Energy Innovations

Power from Within: The Promise of Thermoelectric Wearables

Background Information

The increasing integration of wearable electronics in healthcare, fitness, and environmental monitoring has intensified the demand for reliable, autonomous, and sustainable power sources (Wang et al., 2018). As global population rises and portable electronics usage expand, pressure on conventional energy sources increases correspondingly (Ochieng et al., 2022). The surge in energy demand, combined with concerns over fossil fuel dependency and environmental pollution, has prompted stricter emissions regulations and a heightened pursuit of clean, decentralized, and low-carbon technologies (Ochieng et al., 2022). This has driven interest in energy-harvesting systems capable of converting ambient energy into usable electrical power. Among these, thermoelectric generators (TEGs) offer a promising solution for low-power wearable applications by converting body heat directly into electricity via the Seebeck effect (Wang et al., 2018). Compact, silent, and solid-state, TEGs provide continuous, maintenance-free energy generation without reliance on external charging or chemical fuels. Thus, TEGs represent a leading innovation in wearable energy harvesting, aligning with the growing need for decentralised and sustainable power solutions.

Thermoelectric Generators (TEGs)

TEGs convert heat flow generated by a temperature difference directly into usable electrical energy, ensuring high reliability for applications such as waste heat recovery, remote power generation, and wearable energy harvesting. This conversion is driven by the Seebeck effect. The Seebeck effect is a thermoelectric phenomenon that harnesses a temperature gradient to convert thermal energy into electrical energy. This effect occurs when two junctions of dissimilar conductors or semiconductors are subjected to differing temperatures, leading to the generation of a voltage or electric potential difference (Zhu, Yu & Li, 2019). In semiconductor-based configurations, p-type and n-type materials are used. P-type semiconductors contain an abundance of holes, which are the absence of electrons and function as positive charge carriers, while n-type semiconductors are rich in delocalised electrons, which act as negative charge carriers (Zhu, Yu & Li, 2019). When a temperature gradient is applied, with one junction heated and the other cooled, electrons in the n-type region diffuse from the hot side toward the cooler p-type region, while thermally excited holes in the p-type region similarly migrate toward the cooler n-type region (Zhu, Yu & Li, 2019). Although both charge carriers diffuse from hot to cold, they move in opposite directions due to their opposite charges and differing material properties. This differential diffusion establishes charge separation and an internal electric field, producing an electromotive force and a measurable voltage via the Seebeck effect (Zhu, Yu & Li, 2019).

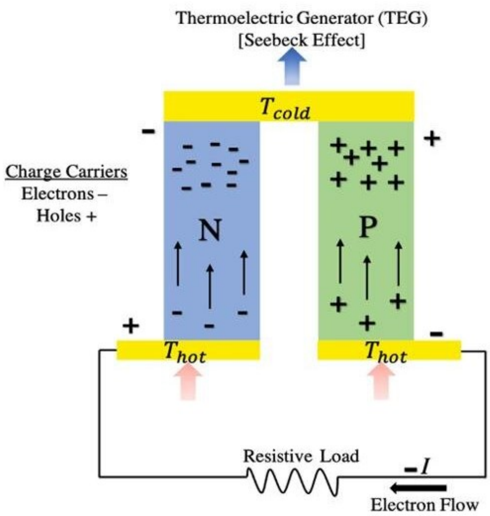


Figure 1. Schematic diagram of the Seebeck effect (Jaafar Ali.Mahdi et al., 2025).

This effect is quantified by the Seebeck coefficient (denoted as $\boldsymbol{\alpha}$), which measures a material's ability to convert a temperature difference into electrical voltage (Prunet et al., 2021). It is defined by the relation:

$$\boldsymbol{a} = -\frac{\Delta \boldsymbol{V}}{\Delta \boldsymbol{T}} = \frac{\boldsymbol{V_{hot}} - \boldsymbol{V_{cold}}}{\boldsymbol{T_{hot}} - \boldsymbol{V_{cold}}}$$

where ΔV is the voltage generated and ΔT is the temperature difference across the material (Prunet et al., 2021). The negative sign reflects the conventional direction of voltage relative to the temperature gradient, depending on the type of charge carriers (Prunet et al., 2021).

