Modular Power Standard – Rechargeable
Version 1.0.0
License: Apache 2.0
Documentation Format: Hybrid ESO-Style
Versioning Model: Semantic (Major.Minor.Patch)

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Section 1 - Core Specification

1. Introduction

The Modular Power Standard – Rechargeable (MPS-R) defines a universal, open, modular energy platform for automotive keys and related micro-power devices. MPS-R establishes the electrical, mechanical, functional, and interoperability rules that allow multiple rechargeable power modules to operate interchangeably within OEM and aftermarket key systems.

MPS-R is designed to replace disposable coin-cell batteries with modern, safe, rechargeable, and serviceable power modules while maintaining full compatibility with existing key electronics, RF systems, immobilizer protocols, and OEM security requirements.

MPS-R is an open standard, intended for adoption by automotive manufacturers, aftermarket accessory designers, and independent engineers.

2. Purpose of the Standard

The purpose of MPS-R is to:

- eliminate disposable coin-cell batteries in automotive keys
- provide a universal rechargeable power platform
- support multiple charging technologies
- ensure interoperability across OEM and aftermarket designs
- define a stable electrical and mechanical interface
- enable modular replacement and upgrades
- support long-term sustainability and serviceability
- establish a foundation for future micro-power innovations

MPS-R is intentionally modular, allowing different charging and storage technologies to coexist under one unified interface.

3. Scope

MPS-R applies to:

- automotive key fobs (smart and dumb keys)
- immobilizer keys
- proximity keys
- remote start keys
- aftermarket key shells
- micro-power accessories using the MPS-R interface

MPS-R does not define:

- RF protocols
- immobilizer encryption
- OEM MCU logic
- button layouts
- vehicle-specific features

These remain under OEM control.
MPS-R defines only the power subsystem.

4. Design Philosophy

MPS-R is built on six architectural principles:

4.1 Modularity

Every power module must be replaceable, upgradeable, and interchangeable.

4.2 Interoperability

All modules must operate with any MPS-R-compatible key design.

4.3 Safety

All modules must include protection circuitry and thermal safeguards.

4.4 Serviceability
Modules must be removable without soldering or adhesives.

4.5 Sustainability
Rechargeable systems must reduce waste and extend product life.

4.6 Neutrality
The standard must remain open, vendor-neutral, and non-proprietary.

5. Terminology
- MPS-R: Modular Power Standard – Rechargeable
- Module: A rechargeable power subsystem compliant with MPS-R
- MPS-Q: Qi Charging Module
- MPS-S: Supercapacitor Module
- MPS-H: Hybrid Energy Harvesting Module
- MPS-R-E8: Universal 8-pin electrical interface
- OEM: Original Equipment Manufacturer
- Aftermarket: Third-party accessory ecosystem

6. Module Families
MPS-R defines three initial module families:

6.1 MPS-Q — Qi Charging Module
Wireless inductive charging using Qi protocol.

6.2 MPS-S — Supercapacitor Module
Ultra-long-life, fast-charging energy storage.

6.3 MPS-H — Hybrid Harvesting Module
Energy harvesting (solar, piezo, RF) with micro-supercap buffer.

Future module families may be added under the same interface.

7. System Goals
MPS-R aims to:

- provide a universal rechargeable alternative to coin cells
- support multiple charging methods without redesigning the key
- maintain OEM RF and immobilizer reliability
- reduce environmental waste
- enable aftermarket customization
- support future energy technologies
- create a stable, open ecosystem for innovation

8. Safety Principles
All MPS-R modules must include:
- over-voltage protection
- over-current protection
- short-circuit protection
- thermal protection
- safe charging profiles
- safe discharge profiles
- shielding to prevent RF interference

Safety is mandatory across all module families.

9. Interoperability Rules
To ensure universal compatibility:

- all modules must use the MPS-R-E8 electrical interface
- all modules must fit the MPS-R mechanical envelope
- all modules must expose CHGSTAT, SOCDATA, and ID_MOD
- all modules must regulate output to OEM electronics
- all modules must be removable without soldering
- all modules must not interfere with RF windows

Interoperability is the core of the standard.

10. Versioning Model
MPS-R uses semantic versioning:

- Major: breaking changes
- Minor: new features or modules
- Patch: corrections or refinements

Example:
MPS-R v1.0.0 (initial release)

Modules follow the same versioning scheme:
MPS-Q v1.0.0, MPS-S v1.0.0, etc.

11. Licensing Model
MPS-R is released under the Apache 2.0 License, providing:

- open adoption
- commercial usage rights
- contributor protection
- patent-safe open-source terms
- compatibility with OEM legal requirements

This ensures the standard remains open and usable by all.

