



ENERGY HARVESTING TECHNOLOGIES FOR RAILWAY SENSOR SYSTEMS: A COMPARATIVE ANALYSIS BY APPLICATION AND DEPLOYMENT LOCATION

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Abstract – Supplying distributed railway sensor systems is challenging at remote and difficult-to-access locations where wired power is impractical and battery replacement increases maintenance requirements. This paper compares representative energy harvesting systems according to sensor application and deployment location. Piezoelectric, electromagnetic, photovoltaic, thermoelectric, magnetic-field and radiofrequency solutions are considered for different railway deployment locations. The systems are compared using reported power or energy output, operating conditions, sensor application and level of experimental validation. The results show that technology selection depends on source availability, installation constraints and sensor-node energy requirements, with some solutions enabling intermittent batteryless operation, while others supplement battery power or remain at the laboratory-validation stage. Efficient power management and energy storage, long-term field testing, and consistent reporting of energy performance are required for reliable assessment and wider railway deployment.

Keywords – railway sensor systems, energy harvesting, deployment location, wireless sensor nodes, autonomous power supply.

1. INTRODUCTION

Railway condition monitoring uses sensor measurements to support maintenance planning [1]. Applications include bridge strain and displacement monitoring [2], axle-box and bearing temperature monitoring [3], and rail vibration measurement [4]. Supplying these sensors can be difficult where electrical connections are unavailable or battery replacement requires access to remote installations [1, 2].

Energy harvesting offers locally available power for distributed sensing. Reviews cover diverse railway energy sources and conversion technologies [1, 5], but selecting a practical supply also requires relating published results to the intended monitoring task.

This paper examines representative energy harvesting systems for different railway applications and deployment locations. The systems were selected to cover different energy sources and installation

environments for which quantitative performance data and information on experimental validation are available. The analysis connects installation constraints and reported electrical performance with demonstrated sensor functionality, distinguishing evidence from laboratory experiments, field measurements and integrated monitoring systems. The objective is to clarify which conclusions about practical suitability are supported by the available tests.

2. ENERGY SOURCES AND CONVERSION TECHNOLOGIES

Piezoelectric harvesters generate electrical charge when their active elements deform under mechanical loading [6]. In vibration-driven electromagnetic harvesters, relative motion between a magnet and a coil induces a voltage; mechanical transmissions can also drive a generator [7, 8].

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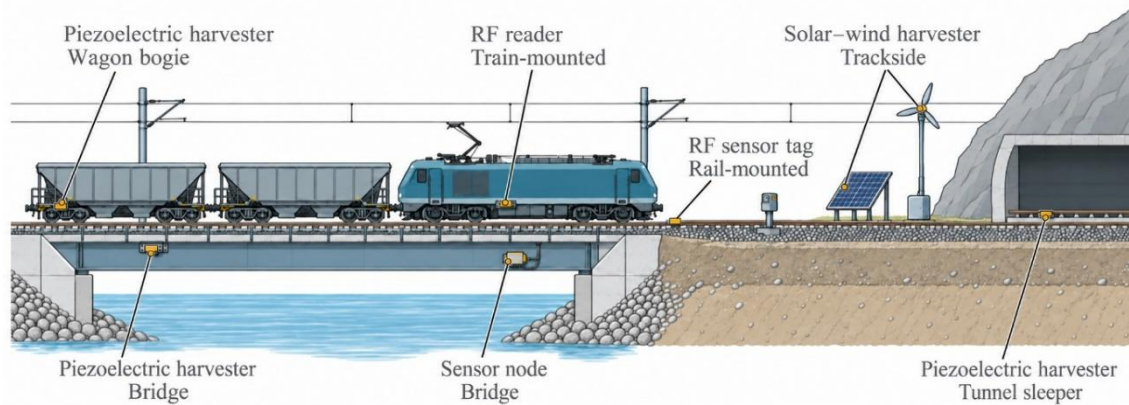


Fig. 1. Schematic illustration of energy harvesters and sensor-system components at representative railway installation locations

Photovoltaic devices convert incident solar radiation into electrical energy [9, 10]. Airflow can drive a turbine coupled to a generator or deform a piezoelectric element [11, 12]. Combining a photovoltaic panel with a wind turbine creates a hybrid system using two energy sources [12].

Thermoelectric generators exploit a temperature difference across their elements [13]. Magnetic-field harvesters use the alternating magnetic field associated with traction return currents [14, 15]. Although they also employ electromagnetic induction, their excitation comes from an externally varying field, without requiring mechanical motion to drive a generator [14].

Radiofrequency (RF) systems receive electromagnetic energy through an antenna and convert it into a DC electrical supply using rectifying circuitry [16]. Ambient RF harvesting uses existing signals, whereas dedicated RF power transfer relies on a transmitter provided for that purpose [16].

Figure 1 schematically illustrates selected energy harvesters and sensor-system components at representative railway installation locations.

3. COMPARISON BY APPLICATION AND DEPLOYMENT LOCATION

The comparison considers installation requirements, the sensor operation supported by the available energy, and experimental validation. Differences in excitation, device design and evaluation methods prevent direct ranking of published outputs [1, 5].

On freight wagons, two piezoelectric systems illustrate different installation conditions. A compact piezoelectric harvester for the restricted space of an axle box was tuned to low-frequency lateral vibrations. It powered commercial wireless sensors in laboratory tests, and its durability was evaluated on a full-scale wagon roller rig [17]. A separate bogie-mounted harvester was field-tested during an eight-hour journey as supplemental power for a node intended to monitor

axle-box and bearing temperature [3]. A photovoltaic wagon node was evaluated through charging measurements, node consumption and almost one year of field monitoring at half-hour intervals [10]. These studies therefore differ in installation location, validation level and whether the harvested energy powers the sensor directly or supplements stored energy.

