# *Chapter 1*

# *Introduction*

## Background and Motivation

Waste heat recovery (WHR) is the process of capturing and reusing excess thermal energy that is typically lost to the environment during industrial processes, power generation, and other thermal applications. Instead of allowing this heat to dissipate, waste heat recovery systems convert it into useful energy, such as electricity or additional thermal power, improving overall efficiency and sustainability. The development of waste heat recovery systems is driven by the need for energy efficiency, cost reduction, and environmental sustainability. A significant portion of energy in industries and power plants is lost as heat, contributing to wasted resources and increased greenhouse gas emissions. By recovering and utilizing this heat, industries reduce fuel consumption, lower operational costs, and minimize their carbon footprint. Additionally, waste heat recovery plays a crucial role in enhancing energy security, reducing dependence on fossil fuels, and promoting sustainable energy solutions (Johnson et al., 2008). Low-grade waste heat recovery refers to the process of capturing and utilizing waste heat with temperatures typically below 250°C. This type of heat is commonly found in industrial processes, power plants, automotive exhaust, and residential heating systems. Unlike high-temperature waste heat, which can be directly reused for power generation, low-grade waste heat is more challenging to recover due to its lower energy density and reduced thermal potential.

A typical waste heat recovery system operates through several key steps to efficiently capture, convert, and utilize excess thermal energy. Firstly, the system extracts waste heat from high-temperature sources such as exhaust gases, hot surfaces, or process fluids. This is achieved using specialized thermal recovery devices, including heat exchangers, recuperators, regenerators, or thermoelectric generators (TEGs) (Jaafreh et al., 2022). Heat exchangers facilitate efficient heat extraction by allowing thermal energy transfer between the waste heat source and a secondary working fluid, while TEGs directly convert thermal gradients into electricity using the Seebeck effect. Once captured, the thermal energy must be efficiently transferred to a working fluid, which can be air, water, steam, or advanced heat transfer fluids like molten salts or phase-change materials. The heat transfer mechanisms involved include conduction (direct solid-to-solid transfer), convection (fluid-based transport), and radiation (electromagnetic heat transfer). The choice of working fluid and transfer mechanism is crucial, as it affects the system's thermal efficiency, pressure drop, and heat exchanger design. Then, the recovered thermal energy is then converted into a usable form, depending on the application. For electricity generation, thermoelectric modules can convert heat into electrical power, while mechanical systems such as Organic Rankine Cycle (ORC) or Stirling engines utilize thermodynamic cycles to produce mechanical work, which is further converted into electricity through generators. Alternatively, direct heat reuse is employed in industrial processes for preheating raw materials, improving combustion efficiency, or driving absorption refrigeration systems for cooling applications.

Consequently, the converted energy is either stored for future use or directly applied in various energy-demanding applications. Thermal energy storage (TES) systems, including sensible heat storage (using materials like water or rock beds), latent heat storage (phase-change materials), and thermochemical storage, enable heat retention for later use. If direct utilization is preferred, the recovered energy can be integrated into industrial heating systems, district heating networks, or hybrid renewable energy setups to enhance overall system performance. Finally, to maximize efficiency and adaptability, modern waste heat recovery systems incorporate optimization techniques and advanced control algorithms. Predictive models, including machine learning-based optimization, dynamically adjust operational parameters such as flow rates, temperature gradients, and load demands to enhance energy conversion efficiency. Automated feedback mechanisms ensure minimal thermal losses and improved system reliability, while computational fluid dynamics (CFD) simulations aid in designing more efficient heat exchangers and thermal transport pathways. By integrating these sequential steps, which have been illustrated in Fig. 1.1, waste heat recovery systems effectively enhance energy efficiency, reduce environmental impact, and contribute to sustainable industrial and power generation practices.

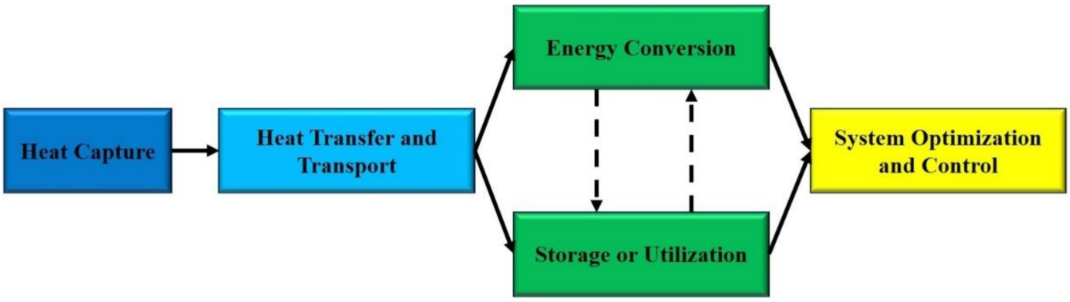

**Fig. 1.1 Typical Waste Heat Recovery Processes**

## 1.1 Advantages of Waste Heat Recovery Systems

Waste heat recovery (WHR) systems offer several benefits across industrial, commercial, and energy sectors by improving efficiency, reducing costs, and promoting sustainability. The key advantages include:

- Enhanced Energy Efficiency: WHR systems utilize otherwise wasted thermal energy, improving overall system efficiency by converting excess heat into useful power or thermal energy. This reduces fuel consumption in industrial processes and power generation.