12. Documentation Format
MPS-R uses a Hybrid ESO-Style format:

- formal specification sections
- architectural rationale
- diagrams and subsystem breakdowns
- narrative clarity
- engineering-grade detail

This format balances readability with technical precision.

13. Compliance Requirements
A module is MPS-R compliant if:
- it meets all electrical interface rules
- it meets all mechanical interface rules

- it passes safety requirements
- it identifies itself via ID_MOD
- it provides regulated output
- it supports charge status reporting
- it fits within the defined envelope

Compliance ensures universal compatibility.

14. Future Expansion Pathways
MPS-R is designed to support future modules such as:

- MPS-D (Dock Charging Module)
- MPS-U (USB-C Micro-Module)
- MPS-X (Experimental Energy Module)
- MPS-L (Long-Life Lithium Module)

The standard is intentionally extensible.

15. Document Structure
The full MPS-R document consists of:

1. MPS-R Core Specification
2. MPS-R Universal Electrical Interface
3. MPS-R Universal Mechanical Interface
4. MPS-Q Module Specification
5. MPS-S Module Specification
6. MPS-H Module Specification
7. Reference Design Packages
8. Compliance Notes
9. Appendices

16. Conclusion
MPS-R establishes a unified, modular, rechargeable power ecosystem for automotive keys. By defining a stable electrical and mechanical interface and supporting multiple energy technologies, MPS-R enables OEMs, aftermarket designers, and engineers to adopt modern rechargeable systems without sacrificing compatibility, safety, or design freedom.

This Core Specification forms the foundation for all MPS-R modules and future expansions.

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Section two - Universal Interfaces
MPS-R universal electrical/mechanical interface

Goal: one common “socket” every module (MPS-Q, MPS-S, MPS-H, future variants) can plug into, so the key electronics don’t care which power module is installed.

1. Electrical connector definition

- Connector type:
  Label: MPS-R-E8
  Form: 8-pin low-profile board-to-board or flex connector.

- Pinout (logical):
  - Pin 1 – VBAT+:
    Raw battery output, \(2.7\text{–}4.2 \text{ V}\).
  - Pin 2 – GND:

Common ground.
- Pin 3 – VREG:
  Regulated output to key electronics, typically \(3.0\text{–}3.3 \text{ V}\).
- Pin 4 – CHG_STAT:
  Charge status (e.g., open-drain, low = charging, high = done).
- Pin 5 – SOC_DATA:
  Optional state-of-charge signal (PWM or simple analog voltage).
- Pin 6 – EN_MOD:
  Enable line from key to module (for low-power modes).
- Pin 7 – ID_MOD:
  Module ID (resistor-coded or 1-wire digital) to identify MPS-Q vs MPS-S vs MPS-H.
- Pin 8 – NC/RES:
  Reserved for future use (e.g., diagnostics).

2. Electrical behavior constraints

- VBAT+ range: \(2.7\text{–}4.2 \text{ V}\).
- VREG range: \(3.0\text{–}3.3 \text{ V}\), max ripple defined for RF stability.
- Max continuous current (VREG): 200 mA.
- Quiescent current (module when idle): $\leq 10\ \mu$A from VBAT+.
- Signal levels: logic at \(3.0\text{–}3.3 \text{ V}\) domain.

MPS-R universal mechanical interface

Goal: any MPS-R module fits any MPS-R-compatible shell/key design.

1. Module envelope

- Max footprint:
  - Length: 45–60 mm
  - Width: 25–35 mm
  - Thickness: $\leq$ 12 mm (including coil, cell, PCB)
- Mounting plane: flat base with defined connector location.

2. Connector placement

- MPS-R-E8 connector:
  - Positioned at one short edge, centered vertically.
  - Standard offset from module corner (e.g., 3 mm inset) so shells can be designed generically.

3. Fixation and access

- Retention:
  - Two or more snap-tabs or screws accessible from inside the shell.
- Serviceability:
  - Module removable without desoldering.
  - No adhesives required for normal replacement.

4. Coil window (for MPS-Q)

- Shell must provide a charging face aligned with the coil region.
- Minimum flat area: $\sim 30 \times 30$ mm for reliable Qi coupling.

