

A Multi-Scale Electromagnetic and Hybrid Energy Harvesting Theory for Near-Continuous Portable Power Systems

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Research Article

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ABSTRACT

The growing demand for portable energy in off-grid environments highlights the limitations of conventional battery-based systems, which rely on finite stored energy and periodic recharging. While energy harvesting offers an alternative, existing approaches remain constrained by single-source dependence and low energy density, particularly in electromagnetic (RF) harvesting. This study proposes a multi-scale hybrid energy harvesting theory that integrates solar, kinetic, RF, and micro-scale energy sources within a unified framework. The model is grounded in the principle that energy availability is determined by the time-integrated accumulation of power rather than instantaneous output. A system-level architecture incorporating hybrid storage and adaptive energy management is developed and evaluated through time-domain simulation. Results show that, although individual sources are insufficient independently, their combined effect significantly improves energy stability and extends operational lifetime. The proposed Energy Continuity Principle establishes a pathway toward near-continuous portable power through multi-scale energy integration.

Keywords: Multi-scale energy harvesting; Hybrid energy systems; RF energy harvesting; Energy continuity principle; Portable power systems.

INTRODUCTION

The increasing global demand for reliable portable energy, particularly in off-grid and resource-constrained environments, has intensified research into alternative energy generation and storage mechanisms. Conventional portable energy systems, predominantly based on electrochemical storage such as lithium-ion batteries, are inherently constrained by finite energy capacity and require periodic recharging from centralized power sources. This dependency limits their effectiveness in remote, mobile, or infrastructure-deficient settings (Priya & Inman, 2009; Paradiso & Starner, 2005).

In response, energy harvesting technologies have emerged as a promising paradigm, aiming to extract usable electrical energy directly from ambient environmental sources. These include solar radiation, mechanical motion, thermal gradients, and electromagnetic (radio frequency, RF) fields. Among these, solar energy harvesting offers relatively high power density but is inherently intermittent and dependent on environmental conditions. Conversely, RF energy harvesting provides a continuous but extremely low-power energy source, typically in the

microwatt to milliwatt range under ambient conditions (Lu et al., 2015; Visser & Vullers, 2013).

Despite significant advances, current energy harvesting systems remain fundamentally limited by two key challenges. First, most implementations rely on single-source harvesting architectures, which are highly susceptible to environmental variability and intermittency. Second, the low energy density of individual ambient sources, particularly electromagnetic harvesting, restricts their ability to independently sustain modern portable electronic devices. As a result, existing systems are often constrained to niche applications such as wireless sensor networks rather than high-demand portable electronics.

This study addresses these limitations by proposing a fundamentally different conceptual framework. Rather than treating energy sources as isolated contributors, we introduce a multi-scale hybrid energy harvesting theory, in which energy is continuously captured and accumulated across multiple physical scales macroscopic (e.g., solar), mesoscopic (e.g., mechanical), and microscopic (e.g., electromagnetic and nano-scale phenomena). These energy contributions are not only aggregated but also dynamically managed through intelligent storage architectures and adaptive switching mechanisms.

The central premise of this work is that energy sustainability in portable systems is not solely determined by instantaneous power availability, but by the cumulative integration of diverse energy inputs over time. By leveraging this principle, the proposed framework seeks to transform low-density, intermittent energy sources into a collectively viable and near-continuous energy supply system.

FOUNDATIONAL ENERGY FRAMEWORK

The proposed system is grounded in the fundamental definition of energy as the time integral of power. For any physical system, the total accumulated energy over a time interval $[0, T]$ is given by:

$$E(T) = \int_0^T P(t) dt$$

This expression establishes a critical insight: energy availability is not solely determined by instantaneous power, but by the cumulative effect of power over time. This becomes particularly important in low-power energy harvesting systems, where individual sources may

provide insufficient instantaneous power but become significant when integrated over extended durations.

Conservation of Energy and System Constraints

From the first law of thermodynamics, the rate of change of energy within the system is governed by:

$$\frac{dE_{sys}}{dt} = P_{in}(t) - P_{out}(t) - P_{loss}(t)$$

This relationship imposes a strict physical constraint:

$$P_{out}(t) \leq \eta_{sys} \cdot P_{in}(t)$$

where $\eta_{sys} \in (0,1)$ represents the overall system efficiency.

This constraint is essential in distinguishing the proposed framework from non-physical “self-generating” systems. The present work does not violate thermodynamic laws; rather, it optimizes energy capture, accumulation, and redistribution.

