DOCUMENT
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BATTERY · CHARGING · BMS · SAFETY · REFERENCE DOCUMENT · PUBLIC

Battery and power management

Reference for Li-ion chemistry selection, charging architectures, battery management system (BMS) design, fuel gauging, and the safety standards (UN 38.3, IEC 62133, EU Battery Regulation) that govern shipping and sale.

REVISION	ISSUED	OWNER	COMPANION
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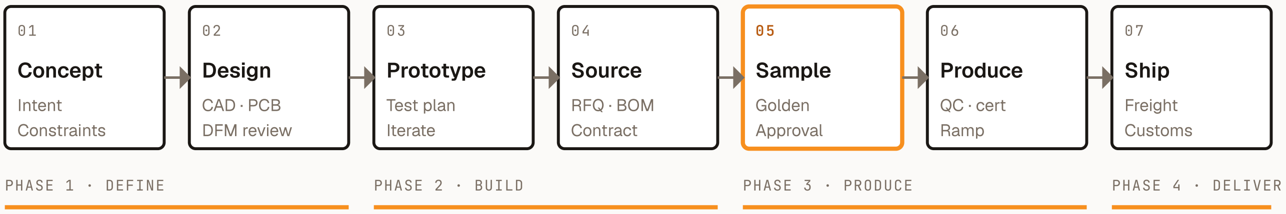
ABSTRACT

Battery and power-management decisions shape five subsequent constraints: runtime, charging time, regulatory compliance (UN 38.3 mandatory for shipping; IEC 62133, EU Battery Regulation, UL 1642), shipping mode (lithium cells restrict air freight), warranty exposure (cycle life), and end-of-life (collection and recycling under EPR).

Section 1 covers chemistry selection. Section 2 covers cell selection and form factor. Section 3 covers BMS architecture. Section 4 covers charging design. Section 5 covers fuel gauging. Section 6 covers safety standards and shipping regulations. Section 7 covers thermal management.

HARDWARE PRODUCT DEVELOPMENT — 7-STAGE PIPELINE



BATTERY DECISIONS SIT IN PHASE 2 (BUILD) BUT RIPPLE THROUGH EVERY LATER PHASE — COMPLIANCE, SHIPPING, WARRANTY, FIELD SERVICE.

CONTENTS

1. Chemistry selection
2. Cell selection + form factor
3. Battery management system (BMS)
4. Charging design
5. Safety standards + shipping
6. Thermal management

1. Chemistry selection

Li-ion is the dominant chemistry for consumer hardware. Pick the variant based on energy density, cycle life, safety, and cost trade-offs.

1.1 Li-ion chemistry comparison

CHEMISTRY	NOMINAL V	ENERGY DENSITY (WH/KG)	CYCLE LIFE	COST / WH	BEST FOR
LCO ($LiCoO_2$)	3.7	150–200	500	$0.12	Compact electronics, phones
NMC ($LiNiMnCoO_2$)	3.6	150–220	1 000–2 000	$0.10	EV, laptops, general use
LFP ($LiFePO_4$)	3.2	90–120	2 000–5 000	$0.10	Solar storage, e-bikes, safety-critical
LTO ($Li_4Ti_5O_{12}$)	2.4	60–80	10 000+	$0.50	Fast-charging, long life, low temp
NCA ($LiNiCoAlO_2$)	3.6	200–250	1 000–2 000	$0.12	Tesla EVs, premium devices
NaCl (sodium-ion)	3.2	100–150	2 000–4 000	$0.06	Emerging; safety-oriented

1.2 Other battery chemistries

- **Lithium polymer (LiPo)**
  Same chemistries above, but in pouch form. Lower weight, more flexible shape, slightly higher cost. Widely used in wearables, drones, slim devices.
- **Alkaline (primary)**
  Non-rechargeable. Used in low-current devices (remotes, sensors). 1.5 V nominal.
- **NiMH**
  Rechargeable, 1.2 V nominal. Largely obsolete except in specific industrial applications.
- **Lead-acid**
  Cheap, robust, heavy. Used in industrial backup, automotive.