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Section three - Module Specifications
Modular Power Standard – Rechargeable (Qi Variant)

MPS-Q — Qi Charging Module
Version: MPS-Q v1.0.0
Parent Standard: MPS-R v1.0.0
Documentation Format: Hybrid ESO-Style
License: Apache 2.0

🧩 1. MPS-Q Overview

MPS-Q is the Qi-based rechargeable power module within the MPS-R Modular Power Standard. It provides a thin, LiPo-based energy subsystem capable of wireless inductive charging using the Qi protocol or compatible low-power inductive charging systems.

MPS-Q is designed to:
- replace disposable coin cells in automotive keys
- integrate seamlessly with OEM key electronics
- fit within modern fob form factors
- support passive entry, RF communication, immobilizer handshake, and all OEM features
- provide a universal, open, rechargeable power solution
- operate as one of multiple interchangeable modules under MPS-R

MPS-Q is the baseline module for MPS-R because Qi charging is the most widely supported, most familiar, and most OEM-friendly charging method.

🧩 2. MPS-Q Core Requirements

These requirements define the minimum acceptable performance and compatibility for any MPS-Q-compliant module.

2.1 Physical Requirements
- Maximum thickness: ≤ 12 mm
- Maximum width: 25–35 mm
- Maximum length: 45–60 mm
- Coil diameter: 20–25 mm
- Coil thickness: ≤ 2.5 mm
- Enclosure must support drop resistance and thermal dissipation

2.2 Electrical Requirements
- Nominal voltage: 3.7V LiPo
- Charge input: Qi inductive, 0.5–1.0 W
- Charge controller: WPC-compatible IC
- Discharge current: ≤ 200 mA peak
- Standby current: $\leq 10\ \mu$A
- Over-voltage protection
- Over-current protection
- Thermal protection

2.3 Functional Requirements
- Must power OEM RF subsystem
- Must power OEM MCU logic
- Must support immobilizer handshake
- Must support passive entry
- Must support LED charge indicator
- Must support 0–100% charge reporting

2.4 Interoperability Requirements
- Must comply with MPS-R Universal Electrical Interface
- Must comply with MPS-R Universal Mechanical Interface
- Must be replaceable without soldering
- Must be compatible with aftermarket shells
- Must not interfere with OEM RF windows

🧩 3. MPS-Q System Architecture Spine

This is the structural backbone of the module — the architecture that all MPS-Q implementations must follow.

3.1 Subsystem Breakdown

MPS-Q consists of five primary subsystems:

- Qi Coil Subsystem
- Charge Controller Subsystem
- Battery Subsystem
- Power Delivery Subsystem
- Indicator Subsystem

Each subsystem is modular and replaceable.

3.2 Qi Coil Subsystem

The Qi coil subsystem must:

- use a flat, ferrite-backed inductive coil
- support 110–205 kHz Qi frequency range
- include shielding to prevent RF interference
- be positioned to maximize coupling efficiency
- be thermally isolated from the LiPo cell

This subsystem is the physical interface to Qi charging pads.

3.3 Charge Controller Subsystem

The charge controller must:

- be WPC-compatible
- support 0.5–1.0 W charging
- include foreign object detection (FOD)
- include thermal throttling
- include trickle charging mode
- communicate charge status to the indicator subsystem

This subsystem ensures safe, reliable charging.

3.4 Battery Subsystem

The battery subsystem must:

- use a thin LiPo cell
- support 3.7V nominal
- include integrated protection circuitry
- support $\geq$ 150 mAh capacity (target)
- support $\geq$ 3–5 days standby
- support $\geq$ 1–2 years shelf life

This subsystem stores energy.

3.5 Power Delivery Subsystem

The power delivery subsystem must:

- regulate output to OEM electronics
- support peak RF transmission current
- support low-noise output
- support immobilizer handshake stability
- comply with MPS-R electrical interface

This subsystem powers the key.

3.6 Indicator Subsystem
The indicator subsystem must:
- display 0–100% charge
- activate on command
- activate during charging
- remain off otherwise
- use low-power LED or micro-OLED

This subsystem communicates charge status.

MPS-Q electrical architecture

1. Power flow overview
Path:
Qi pad → Qi coil → charge controller IC → LiPo cell → protection circuit → regulator → OEM key electronics.

- Input stage:
  $$V_{in} \approx 5\text{–}9 \text{ V (Qi receiver)}$$
  Rectified and filtered from the coil.

- Battery stage:
  $$V_{bat} \approx 3.0\text{–}4.2 \text{ V (LiPo)}$$

- Output stage:
  $$V_{out} \approx 3.0\text{–}3.3 \text{ V regulated}$$
  To RF, MCU, immobilizer.

