WHITEPAPER

Engineering Long-Life Battery-Powered Smart Water Meters

Part 3 — Ultra-Low-Power Hardware Architecture

A Systems Engineering Approach to Battery Life in Advanced Metering Infrastructure

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Part	3 of 7 — **Ultra-Low-Power Hardware Architecture** Whitepaper Series: ☐ Part 1 Understanding Battery Life and the Battery Life Budget ☐ Part 2 Battery Chemistry and Energy Storage ☑ **Part 3** **Ultra-Low-Power Hardware Architecture** ☐ Part 4 Firmware as the Energy Manager ☐ Part 5 Battery Life Qualification and Validation ☐ Part 6 From Laboratory to Field: Achieving Real-World Battery Life ☐ Part 7 Practical Recommendations and the Future of Long-Life Smart Water Metering
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"Firmware manages energy. Hardware determines how much energy is available to manage"

3.1 Hardware Determines the Energy Baseline

Battery life is frequently associated with firmware optimisation and communication scheduling. While both are important, the foundation of long-life operation is established much earlier—during hardware architecture design.

Every resistor, regulator, sensor, memory device, communication module, and protection circuit contributes to the product's total energy consumption.

Unlike firmware, which can often be updated after deployment, hardware decisions are largely permanent once the product enters production.

Consequently, poor hardware architecture cannot usually be corrected through firmware optimisation alone.

An efficient firmware running on an inefficient hardware platform will always be constrained by the hardware's baseline energy consumption.

Every Microampere Matters

For products expected to operate continuously for ten to fifteen years, seemingly insignificant standby currents accumulate into substantial energy consumption.

Consider two otherwise identical smart water meters:

Parameter	Design A	Design B
Sleep Current	**2 µA**	**8 µA**
Difference	—	+6 µA

A difference of only a few microamperes may appear insignificant during laboratory testing.

However, over ten years of continuous operation, this additional current represents a measurable reduction in the available battery energy.

For long-life battery-powered products, **every unnecessary microampere becomes part of the Battery Life Budget**.

This is why experienced hardware engineers often spend considerable effort reducing quiescent current by fractions of a microampere.

Hardware Establishes the Minimum Energy Consumption

Before the firmware executes a single instruction, the hardware already defines:

- Sleep current
- Leakage current

- Regulator quiescent current
- Battery monitoring current
- Sensor standby current
- Memory standby current
- Protection circuit current
- Oscillator current

These currents exist continuously throughout the product lifetime.

Unlike communication events, they cannot be avoided.

Instead, they must be minimised during hardware design.

Energy Efficiency Begins During Schematic Design

Ultra-low-power products are rarely created through optimization at the end of development.

Instead, power efficiency should be considered from the earliest stages of system architecture.

Typical hardware design questions include:

- Does this component remain powered continuously?
- Can this peripheral be completely disconnected when idle?
- Is this regulator's quiescent current acceptable for a ten-year product?
- Can unnecessary pull-up resistors be eliminated?
- Does the battery monitoring circuit consume current continuously?
- Can leakage paths be reduced through PCB layout?

Answering these questions early often provides greater battery life improvements than later firmware optimisation.

Think in Terms of Lifetime Energy

Traditional hardware design often focuses on:

- Functionality
- Performance
- Cost
- Manufacturability

For long-life smart water meters, an additional design criterion should be introduced:

> **Lifetime energy cost**

Every continuously powered component should justify its contribution to the product.

If a component consumes only 1 μA continuously, it will operate every second of every day throughout the service life.

Viewed over ten years, that tiny current becomes part of the permanent Battery Life Budget.

This mindset encourages engineers to evaluate every circuit not only by what it does, but also by how much lifetime energy it requires.

Engineering Insight

Ultra-low-power products are designed one microampere at a time. Small improvements in standby current accumulate into significant gains over the product lifetime.

Practitioner Observation

During hardware design reviews, attention often focuses on processor selection or communication modules. In practice, cumulative standby current from voltage regulators, monitoring circuits, pull-up networks, sensors, and memory devices frequently determines the baseline energy consumption of the entire product. Reducing these continuous currents early in development is usually easier and more effective than attempting to recover the same energy through firmware optimization later.

Key Takeaways

- Hardware architecture establishes the baseline energy consumption of the product.
- Every continuously powered component contributes to the Battery Life Budget.
- Small reductions in standby current accumulate over many years.
- Ultra-low-power design begins during system architecture and schematic development.
- Firmware optimization cannot fully compensate for inefficient hardware.

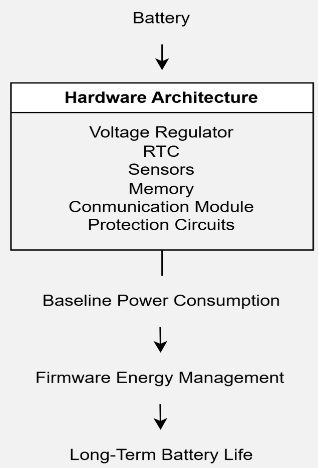

Figure 3.1 — Hardware Establishes the Energy Baseline

Hardware architecture establishes the minimum energy consumption of the system. Firmware optimization builds upon this baseline but cannot eliminate inefficient hardware design.

3.2 Quiescent Current Optimisation

Quiescent current is often one of the first specifications quoted when evaluating the power consumption of a battery-powered product.

However, for long-life smart water meters, quiescent current should not be viewed as a single measurement.

Instead, it is the cumulative result of every circuit that remains active while the device is in its lowest-power operating state.

Understanding where this current originates is one of the most important steps towards achieving a long operational lifetime.

What Is Quiescent Current?

Quiescent current represents the continuous current consumed by the product while no active processing or communication is taking place.