The efficiency of thermoelectric materials is measured by a dimensionless figure of merit (***ZT***):

$$\boldsymbol{ZT} = \frac{\boldsymbol{a}^2}{\boldsymbol{kp}}\boldsymbol{T}$$

where $\boldsymbol{\alpha}$ is the Seebeck coefficient, $\boldsymbol{k}$ is thermal conductivity, $\boldsymbol{p}$ is electrical resistivity, and $\boldsymbol{T}$ is absolute temperature (Ryu et al., 2023; Zhu, Yu & Li, 2019).

An ideal thermoelectric material is one that efficiently converts heat into electricity. To achieve this, it must possess three key properties: high Seebeck coefficient, low thermal conductivity, and low electrical resistivity (Zhu, Yu & Li, 2019). A high Seebeck coefficient increases voltage generation, improving power output (Jaziri et al., 2019). A low thermal conductivity helps sustain the temperature gradient across the material by limiting how quickly heat flows from the hot side to the cold side. This is imperative as the Seebeck effect relies on the presence of a sustained temperature difference (Zhu, Yu & Li, 2019). A low electrical resistivity minimises energy loss as heat by reducing resistance to current flow, thereby allowing more electrical energy to be delivered efficiently to the external circuit (Jaziri et al., 2019).

Possessing the three key properties, semiconductors offer a more favourable balance for thermoelectric applications than metals, as their electrical and thermal conductivities can be adjusted independently (Zhu, Yu & Li, 2019). Metals exhibit low electrical resistivity, high thermal conductivity, and low Seebeck coefficients, resulting in a low thermoelectric figure of merit (Jaziri et al., 2019). In metals, these two properties are directly linked due to the Wiedemann–Franz law, making it difficult to reduce thermal conductivity without also decreasing electrical conductivity (Devanathan, 2021). This interdependence limits the ability to optimise metals for thermoelectric efficiency. In contrast, semiconductors conduct heat via both charge carriers and lattice vibrations (phonons) (Martin-Gonzalez, Lohani & Neophytou, 2025). The lattice thermal conductivity can be selectively reduced through doping, nanostructuring, or the introduction of crystal defects (Martin-Gonzalez, Lohani & Neophytou, 2025). These strategies scatter phonons and suppress heat transfer without significantly impairing electrical conductivity (Martin-Gonzalez, Lohani & Neophytou, 2025). Resultantly, semiconductors can sustain high electrical performance while minimising thermal losses, making them more efficient than metals for thermoelectric energy conversion. Thermoelectric materials such as bismuth telluride (Bi_2Te_3), lead telluride (PbTe), skutterudite ($CoSb_3$) and silicon-germanium (SiGe) alloys have historically demonstrated high performance, and ongoing research by institutions such as NASA now targets next-generation materials with ZT values exceeding 3 (Jaziri et al., 2019; Zhu, Yu & Li, 2019) (***Figure 2; Table 1***).