Electromagnetic Energy as a Harvestable Resource

Electromagnetic waves carry energy that can be described through classical field theory. The energy density of an electromagnetic field is given by:

$$u = \frac{1}{2} \epsilon E^2 + \frac{1}{2\mu} B^2$$

The directional flow of this energy is represented by the Poynting vector:

$$S = \frac{1}{\mu} E \times B$$

The magnitude of S represents the power flux density (W/m²) incident on a receiving structure, forming the theoretical basis for electromagnetic energy harvesting (Balanis, 2016).

For a receiving antenna with effective aperture A_{eff} , the captured power is:

$$P_{rf}(t) = \eta_{ant} \cdot A_{eff} \cdot |S(t)|$$

RF Propagation and Received Power Model

Under far-field conditions, the received power from a transmitter can be approximated using the Friis transmission equation:

$$P_{rx} = P_t G_t G_r \left(\frac{\lambda}{4\pi d} \right)^2$$

This expression highlights the rapid decay of electromagnetic power with distance d , explaining why ambient RF harvesting yields relatively low power levels (Visser & Vullers, 2013; Lu et al., 2015).

However, in realistic environments, multiple RF sources contribute simultaneously. Thus, the total harvested RF power is expressed as:

$$P_{rf}(t) = \eta_{rf} \sum_{i=1}^N P_{rx,i}(t)$$

Multi-Scale Hybrid Energy Model (Core Contribution)

The central theoretical contribution of this work is the formulation of a multi-scale hybrid energy harvesting model, in which total harvested power is expressed as the superposition of multiple energy domains:

$$P_h(t) = P_{sol}(t) + P_{kin}(t) + P_{rf}(t) + P_{\mu}(t)$$

where:

- P_{sol} : macroscopic solar energy input
- $P_{kin}(t)$: mesoscopic mechanical/kinetic energy
- $P_{rf}(t)$: electromagnetic RF energy
- $P_{\mu}(t)$: microscopic/nano-scale energy contributions

This formulation extends conventional hybrid systems by explicitly incorporating multi-scale energy aggregation.

Solar Energy Contribution

Solar harvesting is modelled as:

$$P_{sol}(t) = \eta_{pv} \cdot A \cdot G(t)$$

where:

- A : photovoltaic surface area
- $G(t)$: incident irradiance
- η_{pv} : conversion efficiency

Solar energy provides the dominant power contribution under favourable conditions (Khan et al., 2017).

Kinetic Energy Contribution

Mechanical energy harvesting is derived from classical mechanics:

$$P_{kin}(t) = \eta_{kin} \cdot F(t) \cdot v(t)$$

where $F(t)$ and $v(t)$ represent force and velocity, respectively. This term captures energy generated from motion, vibration, or rotational systems.

Micro/Nano-Scale Energy Accumulation

At the microscopic scale, energy storage follows the capacitive relation:

$$E = \frac{1}{2} CV^2$$

Although individual contributions are extremely small, aggregation across many micro-scale elements yields:

$$P_{\mu}(t) = \eta_{\mu} \sum_{j=1}^M p_{\mu,j}(t)$$

This term represents contributions from:

- nano-rectennas
- micro-capacitive structures
- ultra-low-power electromagnetic interactions

Energy Accumulation Principle

The total harvested energy over time is:

$$E_h(T) = \int_0^T P_{h(t)} dt$$

This leads to a critical theoretical insight:

Even low-power energy sources become significant when integrated over time.

Energy Continuity Condition

For sustained system operation, the following condition must be satisfied:

$$P_h(t) + P_{storage}(t) \geq P_{load}(t)$$

This defines the **minimum requirement for continuous functionality**.

Dual-Bank Energy Dynamics

To maintain continuity, the system employs dual storage units:

$$E_A(t + \Delta t) = E_A(t) + (P_{in,A} - P_{load})\Delta t$$

$$E_B(t + \Delta t) = E_B(t) + P_{in,B}\Delta t$$

This enables:

- simultaneous charging and discharging
- reduced downtime
- improved energy availability

The Energy Continuity Principle (New Concept)

From the above derivations, we define:

Energy Continuity Principle:

A system achieves sustained operation when the time-integrated harvested energy equals or exceeds the time-integrated load demand, regardless of instantaneous power limitations.

Mathematically:

$$\int_0^T P_h(t)dt \geq \int_0^T P_{load}(t)dt$$

The developed framework demonstrates that the limitation of individual energy harvesting methods can be overcome through multi-scale integration and temporal accumulation. While RF and nano-scale sources provide minimal instantaneous power, their continuous availability complements intermittent high-power sources such as solar energy. This theoretical integration transforms the design paradigm from high power, short duration systems to low power, long-duration sustainable systems.

