective Wh (kWh)** | **Uplift (%)** |
| Lead‑acid | 25.50 | 28.71 | 12.6 |
| NiMH | 43.20 | 45.26 | 4.8 |
| Li‑ion LFP | 50.76 | 54.05 | 6.5 |
| Li‑ion NMC/NCA | 52.44 | 55.01 | 4.9 |
| Sodium‑ion | 50.22 | 53.58 | 6.7 |
| Flow battery | 45.00 | 46.20 | 2.7 |

Assumptions used: Lead‑acid baseline usable 50%, RTE 0.85; NiMH 80%, 0.90; LFP 90%, 0.94; NMC/NCA 92%, 0.95; Sodium‑ion 90%, 0.93; Flow 100%, 0.75. Adjust per target product and duty cycle.

## **Paper structure and what we’ll claim**

* **1. Introduction:** Why triadic control in BMS matters now (market growth, Li‑ion dominance, regional dynamics)1.
* **2. Background:** BMS core functions and limits; where losses and buffers come from5.
* **3. TFT design:** The Signal–Structure–Scheduling triad; tiny‑footprint implementation pattern; comms and timing discipline.
* **4. Methods:** Metrics (usable SOC window, RTE, thermal stress); test plans (A/B firmware, HIL bench, drive/ESS cycles).
* **5. Results:** Chemistry‑specific “effective Wh” deltas; sensitivity to temperature, C‑rate, and aging.
* **6. Discussion:** Deployment pathways (EV, ESS), safety envelopes, warranty implications, and fleet‑level impact.
* **7. Conclusion:** Minimal code, maximal coherence—how TFT turns buffers into service.

Market context and BMS function citations to anchor claims14. We can add EV penetration tables and player maps as needed3.

### **Optional: minimal TFT loop (illustrative)**

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// Pseudocode: TFT layer inside BMS main loop  
tick\_sync(); // align ADC/PWM phases  
samples = adc\_read\_sync(); // low-jitter voltage/current/temp  
state = est\_state(samples); // SOC/SOH/SOP with conf. intervals  
cmd = tft\_policy(state, schedule, thermal\_headroom);  
// cmd packs: CC/CV setpoint tweak, balance duty, switch phasing  
apply\_actuation(cmd);  
telemetry\_send\_compact(state, cmd); // deterministic, lossless framing

## **What I need from you to lock this in**

* **Target metrics:** Do you want primary results in gravimetric Wh/kg, volumetric Wh/L, or pack‑level effective Wh for named platforms?
* **Use cases:** Prioritize EV (NMC/NCA, LFP), ESS (LFP, sodium‑ion, flow), or lead‑acid retrofit?
* **Evidence plan:** Bench profiles (drive cycles, duty cycles), temperature setpoints, and acceptance thresholds for uplift.

If you give me the audience and top two chemistries to lead with, I’ll turn this into a 6–8 page paper draft with figures, tables, and a methods appendix.