2. Charge controller logic
Core behaviors:

- Bulk charge:
  Constant current until $\approx 4.1\text{–}4.2 \text{ V}$.
- CV phase:
  Constant voltage, taper current.
- Trickle / maintenance:
  Low current to keep full charge.
- Safety:
  - Over-voltage cutoff
  - Over-current cutoff
  - Thermal throttling
  - Foreign object detection (FOD)

3. Protection and regulation
Protection block:
- Over-charge: hardware cutoff at $\approx 4.25 \text{ V}$.
- Over-discharge: cutoff at $\approx 2.7\text{–}3.0 \text{ V}$.
- Short-circuit: fast electronic fuse behavior.

Regulation block:
- Low-noise LDO or buck to $\approx 3.3 \text{ V}$.
- Separate decoupling for RF and MCU rails to reduce interference.

MPS-Q mechanical constraints

1. Stack layout
Preferred vertical stack (from outside in):
- Outer shell (fob housing)
- Qi coil + ferrite backing
- Thin thermal barrier
- LiPo cell
- PCB (controller + regulation + indicator)
- Interface connector to OEM board

This keeps the coil closest to the pad, battery thermally buffered, and electronics protected.

2. Mounting and alignment
- Coil alignment: centered relative to shell face used for charging.
- Connector alignment: standardized position per MPS-R mechanical interface.
- Fastening: snap-fit or micro-screws; no adhesives required for module replacement.
- Sealing: gasket or overmold to resist sweat, pocket lint, minor moisture.

MPS-Q charging logic and behavior

1. User interaction model

- Place fob on Qi pad: charging auto-starts.
- LED behavior:
  - Single press or proximity gesture → show charge % briefly.
  - During charging → slow pulse or stepped indication.
- No always-on display to preserve standby life.

2. Charge profile targets

- From 10% to 90%:
  Target: ~30–60 minutes at 0.5–1.0 W.
- Top-off from 90% to 100%:
  Slower CV phase to protect LiPo.

MPS-Q integration pathways (under MPS-R)

1. OEM integration

- Premium trim: MPS-Q module as default power system.
- Accessory: optional "Rechargeable Key Pack" sold with wireless pad.
- Retrofit: dealer-installed replacement for coin-cell keys where form factor allows.

2. Aftermarket integration

- Universal shells: designed around MPS-R mechanical/electrical interface.
- Brand-specific kits: MPS-Q module + shell tailored to popular models.
- Capacity variants: same interface, different LiPo sizes.

MPS-Q reference design package (v1.0.0)

This is the "buildable" example implementation under MPS-R.

1. Block diagram (logical)

- Qi coil → Qi receiver IC → LiPo cell + protection → regulator → MPS-R-E8 connector → OEM key board

- Side branch: Qi receiver IC → CHG\STAT + SOC\DATA → indicator LED/driver.

2. Example BOM (high-level)

- Qi coil:
  - Flat, ferrite-backed, ~22–24 mm diameter.
- Qi receiver IC:
  - Low-power WPC-compatible (e.g., 0.5–1 W class).
- LiPo cell:
  - Thin pouch, ~150–250 mAh, sized to fit envelope.
- Protection IC:
  - LiPo protection (OV, UV, OC, short).
- Regulator:
  - Low-noise LDO or buck to 3.3 V.
- Indicator LED / driver:
  - Single RGB or white LED + simple driver logic.
- Connector:
  - MPS-R-E8-compatible board-to-board connector.
- PCB:
  - Single or dual-layer, sized to host ICs and connector.

3. Pin mapping (MPS-Q to MPS-R-E8)

- VBAT+ → LiPo positive after protection.
- VREG → regulator output.
- CHG_STAT → Qi IC status pin.
- SOC_DATA → simple analog or PWM from fuel-gauge or internal estimation.
- EN_MOD → enable pin gating regulator / logic.
- ID_MOD → resistor network or small MCU pin identifying “MPS-Q”.
- GND → common ground.

4. Testing methodology (summary)

- Electrical:
  - Verify charge curve, cutoff thresholds, ripple on VREG, quiescent current.
- RF coexistence:
  - Confirm no significant interference with key RF during normal operation.
- Thermal:
  - Charge at max power on Qi pad; ensure safe temperature rise.
- Mechanical:
  - Drop tests, insertion/removal cycles of module, connector durability.

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Modular Power Standard – Rechargeable (Supercapacitor Variant)

MPS-S — Supercapacitor Module
Version: MPS-S v1.0.0
Parent Standard: MPS-R v1.0.0
Documentation Format: Hybrid ESO-Style
License: Apache 2.0

1. MPS-S Overview
The MPS-S Supercapacitor Module is a high-durability, ultra-fast-charging energy subsystem designed for automotive keys requiring extreme longevity, rapid recharge cycles, and high reliability under temperature and environmental stress.