For track installations, an electromagnetic system demonstrated wireless sensor operation during laboratory replay of recorded railway vibrations [7]. A piezoelectric device for tunnel sleepers was also tested with recorded train excitation, but sensor and radio integration remained future work [18]. The former demonstrates an operational load, while the latter establishes an energy resource requiring further system integration.

On electrified tracks, the magnetic-field device in [15] was evaluated by combining field magnetic measurements with laboratory characterisation to estimate electrical output; an integrated sensor node was not demonstrated in service. In the RF approach, a train-mounted reader supplies energy and receives vibration data from a rail-mounted tag, with tests performed on a scaled railway system [4]. Its operating opportunity is therefore linked to reader-tag interaction.

Bridge monitoring illustrates how energy replenishment determines measurement timing. A piezoelectric system accumulated energy before activating strain and displacement nodes, with approximately 2.6 J required per activation [2]. Its field demonstration supports periodic observations. An airflow harvester proposed for bridge wind barriers was evaluated through wind-tunnel experiments and numerical analysis [11], providing less direct evidence of complete monitoring-node operation.

Table 1 summarises the quantitative results, applications and validation conditions of representative systems.

Tab. 1. Comparison of selected railway energy harvesting systems

Ref.	Location / technology	Reported performance / test conditions	Application / validation
[3]	Wagon bogie / piezoelectric	$\approx 60 \mu\text{W}$; vibrations at 4–10 Hz	Temperature monitoring; battery supplementation; onboard tests
[10]	Freight wagon / photovoltaic	Charging limited to $\approx 40 \text{ mW}$ in direct sunlight; mean node consumption $\approx 2 \text{ mW}$	Condition monitoring; almost one year of field testing
[7]	Track / electromagnetic	Mean power 9.1–29.3 mW; energy 77–167 mJ per replayed train passage	Laboratory vibration replay; wireless sensor demonstrated
[15]	Rail / magnetic field	Laboratory: 184–5178 mW at 100–500 A; estimated $1138 \pm 1603 \text{ mJ/train}$ from field data	Laboratory tests; output estimated from field magnetic measurements
[4]	Rail tag / RF	Activation up to 2.3 m; maximum conversion efficiency 25%	Vibration sensing; dedicated reader; scaled-system tests
[2]	Bridge / piezoelectric	Energy demand $\approx 2.6 \text{ J}$ per activation; mean interval 57–59 min	Strain and displacement monitoring; field demonstration
[18]	Tunnel sleeper / piezoelectric	Mean 260 μJ per replayed train passage	Laboratory vibration replay; complete node integration pending
[13]	Rail-ground / thermoelectric	Field: 5.8 mW at $\Delta T = 8 \text{ }^\circ\text{C}$; lab: 316.8 mW at $\Delta T = 29.2 \text{ }^\circ\text{C}$	Field and laboratory tests; charging demonstrated
[12]	Trackside / solar-wind	Mean 12.31 W at 17.5 m/s and 1700 W/m^2	Laboratory tests; sensor power supply proposed

Note: Reported power, harvested energy, node demand, and RF transfer characteristics are different metrics and are not directly comparable.

At exposed trackside locations, photovoltaic and hybrid solar-wind devices have been investigated for railway equipment and wireless sensors [9, 12]. The hybrid output was measured under specified laboratory airflow and irradiance conditions and cannot be assumed continuously available [12]. The rail-ground thermoelectric study demonstrated battery charging, with field and laboratory outputs obtained at different temperature differences [13]. These results establish source and charging performance within the tested conditions, rather than a verified sensing schedule.

Across the considered deployment locations, the practical applicability of a technology is determined less by the maximum output power of the energy harvesting system than by whether sufficient energy is available when required and whether system operation has been demonstrated under the complete sensing and communication load.

4. FUTURE RESEARCH DIRECTIONS

Power-management research should address the energy consumed within the supply system itself. Storage leakage can reduce the energy retained between sensor activations [2], making low-loss storage and low standby consumption important design objectives. Future experiments should separately measure losses in rectification, voltage conversion, and storage, and evaluate whether the system can restart after its stored energy has been depleted. Control strategies should also be tested for their ability to adjust

sensing and transmission intervals while meeting the application's minimum monitoring requirements.

Mechanical durability, environmental resistance, and economic feasibility are further priorities for railway deployment [5]. Extended field trials should track changes in output, mounting integrity, and component condition under repeated loading and exposure to temperature variations, moisture, and dust. Economic assessment should include installation and maintenance costs alongside the battery replacements and service visits avoided. This would establish whether a technically functional device offers a practical benefit over its expected service life.

For future evaluations, this review proposes a common reporting framework that specifies the excitation or environmental conditions, the period over which power is averaged, and the point in the electrical circuit where output is measured. Results should additionally state usable stored energy, consumption per complete sensing and communication cycle, and the proportion of scheduled measurements successfully delivered. Recording interruptions and recovery times would provide a measurable basis for assessing the continuity of the monitoring service.

5. CONCLUSION

Energy harvesting can reduce dependence on conventional power supplies in railway sensing, but its contribution varies with the application and installation location. The reviewed systems support different

outcomes, from battery supplementation to intermittent sensor operation, with unequal levels of experimental validation. Technology selection should therefore begin with the required measurements and their timing, followed by an assessment of locally available energy and installation constraints. Demonstrated operation of the complete sensor node provides the clearest basis for judging practical suitability. Consistent reporting of energy availability, system losses, and energy consumption per complete sensing and communication cycle would enable more reliable comparison between technologies. Claims of energy autonomy should remain tied to the operating conditions and monitoring functions actually demonstrated.

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