Although the microcontroller may be asleep, many supporting circuits remain powered.

Typical contributors include:

- Voltage regulators

- Real-Time Clock (RTC)
- Battery monitoring circuits
- Memory devices
- Sensors
- Leakage through GPIOs
- Pull-up and pull-down resistors
- Communication module standby current
- PCB leakage paths

The total sleep current is therefore the sum of many small contributors rather than a single component.

The Hidden Contributors

During design reviews, engineers often focus on selecting an ultra-low-power microcontroller.

While this is important, the MCU is frequently **not** the dominant contributor during sleep mode.

Examples of hidden current sources include:

Voltage Regulators

Selecting a regulator with an unnecessarily high quiescent current can permanently increase standby consumption throughout the product lifetime.

Battery Voltage Measurement

Some battery monitoring circuits continuously consume current.

A better approach is often to enable the measurement circuit only when battery voltage is required.

External Sensors

Many sensors support standby or shutdown modes.

Keeping sensors continuously powered without necessity increases lifetime energy consumption.

Pull-up Networks

Pull-up resistors appear insignificant individually.

However, inappropriate resistor values or permanently enabled pull-ups can contribute measurable standby current over many years.

Communication Modules

Cellular and RF communication modules often provide multiple sleep states.

Selecting the correct low-power mode can significantly reduce standby current.

Leakage Current Is Often Overlooked

Even when all active circuitry has been optimised, leakage current may still reduce battery life.

Common sources include:

- PCB contamination
- Moisture
- Flux residue
- Poor PCB layout
- ESD protection devices
- Reverse leakage through semiconductor junctions

These currents may only be measured in nanoamperes or microamperes, but they remain present continuously throughout the service life.

Consequently, manufacturing quality can directly influence battery performance.

Measure the Whole System

One of the most common mistakes during qualification is measuring the current consumption of individual components while neglecting the complete assembled product.

Engineers should measure:

- Complete PCB
- Complete firmware
- Complete communication module
- Battery monitoring circuit
- All enabled peripherals

Only system-level measurements accurately represent the Battery Life Budget.

Optimisation Is an Iterative Process

Reducing quiescent current is rarely achieved through a single design change.

Instead, engineering teams typically perform multiple optimisation cycles:

1. Measure baseline current.
2. Identify dominant contributors.
3. Modify hardware.
4. Update firmware if necessary.
5. Re-measure.
6. Repeat until further improvements become insignificant.

This iterative approach often yields substantial improvements before production release.

Engineering Insight

Quiescent current is not determined by the microcontroller alone. It is the sum of every circuit that remains alive while the product sleeps.

Practitioner Observation

During ultra-low-power optimisation, significant improvements are often achieved not by replacing the processor, but by identifying overlooked standby loads such as battery monitoring circuits, pull-up networks, communication modules, or leakage paths. The final microampere is usually the hardest to eliminate because it requires understanding the behaviour of the complete hardware system rather than individual components.

Key Takeaways

- Quiescent current is the sum of all continuously powered circuits.
- Voltage regulators, monitoring circuits, sensors, and leakage paths often dominate standby current.
- Manufacturing quality can influence long-term leakage current.
- System-level measurements provide a more accurate representation of standby consumption than individual component measurements.
- Ultra-low-power optimization is an iterative engineering process.