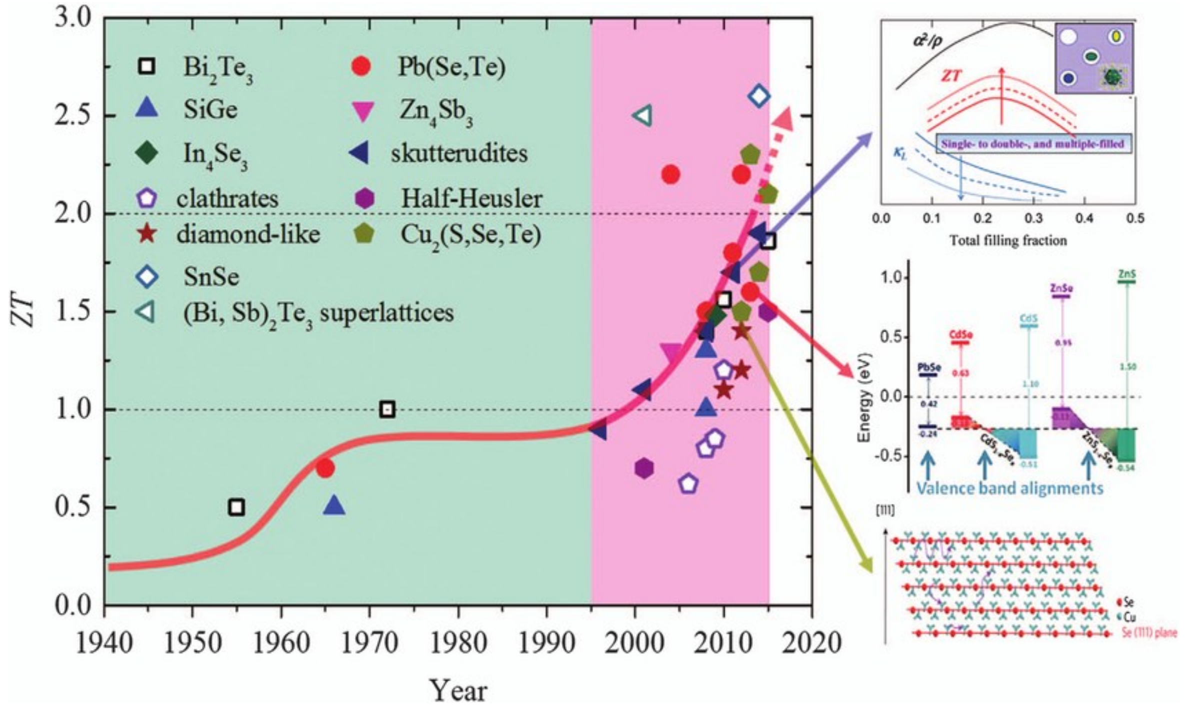


Figure 2. The chronological evolution of ZT values in various thermoelectric materials (Yang, et al., 2016).

Table 1. Voltage, current, power, and size of wearable TEGs in different materials (Yu et al., 2024).

Material	Voltage	Current	Power	Size
Bi_2Te_3 nanoparticles, poly(3,4-ethylenedioxythiophene (PEDOT) nanowires	65.1 mV/cm^2 (Δ T = 17.8 K)	208.8 μA (ΔT = 17.8 K)	3.48 μW/cm^2 (Δ T = 17.8 K)	14 × 6 × 5 mm
Graphene (thermoelectric threads)	1.1 mV (Δ T = 27.7 K)	3.3 μA (ΔT = 27.7 K)	0.7 nW (ΔT = 27.7 K)	diameter = 2 mm
Polyacrylamide (PAAm) hydrogel, graphene electrode	160 mV (Δ T = 4.1 K)	40 μA (Δ T = 4.1 K)	37 μW/cm^2 (Δ T = 4.1 K)	20 × 10 × 1 mm
PAAm / TEMPO-oxidised bacterial cellulose (TOBC) / lithium salt (LiTFSI) hydrogel	231 mV (Δ T = 20 K)	9.28 μA (Δ T = 20 K)	538 nW (Δ T = 20 K)	30 × 10 × 3 mm

A TEG consists of an array of thermocouples composed of alternating p-type and n-type semiconductor elements, sandwiched between two electrically insulating and thermally conductive ceramic substrates (Piggott, 2018) (***Figure 3 and 4***). These elements are electrically connected in series to increase the total voltage output, and thermally in parallel to ensure uniform exposure to the temperature gradient. The ceramic plates provide mechanical stability, facilitate efficient thermal contact with external heat sources and sinks, and serve as dielectric barriers to prevent electrical short circuits (Piggott, 2018).

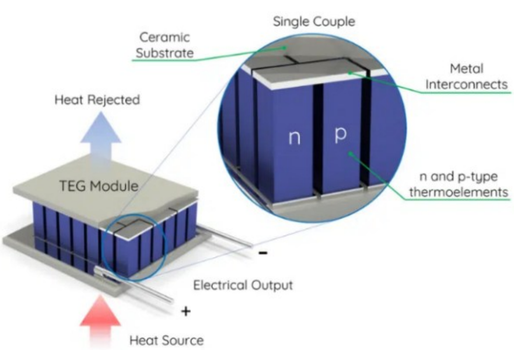


Figure 3. Structure of a TEG module (Piggott, 2018).