METHODOLOGY

Research Design Framework

This study adopts a system-level modeling and simulation-based methodology, supported by theoretical derivation and component-level design. The approach is structured to validate the proposed multi-scale hybrid energy harvesting theory through controlled simulation of energy flows, storage dynamics, and load interactions.

The methodology is organized into three interconnected stages:

1. Mathematical modelling of energy sources and system dynamics
2. System architecture design and integration of harvesting subsystems
3. Simulation and performance evaluation under varying environmental conditions

This multi-layered approach is consistent with prior research in hybrid energy harvesting systems, where analytical models are coupled with simulation frameworks to evaluate feasibility and performance (Lu et al., 2015; Khan et al., 2017).

System Architecture Definition

The proposed system consists of four primary energy harvesting subsystems integrated into a unified architecture:

- Solar Energy Subsystem (macroscopic scale)
- Kinetic Energy Subsystem (mesoscopic scale)
- RF Energy Harvesting Subsystem (electromagnetic scale)
- Micro/Nano Energy Accumulation Subsystem (microscopic scale)

These subsystems are connected through a shared energy management and storage framework, comprising:

- A super-capacitor buffer layer for rapid charge accumulation
- A dual-bank lithium-ion storage system for sustained energy delivery
- A power management unit (PMU) for regulation and control

The architecture enables simultaneous energy harvesting, storage, and delivery, thereby operationalizing the energy continuity principle established in the Theory section.

Mathematical Modeling of Energy Sources

Each energy source is modelled as a time-dependent power function, consistent with the theoretical framework:

Solar subsystem:

$$P_{sol}(t) = \eta_{pv} \cdot A \cdot G(t)$$

Kinetic subsystem:

$$P_{kin}(t) = \eta_{kin} \cdot F(t) \cdot v(t)$$

RF subsystem:

$$P_{rf}(t) = \eta_{rf} \sum_{i=1}^N P_{rx,i}(t)$$

Micro-scale subsystem:

$$P_{\mu}(t) = \eta_{\mu} \sum_{j=1}^M p_{\mu,j}(t)$$

The total harvested power is:

$$P_h(t) = \sum P_i(t)$$

These models form the basis of the simulation environment.

RF Harvesting Subsystem Implementation

The RF harvesting unit is modelled based on a rectenna architecture, consisting of:

- A multi-band antenna (covering 900 MHz–2.4 GHz)
- An impedance matching network
- A Schottky diode rectifier (voltage doubler configuration)
- A smoothing capacitor and DC output stage

The rectified output power is computed as:

$$P_{rf,out}(t) = \eta_{rect} \cdot P_{rf,in}(t)$$

where η_{rect} includes matching and rectification losses.

To reflect real-world conditions, RF input power is modeled as a low-amplitude, time-varying signal, consistent with ambient electromagnetic environments (Visser & Vullers, 2013).

Energy Storage and Management Strategy

The system incorporates a hybrid storage mechanism consisting of:

1. Super-capacitor Layer
 - Rapid charge/discharge
 - Captures intermittent and low-power inputs

- Modelled using:

$$E = \frac{1}{2} CV^2$$

2. Dual-Bank Battery System

- Two independent storage units (A and B)
- Alternating roles: charging vs. discharging

Energy evolution is described as:

$$E_A(t + \Delta t) = E_A(t) + (P_{in,A} - P_{load})\Delta t$$

$$E_B(t + \Delta t) = E_B(t) + P_{in,B}\Delta t$$

Switching logic is implemented based on state-of-charge thresholds.

Simulation Environment

The system is implemented in **MATLAB/Simulink**, where time-domain simulations are performed to evaluate system performance.

Simulation Inputs:

- Solar irradiance profile $G(t)$
- Mechanical excitation profile $F(t), v(t)$
- RF power density profile
- Load demand profile $P_{load}(t)$

Simulation Time Horizon:

- 24-hour cycle
- Extended multi-day scenarios

Performance Metrics

System performance is evaluated using the following metrics:

Total harvested energy

$$E_h = \int_0^T P_h(t) dt$$

Energy continuity ratio

$$\gamma = \frac{\int_0^T P_h(t) dt}{\int_0^T P_{load}(t) dt}$$

Where:

- $\gamma \geq 1 \rightarrow$ continuous operation
- $\gamma < 1 \rightarrow$ energy deficit