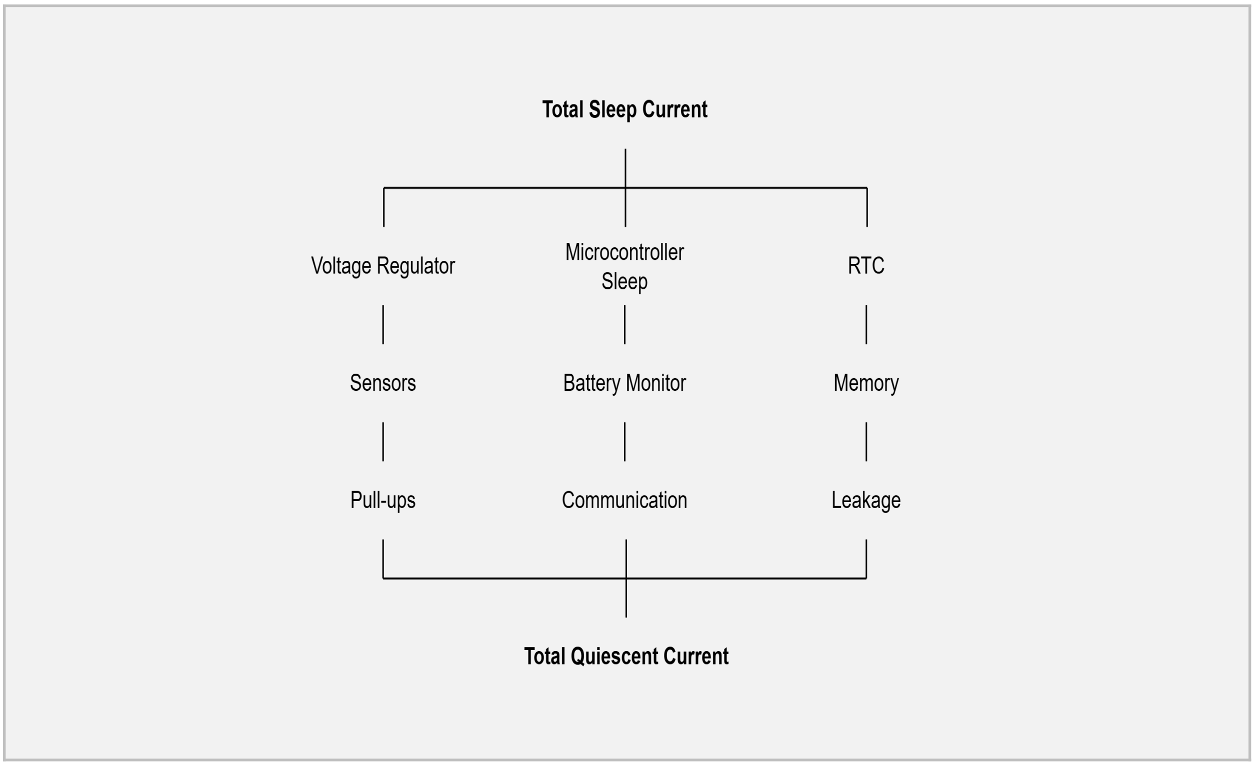

Figure 3.2 — Sources of Quiescent Current

Total quiescent current is the cumulative contribution of all circuits that remain active during sleep mode. Reducing standby current requires optimisation of the complete hardware system rather than a single component.

3.3 Power Domain Architecture

Ultra-low-power smart water meters are not achieved simply by selecting low-power components.

They are achieved by ensuring that components consume power **only when they are required**.

One of the most effective methods of reducing long-term energy consumption is the use of carefully designed **power domains**, allowing sections of the hardware to be completely disconnected from the battery when idle.

Rather than attempting to reduce the current consumption of every component individually, power domain architecture eliminates unnecessary current altogether.

What Is a Power Domain?

A power domain is a group of electronic circuits that share a common power supply and can be controlled independently of other parts of the system.

Instead of energising the entire product continuously, the system powers only the hardware required for the current operating task.

For example, a smart water meter may contain separate power domains for:

- Microcontroller
- Communication module
- Sensor interface
- External memory
- Battery measurement circuitry
- Display or user interface (where applicable)

Each domain can then be switched on or off according to operational requirements.

Always-On Versus Switched Power

Not every circuit should remain powered continuously.

A useful design exercise is to classify every circuit into one of two categories.

Always-On Circuits

These remain powered throughout the product lifetime because they support essential low-power operation.

Typical examples include:

- Real-Time Clock (RTC)
- Backup registers
- Essential MCU sleep domain
- Watchdog (if required)

These circuits should be designed to consume the lowest practical current.

Switched Power Domains

These are powered only when required.

Typical examples include:

- Cellular modem
- RF transceiver
- External sensors
- EEPROM or Flash memory
- Diagnostic LEDs
- Programming interfaces
- User displays

Once the required operation has been completed, power should be removed completely rather than leaving the device in an idle state.

Power Gating Versus Sleep Mode

Many integrated circuits provide low-power sleep modes.

While useful, sleep mode does not necessarily eliminate power consumption.

Engineers should therefore distinguish between:

Sleep Mode

- Internal circuitry remains partially powered.
- Some functions remain active.
- Current consumption is reduced but not eliminated.

Power Gating

- Supply voltage is physically disconnected.
- Current consumption approaches zero (excluding leakage).
- The device restarts when power is restored.

Where operationally acceptable, power gating generally provides the lowest long-term energy consumption.

However, it also introduces additional design considerations such as start-up time, state restoration, and communication reinitialisation.

Design for Predictable Wake-Up Behaviour

Removing power from a subsystem is only beneficial if the wake-up process is reliable.

Engineers should evaluate:

- Power stabilisation time
- Oscillator start-up delay
- Sensor warm-up requirements
- Communication module boot time
- Firmware initialisation sequence
- Battery voltage stability during power-up

A poorly designed wake-up sequence may consume more energy than it saves.

Consequently, power domain design should always be considered together with firmware scheduling.

Communication Modules Deserve Special Attention

For NB-IoT and LTE Cat 1 bis smart water meters, the communication module is often the largest consumer of energy.

During transmission, instantaneous current may exceed several hundred milliamperes.

For this reason, communication modules should normally remain completely unpowered except during:

- Scheduled reporting
- Alarm transmission
- Remote configuration
- Firmware updates
- Diagnostic sessions

Keeping a communication module permanently energised, even in idle mode, can significantly reduce operational lifetime.

Hardware and Firmware Must Work Together

Power domain architecture cannot be designed independently of firmware.

Hardware determines **what can be switched off**.

Firmware determines **when it should be switched off**.

Successful ultra-low-power products therefore require close collaboration between hardware and firmware engineering teams.

Engineering Insight

> **The lowest power consumption is achieved not by placing unused hardware into sleep mode, but by ensuring it consumes no power at all whenever practical.**

Practitioner Observation

In long-life AMI product development, significant battery life improvements are frequently achieved through system partitioning rather than component replacement. Separating high-energy peripherals into independently controlled power domains allows hardware to remain completely unpowered for the vast majority of the product's lifetime. This architectural approach often delivers larger gains than attempting to optimise already efficient components.

Key Takeaways

- Power domains allow hardware to consume energy only when required.
- Always-on circuits should be minimised and highly optimised.
- Switched power domains reduce unnecessary standby consumption.
- Power gating generally provides greater energy savings than sleep mode alone.
- Hardware partitioning and firmware scheduling must be designed together.

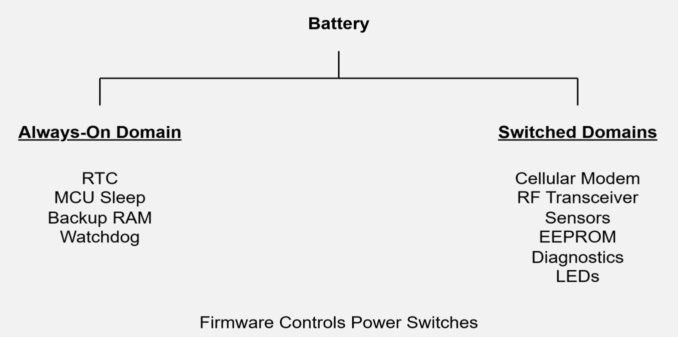

Figure 3.3 — Example Power Domain Architecture

> *Separating hardware into independently controlled power domains allows high-energy subsystems to remain completely unpowered until required, reducing overall energy consumption throughout the product lifecycle.*

3.4 Voltage Regulators: The Silent Energy Consumer

Every battery-powered smart water meter relies on a stable power supply to operate reliably.