Unlike LiPo-based modules, MPS-S uses dual supercapacitors (or a single multi-layer supercap) to provide:

- near-instant charging
- extremely long cycle life (100,000+ cycles)
- stable discharge characteristics
- high peak current capability
- minimal degradation over time

MPS-S is ideal for:

- high-use fleet keys
- commercial vehicles
- harsh environments
- keys exposed to temperature extremes
- applications where long-term reliability outweighs capacity

MPS-S operates under the same MPS-R universal electrical and mechanical interfaces, ensuring full interoperability with OEM and aftermarket key designs.

2. MPS-S Core Requirements

2.1 Physical Requirements
- Maximum thickness: $\leq$ 12 mm
- Maximum width: 25–35 mm
- Maximum length: 45–60 mm
- Supercapacitor diameter (if cylindrical): $\leq$ 10 mm
- Supercapacitor height (if stacked): $\leq$ 2–3 mm per layer
- Enclosure must support vibration and shock resistance

2.2 Electrical Requirements
- Nominal voltage: 2.7–5.5V (depending on supercap configuration)
- Charge input: 0.5–2.0 W (fast charge capable)
- Charge controller: supercap-compatible boost/buck IC
- Peak discharge current: $\geq$ 300 mA
- Standby current: $\leq$ 10 μA
- Required protections:
  - over-voltage
  - over-current
  - short-circuit
  - thermal

2.3 Functional Requirements
- Must power OEM RF subsystem
- Must power OEM MCU logic
- Must support immobilizer handshake
- Must support passive entry
- Must support LED charge indicator
- Must support charge-level reporting (supercap SOC estimation)

2.4 Interoperability Requirements
- Must comply with MPS-R-E8 electrical interface
- Must comply with MPS-R mechanical envelope
- Must be replaceable without soldering
- Must not interfere with RF windows
- Must identify itself via ID_MOD = MPS-S

3. MPS-S System Architecture Spine

MPS-S consists of five primary subsystems:

- Supercapacitor Storage Subsystem
- Charge Controller Subsystem
- Voltage Regulation Subsystem
- Power Delivery Subsystem
- Indicator Subsystem

3.1 Supercapacitor Storage Subsystem
The storage subsystem must:

- use one or more supercapacitors rated for ≥ 100,000 cycles
- support operating temperatures from −20°C to +60°C
- include balancing circuitry for dual-supercap configurations
- include thermal isolation from the PCB
- include mechanical reinforcement for shock resistance

Supercapacitors may be:

- cylindrical
- flat-stacked
- multi-layer polymer supercaps

3.2 Charge Controller Subsystem
The charge controller must:

- support rapid charging (target: 10–60 seconds for usable charge)
- include voltage balancing (if dual supercaps)
- include thermal throttling
- include over-voltage protection
- include trickle/maintenance mode
- communicate charge status to indicator subsystem

3.3 Voltage Regulation Subsystem
Because supercaps discharge linearly, the regulator must:

- provide stable 3.0–3.3V output
- support high peak current
- include low-noise filtering for RF stability
- include brownout protection for MCU logic

3.4 Power Delivery Subsystem
Must:

- regulate output to OEM electronics
- support peak RF transmission current
- maintain immobilizer handshake stability
- comply with MPS-R electrical interface

3.5 Indicator Subsystem
Must:

- display charge readiness (supercaps do not use % the same way LiPo does)

- support “ready/not ready” or stepped charge indication
- activate on command
- activate during charging
- remain off otherwise

4. MPS-S Electrical Architecture

4.1 Power Flow Overview
Path:
Fast charge input → charge controller → supercapacitor array → regulator → MPS-R-E8 → OEM key electronics

4.2 Charge Profile
Supercapacitors charge differently from LiPo:

- Rapid charge phase:
  0–80% usable energy in seconds
- Balancing phase:
  equalizes dual supercaps
- Maintenance phase:
  keeps caps topped without over-voltage

4.3 Discharge Profile
Supercaps discharge linearly:

- regulator must maintain stable output
- brownout protection required near depletion

5. MPS-S Mechanical Constraints

5.1 Stack Layout
Preferred vertical stack:

- Outer shell
- Supercapacitor array
- Thermal barrier
- PCB (controller + regulator + indicator)
- MPS-R-E8 connector