Source Contribution Ratio

$$\alpha_i = \frac{\int_0^T P_i(t) dt}{E_h}$$

This evaluates the contribution of:

- solar
- kinetic
- RF
- micro-scale sources

Storage Stability

- Battery state-of-charge over time
- Super-capacitor voltage variation

Output Reliability

$$R = \frac{T}{t_{active}}$$

Where:

- t_{active} : time system meets load demand

Validation Strategy

The proposed system is validated through:

1. **Comparative analysis**
 - Hybrid system vs. solar-only
 - Hybrid system vs. battery-only
2. **Sensitivity analysis**
 - Variation in RF power density
 - Variation in solar availability
 - Load fluctuation scenarios
3. **Stress testing**
 - Low-energy environments
 - Intermittent harvesting conditions

Methodological Contribution

The methodology advances existing approaches by:

- Integrating multi-scale energy models into a unified simulation framework
- Introducing energy continuity as a measurable performance metric
- Combining theoretical derivation with system-level validation

RESULTS AND DISCUSSION

Overview of Simulation Outcomes

The performance of the proposed multi-scale hybrid energy harvesting system was evaluated through a 24-hour time-domain simulation, designed to reflect realistic environmental and operational conditions. The simulation incorporated time-varying solar irradiance, periodic load demand, and continuous low-level contributions from RF and kinetic energy sources. Within this framework, two primary system responses were analyzed, namely the relationship between harvested power and load demand, and the temporal evolution of stored battery energy.

Harvested Power and Load Interaction

The simulation results reveal that the total harvested power, $P_h(t)$, is strongly influenced by solar irradiance, particularly during daylight hours. In this regime, the harvested power can be approximated as:

$$P_h(t) \approx P_{sol}(t) + P_{kin}(t) + P_{rf}(t)$$

This indicates that solar energy constitutes the dominant component of the energy mix, with kinetic and RF contributions acting as supplementary inputs. The harvested power reaches its maximum during peak irradiance conditions, confirming the macroscopic dominance of solar energy within the hybrid framework.

However, despite this peak, the harvested power does not consistently exceed the system load during high-demand intervals, such that:

$$P_h(t) < P_{load}(t)$$

during load spikes. This demonstrates that even under optimal solar conditions, the system is not capable of sustaining continuous operation without reliance on stored energy.

Following sunset, the solar contribution diminishes to negligible levels, and the harvested power reduces to:

$$P_h(t) \approx P_{kin}(t) + P_{rf}(t)$$

In this regime, the remaining energy sources provide continuous but low-level input, which is insufficient to meet the load demand independently. Nevertheless, these contributions play a

critical role in slowing the rate of energy depletion, highlighting their importance within the hybrid system.

Battery Energy Evolution

The temporal evolution of the battery state of energy, defined as:

$$SoE(t) = \frac{E_b(t)}{E_{b,max}}$$

provides further insight into system dynamics. At the initial stage, the battery undergoes discharge due to the condition:

$$\frac{dE_b}{dt} < 0,$$

where the load demand exceeds the harvested energy. As solar input increases during daylight hours, the rate of discharge is significantly reduced, approaching a quasi-equilibrium condition:

$$P_h(t) \approx P_{load}(t).$$

This results in a quasi-stable operating region, observed approximately between 5 and 10 hours, where the battery energy decreases at a minimal rate. Such behavior indicates partial realization of the energy continuity condition.

However, after sunset, the harvested power becomes substantially lower than the load demand:

$$P_h(t) \ll P_{load}(t),$$

leading to rapid battery depletion. Ultimately, the battery reaches zero energy, marking system failure under continuous load conditions.

Energy Continuity Analysis

The theoretical condition for sustained operation is given by:

$$\int_0^T P_h(t)dt \geq \int_0^T P_{load}(t)dt$$

The simulation results indicate that this condition is not fully satisfied for the selected system parameters. Nevertheless, the hybrid system significantly delays the point of failure compared to single-source systems.

This leads to a critical insight:

While full energy autonomy is not achieved, the integration of multiple energy sources substantially extends the operational lifetime of the system.

Contribution of Energy Sources

The contribution of each energy source is quantified using the ratio:

$$\alpha_i = \frac{\int_0^T P_i(t)dt}{\int_0^T P_h(t)dt}$$

Analysis of the simulation reveals that solar energy remains the dominant contributor, while kinetic energy provides moderate supplemental input and RF energy contributes a small but continuous baseline.

From a system perspective, RF energy functions as a background stabilizer, ensuring persistent low-level energy input. Kinetic energy introduces intermittent bursts, while solar energy provides the primary charging mechanism. This distribution validates the proposed multi-scale hybrid energy framework.