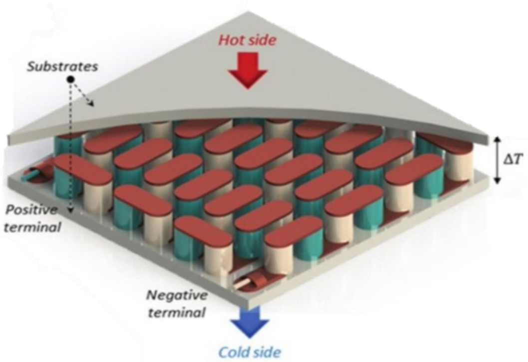


Figure 4. TEG module (Zhu et al., 2022).

The fabrication process of a wearable TEG involves assembling thermoelectric legs onto a flexible substrate, connecting them with conductive materials such as solder and copper strips, aligning components with precision tools, and encapsulating the device in a protective polymer to ensure structural integrity, electrical insulation, and flexibility for wearable integration (Wang et al., 2018) (***Figure 5***).

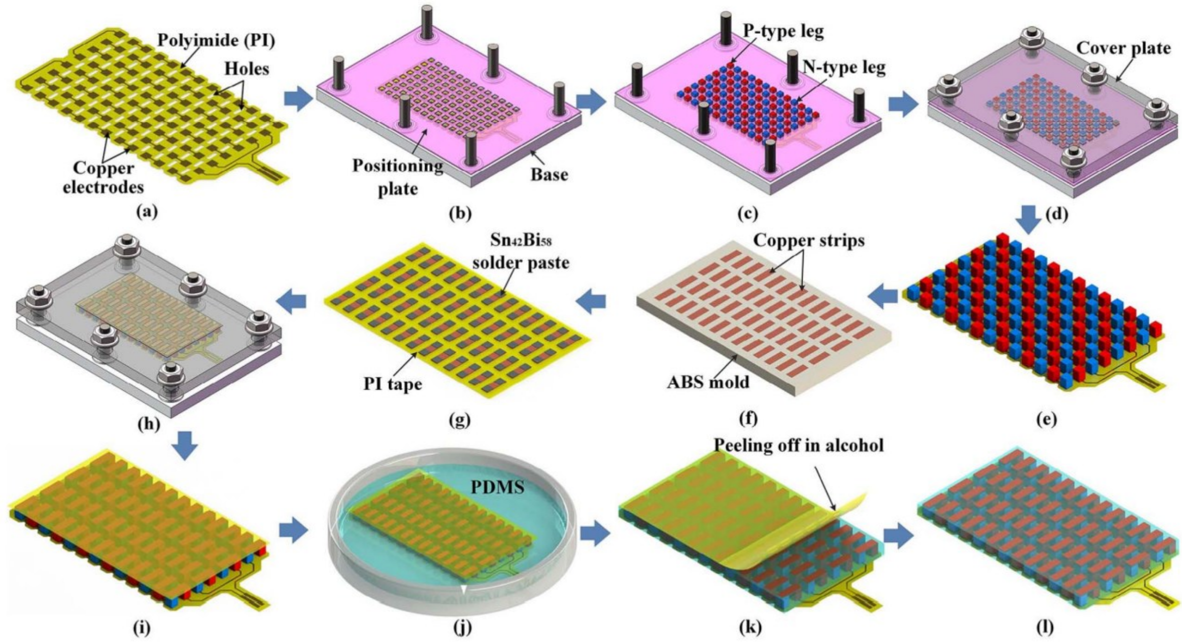


Figure 5. Fabrication process for the wearable TEG (Wang et al., 2018).

The Promise of Wearable Energy Harvesting

TEGs offer several key advantages. Their solid-state design, with no moving parts or working fluids, allows silent, reliable, and maintenance-free operation, while enhancing mechanical stability and extending operational lifespan (Champier, 2017; Zhu, Yu & Li, 2019). By generating electricity directly from thermal energy, TEGs eliminate the need for intermediate mechanical or chemical conversions, enabling instant, continuous power generation wherever a temperature gradient exists (Champier, 2017). Their compact, lightweight, and scalable architecture makes them ideal for diverse applications, from wearable electronics, sensors, and microdevices to industrial waste heat recovery and other space-constrained systems (Champier, 2017; Zhu, Yu & Li, 2019). Moreover, as they generate electricity without combustion or emissions, TEGs support cleaner and more efficient energy systems. Capable of operating passively and reliably across broad temperature ranges, TEGs are particularly effective for harsh environments such as space missions, remote locations, and high-temperature industrial settings (Champier, 2017; Zhu, Yu & Li, 2019).