1.3 Selection criteria

PRIORITY	BEST CHEMISTRY
Maximum energy density	LCO, NCA
Long cycle life	LFP, LTO
Safety + thermal stability	LFP, LTO
Cost-sensitive	NMC, sodium-ion (emerging)
Low-temperature operation	LTO, special NMC blends
Fast charging (>2C)	LTO, modified NMC
Slim form factor	LiPo (any chemistry)

2. Cell selection + form factor

Cell choice locks the mechanical design, charge architecture, and BMS topology.

2.1 Standard cylindrical cell sizes

CELL	DIAMETER × LENGTH (MM)	TYPICAL CAPACITY	COMMON CHEMISTRY	USE CASE
10440 (AAA size)	10 × 44	350 mAh	NMC	Compact electronics
14500 (AA size)	14 × 50	800 mAh	LFP, NMC	Replacement for AA
14650	14 × 65	1 200 mAh	NMC	Mid-size devices
18650	18 × 65	2 500–3 500 mAh	NMC, LFP, NCA	Laptops, e-bikes, tools
21700	21 × 70	4 000–5 000 mAh	NMC	EVs, premium laptops
26650	26 × 65	5 000 mAh	LFP	Stationary, marine
32700	32 × 70	6 000 mAh	LFP	Stationary, large packs

2.2 Pouch (LiPo) cell sizing

Pouch cells are typically specified by **width × length × thickness** in mm, plus capacity.

- **Examples: 503450 = 5 mm × 34 mm × 50 mm; 853450 = 8.5 mm × 34 mm × 50 mm.**
- **Capacity ≈ 1.5 × thickness (mm) × width (mm) × length (mm) × 0.1 mAh (rough estimate, varies by chemistry density).**
- **Discharge rate (C-rate)**
  1C = capacity per hour. 2C means 2× capacity per hour. Most LiPo cells safe at 1–2C continuous.

2.3 Pack topology

TOPOLOGY	NOTATION	USE
Single cell	1S	Wearables, low-power IoT
2 cells series	2S	7.4 V devices (some phones)
3 cells series	3S	11.1 V (drones, power tools)
4S+	4S, 5S, etc.	Higher-voltage applications
Parallel cells	1P, 2P, etc.	Capacity multiplication
Series + parallel	2S2P, 3S4P, etc.	Combined voltage + capacity

Example: 3S2P pack = 3 cells in series (×3.7 = 11.1 V), 2 in parallel (×capacity). Total capacity = 2× single cell.

3. Battery management system (BMS)

The BMS protects the cell(s) and presents a managed interface to the rest of the system.

3.1 Core BMS functions

- **Overcharge protection**
  Disconnects charge path when cell voltage exceeds limit (typically 4.20 V ± 50 mV for Li-ion).
- **Over-discharge protection**
  Disconnects load when cell voltage drops below limit (typically 2.50–3.00 V).
- **Over-current protection**
  Disconnects on excess current (charge or discharge).
- **Short-circuit protection**
  Fast disconnect (10–100 µs typical).
- **Over-temperature protection**
  Disconnects on cell temp exceeding limit (typically 60 °C charge, 70 °C discharge).
- **Cell balancing**
  For multi-cell packs, equalises charge across cells (passive or active).
- **State of Charge (SoC) reporting**
  Coulomb counting or voltage-based estimation.

3.2 BMS chip categories

TYPE	EXAMPLES	BEST FOR
Single-chip BMS for 1S	TI BQ24074, MAX17048, ADP5350	Wearables, single-cell devices
Multi-cell BMS controller	TI BQ76952, BQ40Z80	2S–16S packs
Smart battery fuel gauge	TI BQ27Z561, MAX17260	Battery state reporting
Battery pack microcontroller	ADC-based custom	Complex packs, multi-cell
Integrated charger + BMS	TI BQ25895, BQ24180	USB-charged single-cell devices

3.3 Cell balancing methods

- **Passive balancing**
  Bleeds excess charge through a resistor on cells with higher SoC. Cheap, simple. Wastes energy (heats up).
- **Active balancing**
  Transfers charge from higher-SoC cells to lower-SoC cells via inductors or capacitors. More expensive, more efficient. Used in large packs (EV, energy storage).