5.2 Mounting
- shock-resistant mounting required
- vibration-resistant retention tabs
- no adhesives required

6. MPS-S Integration Pathways

6.1 OEM Integration
Ideal for:

- fleet vehicles
- commercial vehicles
- harsh environments
- keys requiring extreme durability

6.2 Aftermarket Integration
Supports:
- universal shells

- brand-specific kits
- high-durability variants

7. MPS-S Reference Design Package (v1.0.0)

7.1 Block Diagram
Charge input → boost/buck controller → supercap array → regulator → MPS-R-E8 → OEM board
Side branch: controller → CHGSTAT + SOCDATA → indicator LED

7.2 Example BOM
- Supercapacitors (dual 2.7V or single 5.5V)
- Charge controller IC
- Balancing circuitry
- Regulator (3.3V)
- Indicator LED + driver
- MPS-R-E8 connector
- PCB

7.3 Pin Mapping
- VBAT+ → supercap output
- VREG → regulator output
- CHG_STAT → controller status
- SOC_DATA → supercap readiness signal
- EN_MOD → regulator enable
- ID_MOD → identifies module as MPS-S
- GND → common ground

7.4 Testing Methodology
- rapid charge test
- discharge stability test
- RF coexistence test
- thermal stress test
- vibration/shock test

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Modular Power Standard – Rechargeable (Hybrid Variant)

MPS-H — Hybrid Energy Harvesting Module
Version: MPS-H v1.0.0
Parent Standard: MPS-R v1.0.0
Documentation Format: Hybrid ESO-Style
License: Apache 2.0

1. MPS-H Overview
The MPS-H Hybrid Energy Harvesting Module is a multi-source micro-power subsystem designed to harvest ambient energy from the environment and store it in a micro-supercapacitor buffer. MPS-H provides continuous trickle-charging capability and long-term maintenance power without requiring user interaction or external charging pads.

MPS-H is ideal for:
- low-use keys
- emergency-ready keys
- keys stored for long periods
- keys exposed to sunlight, motion, or RF fields
- sustainability-focused applications

MPS-H integrates three possible harvesting pathways:

- Solar harvesting (photovoltaic micro-cells)
- Piezoelectric harvesting (motion/vibration)
- RF/NFC/UWB harvesting (ambient electromagnetic fields)

All harvested energy is buffered through a micro-supercapacitor, ensuring stable output and compatibility with the MPS-R electrical interface.

2. MPS-H Core Requirements

2.1 Physical Requirements
- Maximum thickness: $\leq$ 12 mm
- Maximum width: 25–35 mm
- Maximum length: 45–60 mm
- Solar cell area: 10–25 mm² (if included)
- Piezo element thickness: $\leq$ 1 mm
- Micro-supercap thickness: $\leq$ 1–2 mm
- Enclosure must support exposure to sunlight and vibration

2.2 Electrical Requirements
- Nominal buffer voltage: 2.7–5.5V (micro-supercap)
- Harvesting input: 1–100 mW depending on source
- Charge controller: multi-input harvesting IC
- Peak discharge current: $\geq$ 150 mA
- Standby current: $\leq$ 10 μA
- Required protections:
  - over-voltage
  - over-current
  - short-circuit
  - thermal

2.3 Functional Requirements
- Must power OEM RF subsystem
- Must power OEM MCU logic
- Must support immobilizer handshake
- Must support passive entry
- Must support LED charge indicator
- Must support harvest-level reporting (optional)

2.4 Interoperability Requirements
- Must comply with MPS-R-E8 electrical interface
- Must comply with MPS-R mechanical envelope
- Must be replaceable without soldering
- Must not interfere with RF windows
- Must identify itself via ID_MOD = MPS-H

3. MPS-H System Architecture Spine

MPS-H consists of six primary subsystems:

- Solar Harvesting Subsystem
- Piezoelectric Harvesting Subsystem
- RF/NFC/UWB Harvesting Subsystem
- Harvest Controller Subsystem
- Micro-Supercapacitor Buffer Subsystem
- Power Delivery & Indicator Subsystem

Not all harvesting subsystems are mandatory; at least one must be present.

3.1 Solar Harvesting Subsystem
The solar subsystem must:

- use thin-film or micro-photovoltaic cells
- support low-light operation
- integrate into the shell surface or module top
- include reverse-current protection
- feed into the harvest controller

Solar harvesting provides the highest average energy yield.

3.2 Piezoelectric Harvesting Subsystem
The piezo subsystem must:

- use a thin piezoelectric film or ceramic element
- convert motion/vibration into charge pulses
- include rectification circuitry
- include mechanical isolation to prevent damage
- feed into the harvest controller

Piezo harvesting is ideal for keys carried daily.