Wearable energy harvesting technologies aim to supply power to electronic devices by converting ambient energy from the human body or surrounding environment into electrical energy (Ali et al., 2023). Several transduction mechanisms are utilised, including kinetic energy harvesters that exploit biomechanical motion, photovoltaic cells for solar energy conversion, piezoelectric materials that generate electricity under mechanical stress, and TEGs (Ali et al., 2023; Sezer & Koç, 2021). Among these, body heat represents a viable energy source due to its continuous, stable, and passive nature, especially under conditions where other source such as motion or light, are intermittent or unavailable (e.g., during rest or in indoor environments) (Ali et al., 2023; Tabaie & Omidvar, 2023) (***Figure 6 and*** *7*). Unlike kinetic and solar systems, TEGs function independently of user activity and ambient illumination, enabling uninterrupted power generation. This makes them suitable for low-power, long-duration applications such as physiological monitoring and biomedical wearables, where reliable and maintenance-free operation is critical (Ali et al., 2023). Consequently, TEGs represent a leading candidate for next-generation wearable technologies requiring autonomous and sustainable energy solutions.

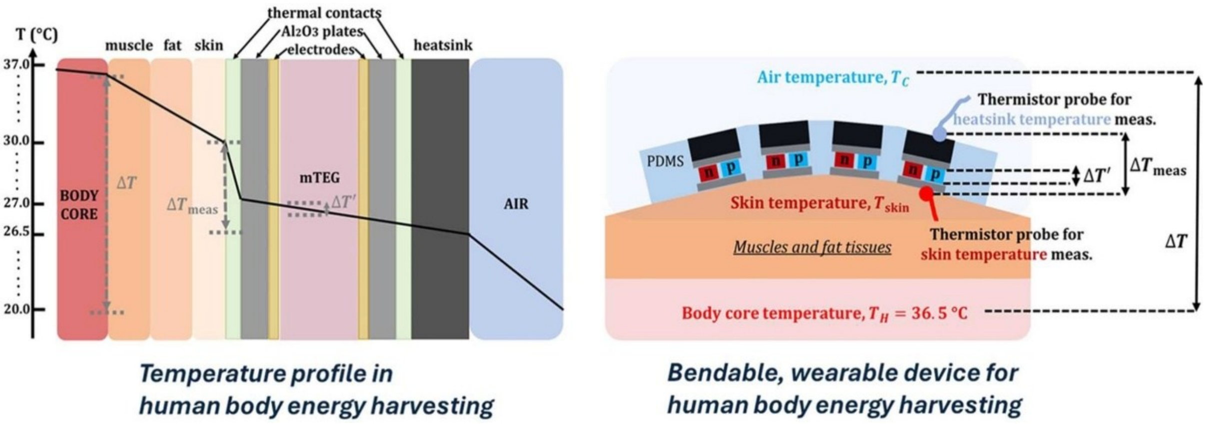


Figure 6. Temperature profile of TEG wearable in human body energy harvesting (Proto et al., 2024).

