

CHAPTER I

INTRODUCTION

1.1 Background

Energy is a fundamental necessity for human activities in daily life. Along with rapid population growth, global energy demand continues to increase (Kharisma et al., 2024). Currently, the majority of energy production still relies on non-renewable resources such as fossil fuels and coal, whose utilization generates carbon emissions that contribute to the greenhouse effect and global warming (Setyono et al., 2019).

Renewable energy has become one of the major priorities in global research and technological development. Indonesia has abundant natural resources, which provide significant potential for improving renewable energy technologies. However, renewable energy currently contributes 4% of the national energy mix. Several renewable energy sources that have been utilized include solar energy, industrial waste, livestock waste, and hydropower (Paturu & Yulianingrum, 2023). In addition to natural resources, energy can also be harvested from the human body, such as through physical movement and body heat. The surface temperature of human skin is usually higher than the surrounding temperature. The human body generates about 60 to 180 W of metabolic heat, which is released into the environment through convection and radiation (Tabaie & Omidvar, 2023). Much of this thermal energy has the potential to be transformed into electrical energy for wearable devices. However, most body heat is currently lost to the environment without being used. Existing wearable health-monitoring devices, like those that measure temperature, heart rate, and oxygen levels, primarily serve as sensors without energy conversion or storage features.

Energy can be converted from heat to electricity using the Seebeck effect. This process relies on a temperature difference to create an electrical potential. When two sides of a material, either metal or semiconductor, experience different temperatures, they generate an electrical voltage. The larger the temperature difference, the greater the output voltage (Lapalutu & Arbie, 2025). One technology being developed based

on this principle is the Thermoelectric Generator (TEG), which converts temperature differences directly into electrical energy (Rokhim et al., 2023). However, TEG development and large-scale use as an alternative energy source have not been fully optimized. To move this technology forward, support from the government, industry, academic institutions, and the wider community is necessary (Diki et al., 2022).

A Thermoelectric Generator (TEG) is a device that produces a steady and continuous DC voltage by taking advantage of the temperature difference between its two sides. One key benefit of TEG systems is that they can operate continuously and reliably without needing complicated environmental conditions or external power sources. This makes TEG particularly suitable for wearable devices like smartwatches, health-monitoring sensors, and other portable gadgets (Rizaldi & Edahwati, 2022). Additionally, integrating TEG can extend battery life and, in some cases, allow devices to work independently with extra battery support.

The use of Thermoelectric Generators has grown significantly due to the rising demand for eco-friendly alternative energy sources. Initially, TEGs were mainly used in simpler devices, such as portable coolers that help maintain stable temperatures (Mustakim et al., 2022). Recently, research has focused on combining TEG systems with wearable technology, including wearable bracelets (Yang et al., 2023) and wearable energy storage (Lv et al., 2021). These technologies take advantage of the temperature difference between the human body and the surrounding environment to generate and store electrical energy.

In general, a Thermoelectric Generator (TEG) is composed of n-type and p-type semiconductor materials. P-type materials lack electrons, which creates holes as the main charge carriers. In contrast, n-type materials have electrons as the primary charge carriers. When a temperature gradient exists between the two semiconductor materials, where one side is heated and the other side is cooler, electrons in the n-type material migrate from the hot region toward the cold region. At the same time, holes in the p-type material move in the opposite direction, generating an electric potential difference

(Pradana & Widyartono, 2020). Several semiconductor materials commonly used in thermoelectric applications include Bi_2Te_3 (*bismuth telluride*), Sb_2Te_3 (*antimony telluride*), Ag_2Se (*silver (I) selenide*), and other semiconducting compounds with high electrical conductivity. However, the negative value of its Seebeck coefficient shows that ZnO acts as an n-type semiconductor with electrons as the main charge carriers. Consequently, a doping process is needed to change its electrical properties and possibly achieve p-type characteristics (Fitriyani et al., 2024). One of the materials often used to modify ZnO is copper (Cu). Cu doping has been shown to lower the band gap energy of ZnO from about 3.37 eV to around 3.13 eV, while also improving its electrical and magnetic properties. In addition, copper's high electrical conductivity, wide availability, and relatively low cost make it a promising dopant candidate for ZnO-based thermoelectric materials (Supu et al., 2022).

Thermoelectric Generators operate based on three fundamental thermoelectric phenomena, namely the *Seebeck* effect, the Peltier effect, and the Thomson effect. Among these, the *Seebeck* and Peltier effects serve as the primary mechanisms in heat-to-electricity energy conversion (S. S. Putra & Habibullah, 2023). The *Seebeck* mechanism, illustrated in Figure 1.1, takes place when a temperature difference is created across semiconductor materials containing charge carriers. Under this condition, electrons in n-type materials and holes in p-type materials migrate from the higher-temperature area, resulting in an electric potential difference (E. N. Irawan et al., 2019). One of the most widely used thermoelectric materials for both n-type and p-type applications is bismuth telluride (Bi_2Te_3).