Although voltage regulators are often regarded as supporting components, they remain active throughout much of the product's operational life and therefore make a continuous contribution to the Battery Life Budget.

Unlike communication modules, which consume energy intermittently, the voltage regulator may remain operational twenty-four hours a day for more than a decade.

Consequently, even small differences in regulator characteristics can accumulate into measurable differences in long-term battery performance.

Selecting a Regulator Is More Than Choosing an Output Voltage

During component selection, engineers often compare regulators based on:

- Output voltage
- Maximum output current
- Package size
- Cost

For ultra-low-power products, these criteria are only part of the decision.

Engineers should also evaluate:

- Quiescent current (Iq)
- Shutdown current
- Dropout voltage
- Load transient response
- Start-up behaviour
- Operating temperature range
- Long-term stability
- Reverse leakage characteristics

These parameters directly influence both energy consumption and system reliability.

Quiescent Current Never Sleeps

The quiescent current of a voltage regulator is consumed continuously whenever the regulator is enabled, regardless of whether the downstream circuitry is active.

Consider two regulators supplying the same hardware:

Parameter	Regulator A	Regulator B
Quiescent Current	**800 nA**	**8 µA**

The difference is only **7.2 µA**.

At first glance, this appears insignificant.

However, because this current is drawn continuously throughout the service life, the cumulative energy consumption over ten to fifteen years becomes substantial.

For long-life smart water meters, selecting an ultra-low-Iq regulator can therefore deliver greater lifetime benefit than optimising a circuit that operates only for a few seconds each day.

One Regulator Does Not Fit Every Power Domain

Many smart water meters contain multiple power domains with different electrical requirements.

For example:

Power Domain	Design Priority
MCU Sleep Domain	Ultra-low quiescent current
Cellular Modem	High peak current capability
Sensors	Fast start-up
Memory	Stable voltage during writes
RTC	Low long-term drift

Attempting to power all domains from a single regulator may simplify the schematic but often reduces overall efficiency.

Instead, different regulators may be selected for different functional domains according to their operating requirements.

Consider Shutdown Behaviour

Many regulators provide an **enable (EN)** input that allows the output to be disabled when the associated subsystem is not required.

However, engineers should verify:

- Shutdown current
- Output leakage
- Reverse current protection
- Wake-up delay
- Output discharge characteristics

Some regulators continue to consume measurable current even when disabled.

Consequently, enabling and disabling regulators should be validated during hardware qualification rather than assumed from the datasheet alone.

Dropout Voltage Matters Near End-of-Life

As the battery gradually discharges over many years, its terminal voltage decreases.

The regulator must continue operating correctly during this period.

If the dropout voltage is too high:

- Available battery capacity may not be fully utilised.
- Early low-voltage shutdown may occur.
- Effective service life may be shortened.

Selecting a regulator with an appropriate dropout characteristic therefore allows more of the battery's stored energy to remain usable before end-of-life.

Validate Under Dynamic Loads

Modern communication technologies create rapidly changing load conditions.

During NB-IoT transmission, current demand may increase from microamperes to hundreds of milliamperes within milliseconds.

Voltage regulators should therefore be evaluated under:

- Peak transmission current
- Rapid load transitions
- Cold-start conditions
- Battery ageing
- Low battery voltage
- High operating temperatures

Qualification should verify not only average efficiency but also voltage stability during dynamic operating conditions.

Engineering Insight

> **A voltage regulator is not simply a power supply component. It continuously shapes the Battery Life Budget by determining how efficiently stored energy is delivered throughout the product's lifetime.**

Practitioner Observation

During design optimisation, attention is often focused on reducing processor sleep current by a few hundred nanoamperes. In many cases, selecting a regulator with significantly lower quiescent current or better shutdown performance provides a larger reduction in overall standby consumption. System-level optimisation therefore requires evaluating the regulator with the same rigour applied to the microcontroller.

Key Takeaways

- Voltage regulators contribute continuously to battery energy consumption.
- Ultra-low quiescent current is critical for long-life products.
- Different power domains may require different regulator characteristics.
- Shutdown current and dropout voltage should be considered alongside quiescent current.
- Dynamic load testing is essential for communication-intensive AMI devices.

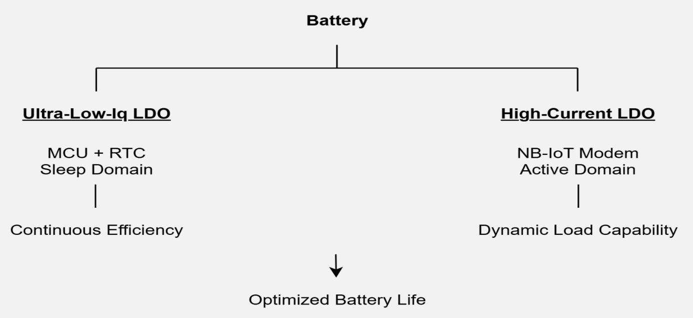

Figure 3.4 — Regulator Considerations in an Ultra-Low-Power Architecture

Different functional domains often require different regulator characteristics. Matching the regulator to the operating profile improves both energy efficiency and system reliability.

3.5 Battery Voltage Monitoring Without Wasting Energy

Monitoring battery voltage is essential for long-life smart water meters.