System-Level Interpretation

The results confirm several key theoretical implications. First, multi-source integration significantly improves system stability by reducing the rate of battery depletion and mitigating fluctuations in available power. Second, the principle of energy accumulation over time is validated, as even low-power contributions from RF and kinetic sources become meaningful when integrated over extended durations:

$$E = \int P(t)dt$$

Third, the system demonstrates partial realization of the energy continuity condition:

$$P_h(t) + P_{storage}(t) \approx P_{load}(t),$$

although this balance is not consistently maintained under all conditions.

Limitations and System Constraints

Despite its advantages, the system exhibits several limitations. The low energy density of RF harvesting restricts its impact on overall system performance. Additionally, the system remains highly dependent on solar availability, leading to energy deficits during nighttime periods. Furthermore, the load demand in the simulation exceeds the combined harvesting capacity, highlighting the need for improved system design.

Pathways for System Improvement

To achieve near-continuous operation, several enhancements are required. Increasing overall system efficiency (η_{sys}) would directly improve energy utilization. Expanding the photovoltaic capture area would increase solar input, while advancements in RF harvesting such as multi-band antennas, higher gain structures, and improved rectification efficiency could enhance electromagnetic energy capture. Additionally, the integration of intelligent energy management strategies, including adaptive load control and AI-driven scheduling, could further optimize system performance.

Final Scientific Positioning

The results provide strong support for the central thesis of this work. The proposed multi-scale hybrid energy harvesting system does not eliminate the fundamental limitations of energy availability; rather, it transforms intermittent and low-density energy sources into a collectively viable and adaptive energy ecosystem. This paradigm shift represents a significant step toward the realization of near-continuous portable energy systems.

CONCLUSION

This study presented a unified theoretical and system-level framework for multi-scale hybrid energy harvesting, aimed at enabling near-continuous energy availability in portable and off-grid applications. Departing from conventional single-source harvesting paradigms, the proposed approach integrates energy capture across macroscopic, mesoscopic, and microscopic domains, including solar, kinetic, electromagnetic (RF), and micro-scale capacitive mechanisms.

From a foundational perspective, the work establishes that energy sustainability in portable systems is governed not solely by instantaneous power availability, but by the time-integrated accumulation of diverse energy inputs. This insight led to the formulation of the Energy Continuity Principle, which defines the condition under which sustained system operation becomes feasible. By rigorously grounding the framework in thermodynamic constraints, the study avoids non-physical assumptions while demonstrating how intelligent system design can maximize usable energy from ambient sources.

The theoretical development was supported by a system-level simulation, which revealed that while no individual harvesting mechanism is sufficient to sustain moderate power loads independently, their combined effect significantly enhances system performance. In particular, solar energy was observed to provide the dominant contribution under favorable conditions, while RF and kinetic sources contributed continuous low-level input that reduced the rate of energy depletion. This multi-source interaction resulted in improved energy stability, extended operational lifetime, and partial realization of energy continuity.

Importantly, the findings highlight a critical paradigm shift: the objective of portable energy systems should not be framed as achieving infinite or self-sustaining energy generation, but rather as constructing adaptive energy ecosystems capable of dynamically balancing harvesting, storage, and consumption. Within this context, RF and micro-scale energy harvesting although individually limited play a crucial role in enhancing system resilience and continuity when integrated within a broader multi-scale architecture.

The study also identifies key limitations, including the low energy density of ambient electromagnetic sources, dependence on environmental conditions such as solar availability, and the mismatch between harvested energy and high-demand load profiles. These challenges underscore the need for further advancements in energy conversion efficiency, storage technologies, and intelligent power management strategies.

Future research directions include the development of multi-band and high-efficiency rectenna systems, optimization of hybrid storage architectures combining batteries and supercapacitors, and the integration of nano-scale rectifying materials capable of extending energy harvesting into higher-frequency electromagnetic domains. Additionally, the incorporation of adaptive control algorithms, potentially leveraging artificial intelligence, offers a promising pathway for real-time optimization of energy flow and system performance.

his work contributes a mathematically grounded, physically consistent, and system-oriented framework for hybrid energy harvesting, advancing the field beyond fragmented single-source approaches. While the realization of fully autonomous portable energy systems remains constrained by fundamental physical limits, the proposed multi-scale paradigm provides a viable and scalable pathway toward near-continuous energy availability, with significant implications for next-generation portable electronics, remote sensing systems, and energy access in underserved environments.

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