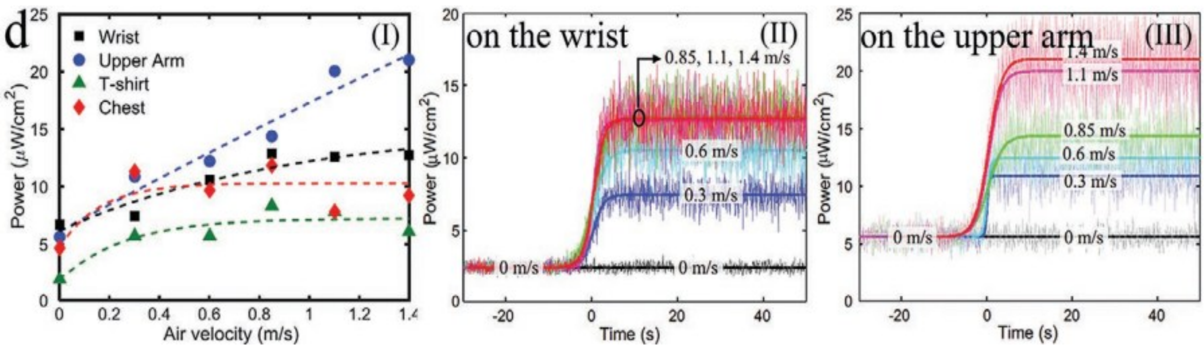
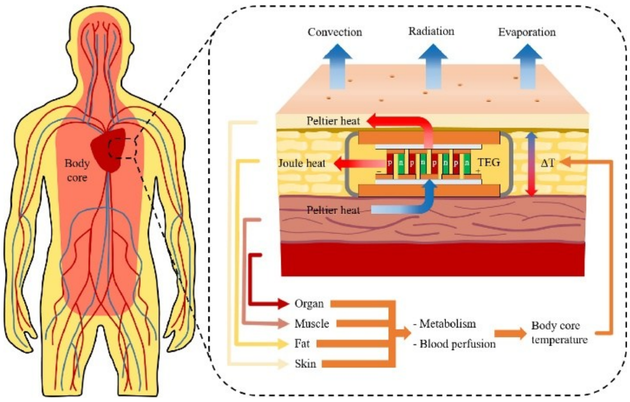


Figure 7. The body heat energy harvesting: I) Comparison of TEG powers when the device is worn on the wrist, upper arm, T-shirt, and chest. Power generated from the TEG on the II) wrist and III) the upper arm at different walking speeds (Jia et al., 2021).

Real-World Applications

Wearable TEGs have diverse real-world applications across healthcare, consumer electronics, military, and industrial sectors, leveraging on their ability to passively harvest body heat and convert it into electrical energy without the need for external power or frequent charging (***Table 2***).

Table 2. Key applications of TEG wearables.

Consumer Electronics	TEGs can be integrated into smartwatches, fitness trackers, and health-monitoring wearables, providing supplemental power or extending battery life, particularly during low-activity periods such as sleep or rest (Tabaie & Omidvar, 2023).
Health Monitoring and Medical Devices	For elderly individuals or patients with chronic conditions, TEG-powered implantable or on-skin biosensors can monitor vital signs (e.g., heart rate, glucose, temperature) without frequent recharging or battery replacement, improving safety and convenience (Jaziri et al., 2019).
Biomedical Implants	Ongoing research is investigating the integration of TEGs into implantable medical electronics, such as pacemakers or drug delivery systems, where harvested thermal energy reduces the need for surgical battery replacements (Rao, Bechtold & Hohlfeld, 2025) (***Figure 8***). Notably, *Torfs, Leonov & Vullers* (2007) developed a wireless pulse oximeter powered by body heat using a compact, watch-sized TEG.  **Figure 8.** Implanted TEG (Rao, Bechtold & Hohlfeld, 2025).
Military and Emergency Use	In disaster relief or military operations, TEGs embedded in uniforms or gear can power communication devices, GPS trackers, or environmental sensors in remote or off-grid locations (Liu et al., 2021).
Space exploration	TEGs have been used extensively in space missions in the form of radioisotope TEGs, which convert heat from radioactive decay into electrical energy (Champier, 2017). Their long-term reliability and ability to operate in solar-deficient, extreme conditions demonstrate the same passive, maintenance-free qualities being leveraged in wearable designs (Champier, 2017).