Utilities rely on battery status to support preventive maintenance, replacement planning, and operational monitoring. Firmware also uses battery voltage information to determine when to generate low-battery alarms, adjust operating behaviour, or initiate controlled end-of-life procedures.

However, obtaining this information also consumes energy.

If the battery monitoring circuit itself continuously draws current, it permanently reduces the energy available for the rest of the product's operational life.

For ultra-low-power systems, battery measurement should therefore be designed to consume energy only when the measurement is actually required.

Why Battery Monitoring Is Necessary

Battery voltage provides valuable information throughout the product lifecycle.

Typical applications include:

- Low battery warning
- Remaining battery estimation
- Battery health trending
- Field diagnostics
- Firmware decision making
- Utility maintenance planning
- Production testing

Without periodic battery measurements, utilities lose visibility into one of the most critical components of the smart meter.

The challenge is to acquire this information with minimal impact on battery life.

The Hidden Cost of Continuous Voltage Dividers

One of the simplest methods of measuring battery voltage is to connect a resistive voltage divider directly across the battery.

Although electrically straightforward, this approach creates a continuous current path from the battery to ground.

That current flows:

- During operation
- During sleep
- During storage
- Every second of the product's service life

Over ten to fifteen years, even a small divider current becomes a permanent entry in the Battery Life Budget.

For products targeting very long operational lifetimes, continuously powered voltage dividers should therefore be evaluated carefully.

Measure Only When Necessary

A more energy-efficient approach is to enable the battery measurement circuit only when a voltage reading is required.

This may be achieved using:

- MCU-controlled MOSFET switching
- Analogue switches
- Dedicated battery monitor enable signals
- GPIO-controlled measurement paths

The measurement sequence typically follows these steps:

1. Enable the voltage divider.
2. Allow the voltage to stabilise.
3. Perform ADC conversion.
4. Store or transmit the measurement if required.
5. Disable the measurement circuit.

The circuit then consumes virtually no current until the next scheduled measurement.

How Often Should Battery Voltage Be Measured?

More frequent measurements do not necessarily provide greater operational value.

For many utility applications:

- Daily measurement is sufficient.
- Weekly trending may be adequate.
- Battery alarms may only require periodic verification.

Measurement frequency should therefore be determined by operational requirements rather than technical capability.

Every unnecessary measurement consumes additional energy through:

- Divider current
- ADC operation
- MCU processing
- Memory updates
- Potential communication overhead

Voltage Alone Does Not Reveal Remaining Battery Life

Battery voltage is an important indicator, but it should not be interpreted as a direct measure of remaining capacity.

Several factors influence measured voltage, including:

- Instantaneous load current
- Battery temperature
- Battery chemistry
- State of charge
- Internal resistance
- Cell ageing

For example, a battery measured immediately after an NB-IoT transmission may exhibit a temporary voltage drop that recovers after the load is removed.

Likewise, low ambient temperatures may reduce terminal voltage without indicating permanent capacity loss.

For this reason, battery voltage should be interpreted together with operating conditions rather than in isolation.

Engineering Recommendations

Battery monitoring circuits should:

- Consume negligible current when idle.
- Measure only when operationally necessary.
- Allow sufficient settling time before ADC conversion.
- Record measurements under consistent conditions where practical.
- Be validated across temperature and battery ageing conditions.

This ensures battery monitoring remains a useful diagnostic tool without becoming a significant contributor to battery consumption.

Engineering Insight

A battery monitoring circuit should consume as little energy measuring the battery as possible. Otherwise, the act of measurement becomes part of the problem it is intended to solve.

Practitioner Observation

During ultra-low-power optimisation, battery monitoring circuits are sometimes overlooked because they appear electrically simple. However, continuously powered voltage dividers or unnecessarily frequent measurements can consume measurable energy over the service life of the product. In long-life AMI devices, battery monitoring should be treated as another energy consumer within the Battery Life Budget and optimised accordingly.

Key Takeaways

- Battery monitoring is essential for reliable long-term operation.
- Continuous voltage dividers can become permanent energy drains.
- Measurement circuits should be enabled only when required.
- Measurement frequency should be driven by operational needs, not technical capability.
- Battery voltage should be interpreted alongside load conditions, temperature, and battery ageing.

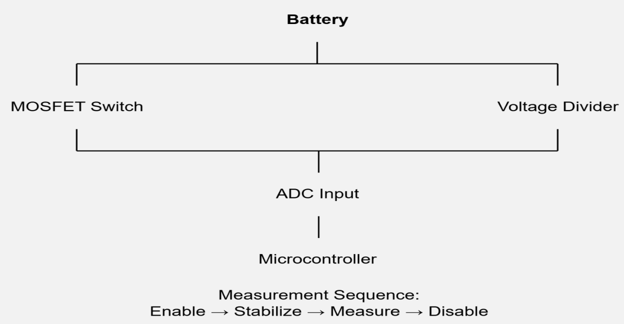

Figure 3.5 — Energy-Efficient Battery Voltage Measurement
Switching the battery measurement circuit on only when required minimises standby energy consumption while maintaining accurate battery monitoring throughout the product lifecycle.

3.6 Brownout Protection and Reliable Low-Voltage Operation

A smart water meter should continue operating reliably throughout its intended service life, including when the battery approaches the end of its usable capacity.

As battery voltage gradually declines over many years, electronic circuits become increasingly vulnerable to unstable operation. If the supply voltage falls below the minimum operating requirement of the microcontroller or memory devices, unpredictable behaviour may occur.

Without appropriate protection, low-voltage conditions can lead to corrupted data, incomplete memory writes, communication failures, or unexpected system resets.

For this reason, brownout protection should be regarded as both a **reliability feature** and an **energy management feature**.