3.3 RF/NFC/UWB Harvesting Subsystem
The RF harvesting subsystem must:

- use a tuned antenna or coil
- capture ambient RF energy (NFC, UWB, etc.)
- include rectification and filtering
- include shielding to avoid RF interference
- feed into the harvest controller

RF harvesting provides small but continuous trickle power.

3.4 Harvest Controller Subsystem
The harvest controller must:
- accept multiple input sources
- perform MPPT-like optimization (if solar included)
- rectify and regulate incoming energy
- prevent over-voltage on the buffer
- manage charge flow into the micro-supercap
- communicate harvest status to indicator subsystem

This subsystem is the “brain” of MPS-H.

3.5 Micro-Supercapacitor Buffer Subsystem
The buffer subsystem must:

- use a micro-supercapacitor rated for $\geq$ 50,000 cycles
- support rapid charge/discharge
- provide stable output to regulator
- include thermal isolation
- include balancing (if multi-layer)

This buffer stores harvested energy.

3.6 Power Delivery & Indicator Subsystem
Must:

- regulate output to OEM electronics
- support peak RF transmission current
- maintain immobilizer handshake stability
- comply with MPS-R electrical interface
- provide harvest-level or readiness indication

4. MPS-H Electrical Architecture

4.1 Power Flow Overview
Path:
Solar/Piezo/RF → harvest controller → micro-supercap → regulator → MPS-R-E8 → OEM key electronics

4.2 Harvesting Profiles
- Solar: continuous trickle, higher yield outdoors
- Piezo: pulse-based, dependent on motion
- RF: low-yield but constant in RF-rich environments

4.3 Buffer Behavior
Micro-supercaps:
- charge quickly
- discharge linearly
- require stable regulation
- provide long service life

5. MPS-H Mechanical Constraints

5.1 Stack Layout
Preferred vertical stack:
- Outer shell (with solar window if applicable)
- Solar/piezo/RF harvesting elements
- Harvest controller PCB
- Micro-supercap buffer
- Regulator + indicator
- MPS-R-E8 connector

5.2 Mounting
- vibration-resistant mounting
- solar window alignment
- RF harvesting coil placement away from OEM RF window

6. MPS-H Integration Pathways

6.1 OEM Integration
Ideal for:

- sustainability-focused trims
- long-storage keys
- emergency keys
- keys for EVs or eco-packages

6.2 Aftermarket Integration
Supports:

- universal shells with solar windows
- motion-harvesting upgrades
- hybrid modules for low-maintenance users

7. MPS-H Reference Design Package (v1.0.0)

7.1 Block Diagram
Solar/Piezo/RF → harvest controller → micro-supercap → regulator → MPS-R-E8 → OEM board
Side branch: controller → CHGSTAT + SOCDATA → indicator LED

7.2 Example BOM
- Thin-film solar cell
- Piezoelectric film
- RF harvesting coil
- Multi-input harvest controller IC
- Micro-supercapacitor
- Regulator (3.3V)
- Indicator LED + driver
- MPS-R-E8 connector
- PCB

7.3 Pin Mapping
- VBAT+ → micro-supercap output
- VREG → regulator output
- CHG_STAT → harvest controller status
- SOC_DATA → harvest readiness signal
- EN_MOD → regulator enable
- ID_MOD → identifies module as MPS-H
- GND → common ground

7.4 Testing Methodology
- solar yield test
- piezo pulse test
- RF harvesting test
- discharge stability test
- RF coexistence test
- environmental exposure test

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Section 4 - compliance

MPS-R Compliance Notes
Version 1.0.0
Applies to: MPS-Q, MPS-S, MPS-H, and all future MPS-R modules

1. Purpose of Compliance Notes
The Compliance Notes define the minimum testing, validation, and verification requirements for any module claiming MPS-R compliance. These requirements ensure that all modules—regardless of charging method, storage technology, or manufacturer—operate safely, reliably, and interoperably within any MPS-R-compatible key system.

Compliance ensures:
- electrical compatibility
- mechanical compatibility

- safety
- RF coexistence
- environmental durability
- correct module identification
- correct interface behavior

Compliance is mandatory for all MPS-R modules.

2. Compliance Categories
All modules must pass validation in the following categories:

1. Electrical Compliance
2. Mechanical Compliance
3. Safety Compliance
4. RF Coexistence Compliance
5. Environmental Compliance
6. Interoperability Compliance
7. Identification Compliance
8. User Interaction Compliance

Each category is defined below.