- Reduced Operational Costs: By recovering and reusing heat, industries can lower energy bills and decrease dependence on primary energy sources. This leads to significant cost savings, particularly in energy-intensive sectors like manufacturing, metal processing, and chemical industries.
- Lower Environmental Impact: WHR systems contribute to sustainability by reducing greenhouse gas (GHG) emissions and overall carbon footprint. By improving fuel utilization, they help industries meet environmental regulations and emission reduction targets.
- Increased Power Generation Potential: Technologies such as thermoelectric generators (TEGs), Organic Rankine Cycles (ORC), and Kalina cycles convert waste heat into electricity, enhancing power generation capacity without additional fuel consumption (Armstead et al., 2013).
- Process and Equipment Longevity: Heat recovery reduces thermal stress on industrial equipment by maintaining optimal operating temperatures. This minimizes wear and tear, leading to extended equipment lifespan and reduced maintenance costs.
- Energy Security and Resource Conservation: WHR reduces reliance on fossil fuels and enhances energy security by optimizing available energy resources. This is particularly crucial in regions with high energy demand and limited natural resources.
- Hybrid Renewable Energy Integration: WHR can complement renewable energy sources like solar and biomass by stabilizing energy supply fluctuations. Waste heat from solar thermal or biogas plants can be recovered and utilized, improving overall system reliability.

- Technological Advancements and Innovation: The adoption of WHR systems drives research and development in advanced materials, nanofluids, heat exchangers, and machine learning-based optimization, paving the way for next-generation energy-efficient technologies.

By implementing waste heat recovery systems, industries, and power plants can significantly enhance energy utilization, reduce costs, and contribute to a more sustainable and environmentally friendly energy landscape.

## 1.2 Thermoelectric generator as a Waste Heat recovery method

The concept of thermoelectric power generation dates back to the early 19th century when Thomas Johann Seebeck discovered the thermoelectric effect in 1821. He observed that a voltage is generated in a closed circuit composed of two different conductive materials when subjected to a temperature gradient. This phenomenon, later termed the Seebeck effect, laid the foundation for thermoelectric technology. Over the years, researchers developed thermoelectric materials and improved efficiency, leading to applications in power generation and cooling (Degousée et al., 2021, Yin et al., 2022). During the mid-20th century, thermoelectric generators (TEGs) gained prominence, especially in space exploration, where radioisotope thermoelectric generators (RTGs) were used to power deep-space missions. TEGs have shown potential to be utilized in automotive, industrial waste heat recovery, and renewable energy applications. The Seebeck effect is the fundamental principle behind thermoelectric generators. It occurs when two dissimilar conductive or semiconductive materials form a closed circuit, and a temperature difference is applied at the junctions. This temperature gradient causes charge carriers (electrons or holes) to migrate from the hot side to the cold side, creating an electric potential (voltage). The magnitude of the voltage depends on the materials'

Seebeck coefficient and the temperature difference. The generated voltage can be harnessed for power generation, making the Seebeck effect a critical mechanism in thermoelectric energy conversion (Yin et al., 2022). A typical TEG consists of the following essential components:

- Thermoelectric Materials (P-Type and N-Type Semiconductors)– The core of a TEG consists of alternating p-type and n-type semiconductor legs, usually made from materials like bismuth telluride ($Bi_2Te_3$) or advanced nanostructured thermoelectric. These materials enable efficient charge carrier movement under a thermal gradient.
- Metallic Interconnects and Electrodes– Conductive metal strips connect the semiconductor legs electrically in series and thermally in parallel. This configuration ensures that the electrical voltage builds up while minimizing thermal losses.
- Ceramic Substrate Layers– A thermoelectric module is sandwiched between two ceramic plates, usually made of alumina ($Al_2O_3$) or other high-temperature-resistant materials. These plates provide mechanical strength, electrical insulation, and efficient heat transfer.
- Heat Source and Heat Sink– To generate power, a TEG module requires a hot side (attached to the heat source) and a cold side (attached to a heat sink or cooling mechanism). The larger the temperature difference, the higher the efficiency and power output.

By combining these components, thermoelectric generators efficiently convert waste heat into electrical energy, making them valuable for power generation in various applications.