What Is a Brownout?

A brownout occurs when the battery voltage falls below the minimum level required for reliable circuit operation but does not fall low enough to completely remove power.

Unlike a total power loss, a brownout places the system in an uncertain operating region where digital circuits may no longer function predictably.

Potential consequences include:

- MCU executing invalid instructions
- Corrupted EEPROM or Flash writes
- Incorrect metering calculations
- Communication failures
- Unexpected resets
- Incomplete firmware updates
- Loss of event logs

For utility infrastructure expected to operate unattended for many years, such failures are unacceptable.

Brownout Is Not Only an End-of-Life Event

Many engineers associate brownout conditions solely with battery depletion.

In practice, temporary voltage drops may also occur during normal operation.

Examples include:

- NB-IoT network attachment
- Cellular transmission bursts
- Firmware OTA updates
- Cold battery conditions
- Aged batteries with increased internal resistance
- High-current peripheral startup

These short-duration voltage dips may briefly reduce battery voltage below the brownout threshold even though significant battery capacity remains.

System design should therefore consider both **temporary voltage sag** and **true end-of-life battery depletion**.

Brownout Detection

Most modern ultra-low-power microcontrollers include Brownout Detection (BOD) or Brownout Reset (BOR) circuitry.

When enabled, these functions monitor the supply voltage and automatically reset or halt processor operation if voltage falls below a defined threshold.

Properly configured brownout detection helps prevent:

- Execution of corrupted instructions
- Invalid memory writes
- Software lock-up
- Unpredictable processor behaviour

Although the brownout detector itself consumes a small amount of current, the reliability benefits generally outweigh the additional energy cost for infrastructure products.

Protect Critical Operations

Certain operations should never be interrupted by insufficient supply voltage.

Examples include:

- EEPROM writes
- Flash programming
- Firmware updates
- Calibration data storage
- Meter index updates
- Configuration changes

Firmware should verify that sufficient battery voltage is available before initiating these operations.

If battery voltage falls below a safe operating threshold, the operation should be postponed until adequate power is available.

Controlled End-of-Life Behaviour

As battery capacity approaches depletion, the objective should not simply be to keep the product running for as long as possible.

Instead, the product should degrade gracefully while preserving essential metering functionality.

Typical end-of-life strategies include:

- Generate low battery alarms.
- Reduce communication frequency.
- Suspend non-essential diagnostics.
- Disable energy-intensive background functions.
- Prioritise meter reading accuracy.
- Preserve event logs.
- Maintain safe shutdown behaviour.

These measures help maximise the useful remaining battery energy while avoiding unpredictable failures.

Brownout Protection Is Part of the Battery Life Budget

At first glance, brownout protection appears unrelated to battery life.

In reality, it plays an important role in ensuring that the remaining battery energy is used effectively.

Without controlled low-voltage operation:

- Failed communication attempts waste energy.
- Corrupted memory writes require repetition.
- Endless processor reset loops consume unnecessary power.
- Recovery procedures may consume more energy than successful operations.

By preventing these failure modes, brownout protection indirectly improves the efficiency of the Battery Life Budget.

Engineering Insight

> **The final months of a battery's life are just as important as the first. Good engineering ensures that remaining energy is used predictably, not wasted recovering from unstable operation.**

Practitioner Observation

Brownout behaviour is often validated only under slowly declining laboratory power supplies. In real deployments, however, battery voltage can fluctuate rapidly during high-current communication events or when ageing batteries encounter low temperatures. Qualification testing should therefore include dynamic voltage conditions representative of actual field operation, ensuring that the product remains stable under realistic supply variations.

Key Takeaways

- Brownout conditions may occur before complete battery depletion.
- Temporary voltage sag during communication is an important design consideration.
- Brownout detection protects system integrity and stored data.
- Critical write operations should be performed only when adequate battery voltage is available.
- Controlled end-of-life behaviour improves reliability and makes better use of the remaining battery energy.

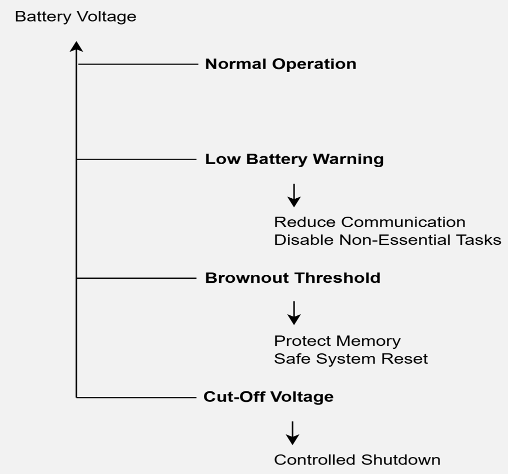

Figure 3.6 — Brownout Management Strategy

A controlled brownout strategy allows the smart water meter to preserve data integrity, maintain essential functionality, and avoid unpredictable behaviour as battery voltage approaches end-of-life.

3.7 Capacitor Selection for Pulse Current Support

Battery-powered smart water meters typically operate with extremely low average current consumption.

For much of their operational life, the system remains in a low-power sleep state, waking only periodically to perform measurements or communicate with the utility backend.

However, during wireless communication, current demand may increase by several orders of magnitude within a very short period.

These rapid transitions place significant stress on the power supply system.

The battery alone may not always be able to respond instantaneously to these transient current requirements.

For this reason, capacitors play an essential role in maintaining voltage stability during high-current events.

Why Capacitors Matter

A battery is an energy storage device, but it is not an ideal voltage source.

Every battery exhibits:

- Internal resistance
- Electrochemical response delay
- Voltage drop under load

When a communication module suddenly demands hundreds of milliamperes, the battery voltage may temporarily decrease before the electrochemical reaction can supply the required current.