3. Electrical Compliance
Modules must demonstrate:

3.1 Interface Compliance
- Correct implementation of the MPS-R-E8 pinout
- VBAT+ output within specified range
- VREG output within 3.0–3.3V
- CHG_STAT behavior consistent with module type
- SOC_DATA behavior consistent with module type
- EN_MOD response within 10 ms
- ID_MOD correctly identifying module family

3.2 Power Stability
- Ripple on VREG must not exceed RF stability threshold
- Brownout protection must activate near depletion
- Peak current capability must meet module spec
- Quiescent current $\leq 10\ \mu A$

3.3 Charging Behavior
- Charge profile must match module specification
- Over-voltage cutoff must activate correctly
- Over-current protection must activate correctly

4. Mechanical Compliance
Modules must demonstrate:

4.1 Envelope Fit
- Must fit within the MPS-R mechanical envelope
- Must align with connector placement rules

4.2 Retention & Serviceability
- Must install without soldering
- Must remove without adhesives
- Must withstand 500+ insertion/removal cycles

4.3 Structural Integrity
- Must pass drop test (1.5 m, 6 faces)
- Must pass vibration test (automotive standard profile)

5. Safety Compliance
Modules must demonstrate:

5.1 Electrical Safety
- Over-voltage protection
- Over-current protection
- Short-circuit protection
- Reverse-current protection (if applicable)

5.2 Thermal Safety
- Must not exceed safe temperature rise during charging
- Must throttle charging under thermal stress
- Must pass thermal cycling (−20°C to +60°C)

5.3 Chemical Safety (LiPo modules only)
- LiPo cell must include integrated protection
- No swelling under normal operation
- No venting under thermal cycling

6. RF Coexistence Compliance
Modules must demonstrate:

6.1 RF Stability
- VREG ripple must not interfere with RF transmission
- Module must not distort OEM RF window
- Module must not introduce EMI beyond automotive limits

6.2 Immobilizer Reliability
- Must support immobilizer handshake under all charge states
- Must maintain stable voltage during RF bursts

7. Environmental Compliance
Modules must demonstrate:

7.1 Moisture Resistance
- Must withstand humidity exposure (95% RH, 48 hours)
- Must resist sweat and pocket moisture

7.2 Dust & Debris Resistance
- Must withstand pocket lint, dust, and debris intrusion

7.3 UV Exposure (solar modules only)
- Solar window must resist UV degradation

7.4 Motion/Vibration (piezo modules only)
- Piezo element must withstand repeated flex cycles

8. Interoperability Compliance
Modules must demonstrate:

8.1 Universal Compatibility

- Must operate with any MPS-R-compatible key shell
- Must operate with any OEM key electronics using MPS-R-E8

8.2 Cross-Module Compatibility
- MPS-Q, MPS-S, and MPS-H must all function in the same shell
- Key electronics must not require firmware changes

8.3 Replacement Compatibility
- Modules must be hot-swappable (power off required, no pairing)
- No recalibration required after replacement

9. Identification Compliance
Modules must demonstrate:

9.1 ID_MOD Behavior
- Must correctly identify module type
- Must respond within 10 ms of power-up
- Must use resistor-coded or 1-wire digital ID

9.2 OEM Behavior
- OEM electronics must read ID_MOD and adjust expectations
- Incorrect ID_MOD behavior is grounds for non-compliance

10. User Interaction Compliance
Modules must demonstrate:

10.1 Indicator Behavior
- Must display charge or readiness status
- Must activate only on command or during charging
- Must remain off otherwise

10.2 Charging Interaction
- MPS-Q must auto-start on Qi pad
- MPS-S must indicate readiness after rapid charge
- MPS-H must indicate harvest activity (optional)

11. Compliance Testing Summary
A module is considered MPS-R compliant when it passes:

- Electrical interface tests
- Mechanical envelope tests
- Safety tests
- RF coexistence tests
- Environmental tests
- Interoperability tests
- Identification tests
- User interaction tests

Manufacturers may self-certify or submit modules for independent testing.

Section 5 - Revision History

| Version | Date | Description |
Update append method;
- 1.0.1 — Minor corrections or clarifications
- 1.1.0 — Addition of new module family (e.g., MPS-D or MPS-U)
- 2.0.0 — Breaking changes to interfaces or mechanical envelope

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| 1.0.0 | July 2026 | Initial release of the Modular Power Standard – Rechargeable (MPS-R). Includes Core Specification, Universal Electrical Interface, Universal Mechanical Interface, MPS-Q Module Specification, MPS-S Module Specification, MPS-H Module Specification, Reference Design Packages, and Compliance Notes. |

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