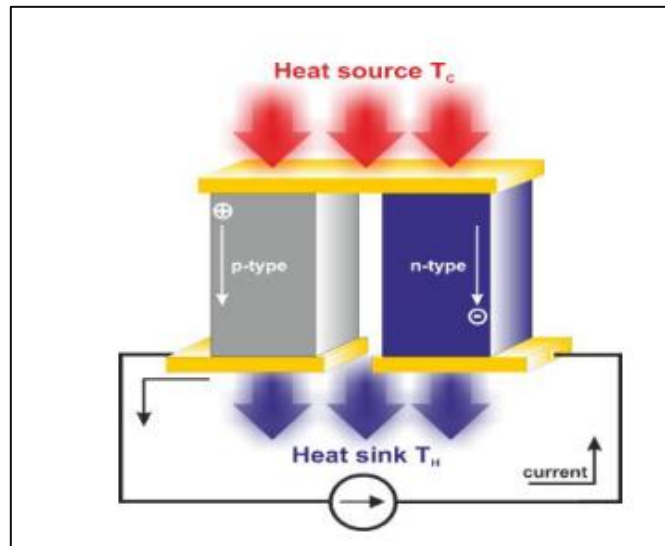


Figure 1.1 Seebeck effect mechanism (adapted from Sasmita et al., 2019)

To generate an electrical voltage, a temperature difference must be established across the ends of the semiconductor material. The region with higher temperature induces charge carrier diffusion, where electrons in the n-type semiconductor migrate toward the p-type material, thereby creating charge accumulation and forming an electric potential difference (Silaban et al., 2024). The magnitude of this generated potential difference (voltage) is directly proportional to the applied temperature gradient (Pranoto et al., 2021).

Numerous previous studies have investigated the development of Thermoelectric Generators (TEGs) utilizing semiconductor materials. For instance, N. R. F. Putra et al. (2019) conducted modeling and fabrication of a Bi_2Te_3 -based thermoelectric generator module using a thermoelement assembly method to generate electrical power. Their study employed four bismuth telluride elements with dimensions of $20\text{ cm} \times 15\text{ cm} \times 15\text{ cm}$ and reported a Seebeck coefficient of $0.410 \times 10^{-3}\text{ V/K}$ (N. R. F. Putra et al., 2019). Similarly, Muntini et al., (2020) successfully fabricated a thermoelectric generator module using antimony telluride (Sb_2Te_3) as the p-type semiconductor and bismuth telluride (Bi_2Te_3) as the n-type semiconductor. More recently, Xu et al. (2024) reconfigured a TEG system using a thermoelectric chop

fabricated from MXene/Bi₂Te₃ composite films. Their results demonstrated that five thermoelectric chips were capable of producing an output power of 7.1 μ W under a temperature difference of $\Delta T=45$ K (Xu et al., 2024). Despite their promising performance, tellurium-based materials present environmental and toxicity concerns, which may limit their long-term sustainability and large-scale application. As a result, researchers have looked into alternative semiconductor materials to replace tellurium-based compounds. Jangra et al. (2022) suggest that thermoelectric materials fall into two main categories: inorganic and organic. Common inorganic materials used in thermoelectric generator (TEG) systems include SiGe (Silicon-Germanium), SnSe (Tin Selenide), and skutterudite-based compounds such as CoAs₂. Organic materials are also gaining popularity, especially in conductive and non-conductive polymers. Examples include polyvinylidene fluoride (PVDF), Poly (3-hexylthiophene) (P3HT), dan poly (3-octylthiophene) (P3OT), polyacetylene (PA), polyaniline (PANi), and poly 3-methylthiophene (P3MT) (Jangra et al., 2022). However, current research on TEG systems using ZnO as the primary semiconductor material is limited, especially in Indonesia. Additionally, there are few studies that explore how temperature changes affect the output voltage in ZnO-based TEG systems. This area is important for assessing performance and practical use of thermoelectric generators, highlighting the need for more in-depth research.

Given this background, developing a TEG requires careful attention to material availability, optimizing performance, and choosing an appropriate synthesis method. It is crucial to create a TEG system that is non-toxic, easy to synthesize, readily available in Indonesia, and affordable for large-scale use. This study aims to develop a thermoelectric generator based on ZnO semiconductor materials. It will use ZnO as one semiconductor and Cu-doped ZnO (ZnO:Cu) as the complementary component. Researchers will systematically apply temperature variations during testing to examine their effect on the output voltage. The prepared samples will undergo characterization using X-Ray Diffraction (XRD) to examine their crystal structure, Fourier Transform Infrared (FTIR) spectroscopy will help identify functional groups, Scanning Electron

Microscopy (SEM) to evaluate surface morphology, UV-Vis spectroscopy to assess optical properties, and electrical voltage measurements to determine thermoelectric performance.

1.2 Problem Statement

1. What are the differences in characteristics between ZnO and Cu-doped ZnO (ZnO:Cu) samples?
2. How does temperature variation influence the voltage output performance of the thermoelectric generator (TEG)?

1.3 Research Objectives

1. To compare the characteristics of ZnO and Cu-doped ZnO (ZnO:Cu) as semiconductor materials for thermoelectric applications.
2. To explore how temperature differences affect the voltage output generated by the thermoelectric generator (TEG).

1.4 Research Benefits

1. To provide scientific information about the characteristics of ZnO and ZnO:Cu, including its structure and electrical properties as semiconductor materials in TEG systems.
2. To find the optimal temperature difference for improving the performance of ZnO and ZnO:Cu-based thermoelectric generators.

1.5 Research Hypothesis

1. Cu doping is expected to slightly modify the ZnO crystal structure while maintaining the dominant wurtzite phase.
2. Increasing the temperature gradient is expected to improve the voltage generated by the thermoelectric generator (TEG).