A properly selected capacitor acts as a local energy reservoir, supplying part of the transient current while the battery responds.

This helps maintain a stable supply voltage during communication.

Pulse Loads in Smart Water Meters

Typical high-current events include:

- NB-IoT network attachment
- LTE Cat 1 bis transmission
- RF transmission bursts
- GNSS acquisition (where applicable)
- Firmware OTA updates
- Initial modem startup

Although these events are relatively brief, they often represent the highest instantaneous current demand experienced by the entire system.

Without adequate energy buffering, the resulting voltage drop may trigger:

- Brownout reset
- Communication failure
- Modem restart
- Incomplete transmission
- Increased retry attempts

Ironically, repeated retries may consume far more battery energy than the original transmission.

Bulk Capacitors and Decoupling Capacitors

Different capacitors perform different functions within the power architecture.

Bulk Capacitors

Bulk capacitors provide short-term energy storage during high-current events.

Their primary role is to:

- Reduce voltage sag
- Support transmission bursts
- Improve system stability

- Reduce battery stress

These capacitors are typically placed close to the communication module power supply.

Decoupling Capacitors

Decoupling capacitors operate at much shorter time scales.

They suppress:

- High-frequency switching noise
- Processor transients
- Oscillator disturbances
- Local voltage fluctuations

Every major integrated circuit should include appropriate local decoupling according to the manufacturer's recommendations.

Capacitor Selection Is a System Decision

Simply increasing capacitor size does not always improve system performance.

Engineers should evaluate:

- Capacitance value
- Equivalent Series Resistance (ESR)
- Equivalent Series Inductance (ESL)
- Voltage rating
- Temperature stability
- Ageing characteristics
- Physical size
- PCB placement

For example, a capacitor with insufficient ESR characteristics may perform poorly during rapid current transients despite having a large nominal capacitance.

Likewise, poor PCB layout can reduce the effectiveness of even the highest-quality capacitor.

Capacitors Do Not Increase Battery Capacity

A common misconception is that adding more capacitance extends battery life.

In reality, capacitors do not create additional energy.

Instead, they help the system **use the available battery energy more effectively** by:

- Reducing unnecessary voltage collapse.
- Preventing failed communication attempts.

- Minimising modem restarts.
- Improving transmission reliability.

This distinction is important.

Capacitors improve energy utilisation, not stored energy.

Validate Under Real Communication Conditions

Capacitor selection should always be validated using realistic operating conditions.

Qualification testing should include:

- Actual communication modules
- Production firmware
- Representative transmission profiles
- Aged batteries
- Low battery voltage
- High and low temperatures

Laboratory bench testing with constant current loads alone cannot accurately represent the highly dynamic behaviour of wireless communication systems.

Engineering Insight

> **Capacitors do not make the battery larger. They allow the battery to deliver its energy more effectively during demanding transient events.**

Practitioner Observation

During communication-intensive applications such as NB-IoT smart metering, many field failures attributed to "weak batteries" are actually caused by inadequate transient power delivery. Appropriate capacitor selection, combined with good PCB layout and realistic qualification testing, often resolves these issues without changing the battery itself.

Key Takeaways

- Communication modules create rapid transient current demands.
- Capacitors support these short-duration events by providing local energy storage.
- Bulk and decoupling capacitors perform different functions.
- Capacitor selection should consider ESR, ageing, and placement as well as capacitance.
- Capacitors improve energy utilisation rather than battery capacity.

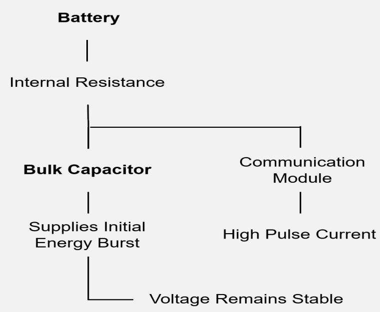

Figure 3.7 — Capacitor Supporting Communication Pulse Loads
During high-current communication events, a bulk capacitor provides immediate transient energy while the battery responds to the increased load, helping maintain voltage stability and reliable operation.

3.8 PCB Layout and Leakage Control

The electrical performance of an ultra-low-power smart water meter is determined not only by the components selected, but also by how those components are physically implemented.

A carefully designed schematic can still exhibit excessive standby current if the printed circuit board (PCB) introduces unintended leakage paths, poor grounding, excessive parasitic effects, or environmental contamination.

For products expected to operate unattended for more than a decade, PCB layout should therefore be regarded as an integral part of the Battery Life Budget.

Leakage Current Is a Physical Phenomenon

Leakage current is often associated with semiconductor devices.

However, unintended current paths can also develop across the PCB itself.

Typical contributors include:

- Flux residue after soldering
- Moisture absorption
- Surface contamination
- Dust accumulation
- Ionic residues
- Condensation
- Poor insulation spacing

These effects are often insignificant in consumer electronics with short service lives.

For long-life utility infrastructure, however, leakage currents of only a few hundred nanoamperes may persist continuously for many years.

Tropical Environments Increase the Challenge

ASEAN deployments present environmental conditions that differ significantly from controlled laboratory environments.

Smart water meters may experience:

- High relative humidity
- Heavy rainfall
- Flood-prone installations
- Underground meter chambers
- Condensation cycles
- Elevated ambient temperatures

These conditions increase the likelihood of surface leakage and corrosion over time.

Consequently, PCB design should account for long-term environmental exposure rather than relying solely on initial laboratory measurements.

Good PCB Layout Supports Low-Power Operation

Ultra-low-power PCB layout should aim to minimise unintended current flow while maintaining signal integrity.