Current Challenges

Despite their advantages and wide-ranging applications, key challenges in TEG development include the need for high-efficiency devices based on materials with a high thermoelectric figure of merit, as well as ensuring the flexibility and biocompatibility required for wearable and biomedical integration (Zhu et al., 2022). Though Bi_2Te_3 exhibit superior thermoelectric performance at room temperature and can be mass-produced, its inherent rigidity, toxicity, and safety concerns pose significant limitations for wearable applications (Zhu et al., 2022). Alternative non-toxic materials such as Ag_2Se, MgAgSb, and SnSe offer promising thermoelectric performance with reduced toxicity; however, challenges remain regarding their mechanical flexibility, thermoelectric efficiency, cost-effectiveness, scalability, and long-term reliability (Zhu et al., 2022). Although integrating heat sinks can enhance TEG efficiency, conventional approaches including hydrogels and copper plates compromise device flexibility (Zhu et al., 2022). Emerging heat dissipation materials such as graphene and radiative cooling structures present new possibilities for flexible, lightweight, and efficient thermal management in wearables. Ongoing advancement in materials science and device engineering are anticipated to expand the potential of wearable TEGs and enable broader, more practical applications.

Future Directions

The advancement of wearable TEGs is closely associated with progress in nanotechnology and novel materials (Shakouri, 2011). Emerging flexible thermoelectric materials, such as nanostructured polymers, carbon-based composites, and low-dimensional semiconductors, offer improved mechanical compliance, improved thermoelectric efficiency, and better compatibility with textiles and skin-mounted devices (Zhang et al., 2014). Though integration remains a key technical hurdle, the development of hybrid energy systems that combine TEGs with photovoltaic cells, piezoelectric harvesters, or triboelectric nanogenerators allows more consistent and robust energy output by leveraging multiple ambient energy sources (Zhu et al., 2022) (***Figure 9***). Such systems address the limitations of individual harvesters and are effective to use in environments with variable thermal, mechanical, or light conditions (***Figure 10***). As material performance, miniaturization, and system integration continue to advance, wearable TEGs are expected to move beyond experimental prototypes toward mass-market applications in consumer electronics, continuous health monitoring, and implantable biomedical devices, potentially revolutionising self-powered, autonomous wearable technologies (Jia et al., 2021).

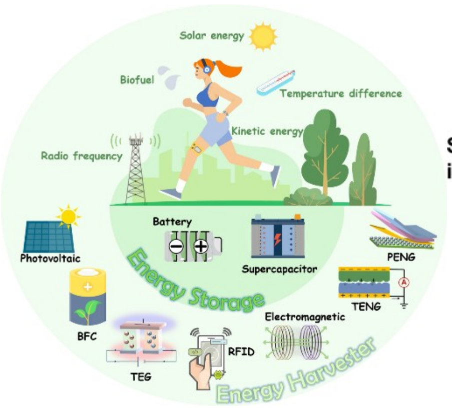


Figure 9. Various energy harvesters and sources (Yu et al., 2024).

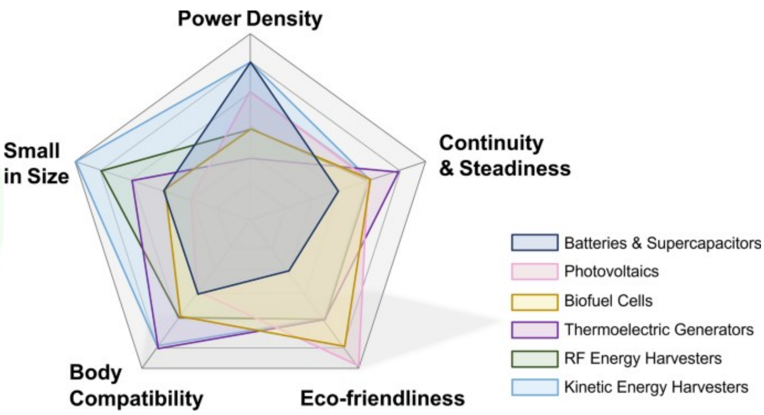


Figure 10. Multi-dimensional performance comparison of various power supply modes used for wearable sensors (Yu et al., 2024).

Conclusion

Thermoelectric wearables have the potential to revolutionise personal electronics by enabling continuous, self-sustaining power from body heat. Their integration could transform healthcare, enhance sustainability, and redefine the future of autonomous wearable technologies. Ongoing research and technological innovation are essential to overcome current challenges and fully realise the potential of thermoelectric generators for current and future generations.

Word Count:

1551 words (excluding headings, titles, tables, images, figure captions, references, and bibliography).

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