3.4 State of Charge (SoC) estimation

- **Voltage-based**
  Reads cell voltage and looks up SoC in a lookup table. Simple but inaccurate during load (voltage sag). Best for low-current devices.
- **Coulomb counting**
  Integrates current in/out. Accurate but drifts over time without reset (typically at full charge).
- **Kalman filter / blended methods**
  Combines voltage + coulomb counting + temperature. Best accuracy, most complex implementation.

4. Charging design

Charging architecture trades off charge time, complexity, efficiency, and standards compliance.

4.1 Charging stages (Li-ion CC/CV)

1. **Pre-charge (trickle)** — Low current (0.05–0.1C) if cell voltage is below ~3.0 V (deep discharge recovery). 2. **Constant current (CC)** — Charges at rated current (typically 0.5–1C) until cell voltage reaches the limit (typically 4.20 V). 3. **Constant voltage (CV)** — Holds voltage at 4.20 V; current decreases as cell saturates. 4. **Termination** — When current drops below 0.05C, charging stops.

4.2 Charging current limits

CELL CLASS	STANDARD CHARGE	FAST CHARGE	ULTRA-FAST
Standard NMC	0.5–1C	1.5–2C	Not recommended
High-discharge NMC	1–2C	2–3C	3–4C (specific cells)
LFP	0.5–1C	1–2C	2–3C
LTO	2–6C	6–10C	10–20C

C-rate × capacity = charge current. Example: 3 000 mAh cell at 1C charge = 3 A.

4.3 Common charging architectures

ARCHITECTURE	COMPONENTS	BEST FOR
Linear charger	Single charger IC	Simple, low current (<1 A), heat-tolerant
Buck charger	Charger IC + inductor	Medium current (1–3 A), better efficiency
Boost charger	Charger IC + inductor (boost mode)	When input voltage < battery voltage
Bidirectional (charger + discharger)	More complex IC	USB-PD with reverse output capability
Wireless (Qi, MagSafe)	Receiver coil + rectifier + linear/buck	Premium devices, no exposed contacts

4.4 USB-PD considerations

- **USB-PD profiles**
  5V, 9V, 12V, 15V, 20V at various currents (up to 100 W with PD 3.0, 240 W with EPR).
- **PPS (Programmable Power Supply)**
  Allows charger to negotiate exact voltage for direct cell charging (more efficient).
- **Direct charge**
  PD source provides cell voltage directly, eliminating an intermediate stage. Used in high-current fast charging (>20 W).