Recommended practices include:

- Keep high-impedance analogue traces short.
- Separate analogue and digital return paths where appropriate.
- Minimise unnecessary copper around sensitive measurement nodes.
- Reduce parasitic leakage between adjacent conductors.
- Ensure adequate creepage and clearance distances.
- Position decoupling capacitors close to device supply pins.
- Minimise loop area for high-current communication paths.

These practices improve both measurement accuracy and long-term power efficiency.

Moisture Protection Matters

For outdoor utility deployments, environmental protection is equally important.

Depending on product requirements, engineers may consider:

- Conformal coating
- Protective enclosure sealing
- Venting strategies to minimise condensation
- Corrosion-resistant materials

- Controlled manufacturing cleanliness

These measures reduce the likelihood of leakage current developing during years of field exposure.

However, protective coatings should also be evaluated for manufacturability, repairability, and long-term compatibility with the enclosure design.

Validate with Real Hardware

PCB-related leakage cannot always be predicted through simulation.

Validation should therefore include:

- Fully assembled production PCBs
- Representative enclosure configurations
- High-humidity testing
- Temperature cycling
- Long-duration standby measurements
- Visual inspection for contamination

Where possible, measurements should be repeated after environmental testing to confirm that standby current remains within specification throughout the product lifecycle.

Manufacturing Quality Is Part of Power Optimisation

Low-power performance is influenced not only by design engineers but also by manufacturing processes.

Factors such as:

- PCB cleaning quality
- Flux removal
- Assembly workmanship
- Component placement
- Inspection procedures

can all affect long-term standby current.

Consequently, battery life should be viewed as a responsibility shared across design, manufacturing, and quality engineering teams.

Engineering Insight

> **An ultra-low-power schematic can become a high-power product if the PCB introduces unintended leakage paths. Battery life depends on physical implementation as much as electrical design.**

Practitioner Observation

During product development, standby current is often measured immediately after PCB assembly under clean laboratory conditions. However, leakage behaviour may change after prolonged exposure to humidity, contamination, or temperature cycling. Qualification testing should therefore verify standby current both before and after environmental stress testing to ensure that low-power performance is maintained throughout the intended service life.

Key Takeaways

- PCB layout directly influences long-term standby current.
- Leakage current may originate from contamination, moisture, or poor layout.
- Tropical environments require additional attention to environmental protection.
- Manufacturing quality affects battery life as well as product reliability.
- Environmental validation should include long-duration standby current measurements.

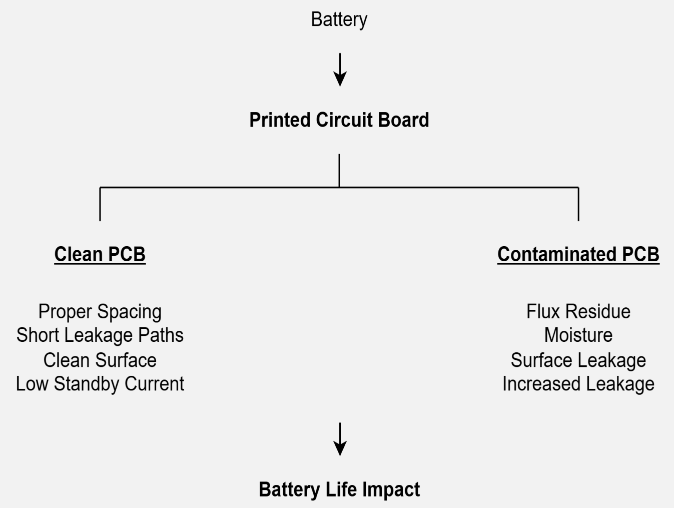

Figure 3.8 — PCB Leakage Mechanisms

PCB cleanliness, environmental exposure, and layout quality influence standby current over the operational lifetime of the product. Preventing leakage paths is an important aspect of ultra-low-power hardware design.

Summary

Hardware architecture establishes the foundation of battery life long before firmware optimisation begins.

Throughout this part of the whitepaper, we examined how engineering decisions relating to quiescent current, power domain partitioning, voltage regulators, battery monitoring, brownout protection, transient power delivery, and PCB implementation collectively determine the baseline energy consumption of a smart water meter.

A recurring principle has been that **every continuously powered circuit becomes part of the Battery Life Budget**. Reducing unnecessary standby current, eliminating avoidable leakage, and ensuring that peripherals consume power only when required can collectively extend operational life far more effectively than focusing on any single component.

Equally important, long-term battery performance depends not only on circuit design but also on manufacturing quality, environmental protection, and system validation under realistic operating conditions. Ultra-low-power engineering is therefore a multidisciplinary effort involving hardware design, firmware development, PCB implementation, manufacturing, and qualification testing.

The next part of the whitepaper builds upon this hardware foundation by examining **firmware power management**—how intelligent software scheduling, sleep strategies, and communication control determine when energy is consumed and how efficiently the available Battery Life Budget is allocated throughout the product lifecycle.

Disclaimer

The views and observations expressed in this paper are the author's own and are intended for general industry discussion and educational purposes. They are based on publicly available research, practical engineering experience, and regional industry observations, and do not represent the official position, product commitments, customer relationships, or commercial practices of any employer, client, utility, or affiliated organisation. Utilities should evaluate deployment decisions within their own operational, technical, regulatory, and procurement context.

About the Author

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Vincent Wong brings over **25 years of engineering and product leadership experience** across industrial infrastructure and technology sectors, with the past decade focused on smart metering, Advanced Metering Infrastructure (AMI), and NB-IoT deployment strategies in ASEAN utility environments. As a senior engineering and product development executive, his work spans hardware engineering, connectivity systems, and utility digitalization initiatives. His writing focuses on the practical operational, connectivity, deployment, and governance realities of smart utility programs in Southeast Asia.

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