4.5 Charging time formula

``` Charging time (h) ≈ Capacity (mAh) / Charge current (mA) × 1.4

Example: 3 000 mAh cell at 1.5 A → 3000 / 1500 × 1.4 = 2.8 hours The 1.4 factor accounts for CV taper at the end. ```
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5. Safety standards + shipping

Battery products must meet multiple standards to ship and sell legally.

5.1 Mandatory safety standards by region

REGION	STANDARD	SCOPE
Global	UN 38.3	Air transport safety (8 tests)
Global	IEC 62133-2	Portable battery safety
US	UL 1642	Lithium battery safety
US	UL 2054	Battery pack safety
EU	EN 62133-2	Same as IEC 62133-2
EU	EU Battery Regulation 2023/1542	Carbon footprint, removability (phased 2024–2027)
China	GB 31241	Portable electronic battery safety
Japan	PSE	Mandatory for certain batteries

5.2 UN 38.3 tests (8 required for shipping)

1. **Altitude simulation** — 11.6 kPa pressure for 6 hours. 2. **Thermal test** — -40 °C and +75 °C cycling. 3. **Vibration** — Sinusoidal vibration test. 4. **Shock** — Mechanical shock test. 5. **External short circuit** — At +55 °C. 6. **Impact / crush** — Mechanical penetration. 7. **Overcharge** — 2× rated current for 24 hours. 8. **Forced discharge** — For primary batteries.

UN 38.3 testing cost: **$3 000–8 000** per cell type. Required for any shipment of Li-ion batteries (loose cells or batteries-in-devices). Certificate is one-time per cell model.

5.3 Shipping regulations

MODE	CLASSIFICATION	LIMITS
Air (passenger aircraft)	UN 3480 (cells alone)	Forbidden as cargo since 2016
Air (cargo aircraft only)	UN 3480	≤30 % SoC for cells; per IATA DGR
Air (in devices)	UN 3481	Per IATA: ≤2 cells / ≤100 Wh per device; less restrictive than alone
Sea	UN 3480 / 3481	Generally permitted, IMDG Code
Ground (US)	UN 3480 / 3481	Per US DOT 49 CFR

CRITICAL — LI-ION AIR SHIPPING

Loose Li-ion cells **cannot be shipped on passenger aircraft** since 2016. Cells in devices are allowed but must be: - Cells at ≤30 % SoC (state of charge) for transport - Properly packaged per IATA Dangerous Goods Regulations - Declared as "lithium-ion batteries contained in equipment" (UN 3481)

This is why first-batch hardware imports from Asia typically ship by sea — the air-freight cost premium for batteries is significant, and many couriers refuse loose cells entirely.

5.4 EU Battery Regulation 2023/1542 highlights (effective 2024–2027 phased)

- **Carbon footprint disclosure**
  Mandatory for industrial + EV batteries from 2025; portable from 2027.
- **Removability**
  End-user must be able to remove and replace portable batteries with commonly available tools (phased; full implementation 2027).

- **Recycled content minimums**
  Cobalt 12 %, lithium 4 %, nickel 4 %, lead 85 % by 2030.
- **EPR fees**
  Producer pays for collection and recycling.
- **Battery passport**
  Digital passport for industrial + EV from 2027.

6. Thermal management

Battery thermal management is the difference between predictable cycle life and field failures.

6.1 Operating temperature ranges

CHEMISTRY	OPTIMAL	ACCEPTABLE	AVOID
Li-ion (NMC, LCO)	15–25 °C	0–45 °C	< -10 °C (charging), > 50 °C
LFP	15–25 °C	-10 to +60 °C	< -10 °C (charging), > 60 °C
LTO	-20 to +55 °C	-40 to +75 °C	Wider range, more tolerant
Alkaline	20 °C	0–55 °C	< -10 °C (capacity loss)

6.2 Heat sources in a battery system

- **I^2R losses**
  Internal resistance × current^2. Rises with current (fast charge / discharge) and as cells age.
- **Charging chemistry**
  Some heat generated during charge.
- **Ambient temperature**
  Higher ambient pushes the whole system warmer.

6.3 Thermal management approaches

- **Passive (heatsink, thermal pad)**
  Adequate for <5 W heat generation in small devices.
- **Active (fan)**
  Required for >10 W sustained heat or premium products.
- **Liquid cooling**
  Required for large packs (EV, energy storage) or very high power density.
- **PCM (phase-change material)**
  Absorbs heat during peak; releases during cool-down. Used in some EV packs.

6.4 Cycle life vs. temperature

TEMPERATURE	CYCLE LIFE IMPACT (NMC CELL)
15 °C	1.0× baseline (e.g., 1 000 cycles to 80 % capacity)
25 °C	0.85× (baseline reference)
35 °C	0.50×
45 °C	0.25×
55 °C	0.10×
60 °C+	Risk of thermal runaway

Storing batteries at high temperature accelerates capacity fade and shortens cycle life. Devices stored in hot cars or warehouses lose capacity faster.

FINAL NOTE. battery design is multi-disciplinary — electrochemistry, electronics, mechanical, regulatory, and supply chain all converge on a single component. Get the chemistry, BMS, and safety standards right at the start. Late-stage changes to battery system require re-certification, re-test, and often re-design. Battery is one of the slowest things to fix once production starts.