## 1.3 Applications of TEG

Thermoelectric generators (TEGs) find diverse applications across multiple industries due to their ability to directly convert heat into electricity with high reliability and minimal maintenance. In waste heat recovery, TEGs are integrated into industrial processes, automotive exhaust systems, and power plants to harness otherwise lost thermal energy, improving overall energy efficiency. In space exploration (Peng et al., 2022), radioisotope thermoelectric generators (RTGs) power deep-space missions by converting heat from radioactive decay into electricity, ensuring the long-term operation of spacecraft. The automotive industry utilizes TEGs for vehicle energy recovery, converting exhaust heat into electrical power to improve fuel efficiency and reduce emissions (Kumar et al., 2021). In renewable energy systems, TEGs complement solar thermal (Manghwar et al., 2024, Sharma et al., 2022) and geothermal energy (Xie et al., 2023) by capturing excess heat and enhancing overall power output. Moreover, in wearable and biomedical applications (Miao et al., 2024), TEGs harvest body heat to power low-energy medical devices such as pacemakers and biosensors, offering self-sustaining energy solutions. Additionally, TEGs are employed in remote and off-grid power generation, providing a reliable source of electricity in harsh environments where conventional power sources are impractical. The ability of TEGs to operate without moving parts, coupled with advancements in thermoelectric materials and nanotechnology, continues to expand their applicability across emerging energy and technological sectors.

## 1.4 Objectives

The objectives of the present research are given as follows:

- ***To enhance heat extraction from exhaust gases by proposing a novel heat exchanger equipped with vortex generators (delta, envelope, and fishtail shape). This work seeks to determine the optimal geometrical arrangement (distance-to-height ratio and angle of inclination) that maximizes thermohydraulic performance.***
- ***To maximize the power output and conversion efficiency of the thermoelectric generator (TEG) by exploring its performance with varying specifications (TEG stages, leg geometry, and new materials). The goal is to quantify the influence of critical design parameters (number of rows of TEG legs, exhaust inlet temperature, and coolant flow rate) on TEG performance under different operating conditions.***
- ***To improve heat rejection on the TEG's cold side by investigating the use of hybrid nanofluids as coolants. This involves identifying the nanoparticle properties (shape aspects and volume fraction of the nanoparticles) and flow conditions (coolant flow rates) that optimize thermohydraulic and exergetic performance.***
- ***To systematically identify the most influential design parameters and create an accurate performance model using the Taguchi method and an Artificial Neural Network (ANN). This work seeks to obtain the optimal vortex generator shape and a high-fidelity predictive model.***
- ***To develop a more efficient and sustainable hybrid system by integrating the TEG with the application of a novel vortex generator (fishtail) with a solar water heater. The analysis seeks to evaluate the overall performance and energy synergy of the resulting hybrid system.***

## 1.5 Contribution of the study

This study makes a significant contribution to the advancement of thermoelectric generator (TEG) performance by systematically evaluating and integrating cutting-edge techniques for heat transfer enhancement, device optimization, and predictive modeling. By investigating hot-side heat transfer augmentation, particularly through the application of vortex generators, this research enhances thermal energy absorption, thereby improving the temperature gradient essential for efficient thermoelectric conversion. Furthermore, by exploring TEG device optimization, including novel thermoelectric materials, multi-stage configurations, and leg geometry modifications, this study provides valuable insights into balancing thermal and electrical transport properties to achieve higher energy conversion efficiency. Additionally, the incorporation of cold-side cooling enhancements, specifically through shape-dependent nanofluid and hybrid nanofluid performance analysis, demonstrates how effective thermal dissipation strategies can mitigate temperature buildup and maximize power output. The study also delves into Taguchi optimization methodologies, leveraging artificial neural networks and predictive modeling to fine-tune system parameters for superior efficiency. Lastly, the exploration of solar-assisted TEG hybrid systems highlights the potential of integrating renewable energy sources to boost TEG performance in sustainable applications. By addressing key performance limitations and proposing innovative strategies, this study serves as a foundation for future advancements in thermoelectric technology, fostering its integration into next-generation energy solutions.

## 1.6 Thesis structure and methodology

The present study is structured into eight comprehensive chapters, each addressing critical aspects of waste heat recovery (WHR) through thermoelectric generators (TEGs). **Chapter 1** establishes the significance of waste heat recovery and the role of thermoelectric generators (TEGs) in energy harvesting. It highlights real-world applications of TEGs across various industries, sets the motivation for the study, and outlines the research objectives and thesis structure. **Chapter 2** presents a structured literature review focusing on five core areas: hot-side heat transfer enhancement, TEG performance optimization, cold-side cooling strategies, advanced optimization techniques, and solar-assisted TEG systems. It discusses vortex generators for heat transfer improvement, high-ZT thermoelectric materials, nanofluid-based cooling techniques, AI-driven performance modeling, and hybrid renewable energy integration. **Chapter 3** investigates the hot-side heat transfer enhancement using novel vortex generators (delta, envelope, and fishtail) in a heat exchanger coupled with a TEG. An experimental study examines the effects of vortex shape, spacing, and inclination on heat transfer coefficient, pressure drop, and overall thermal performance, aiming to identify an optimal design for improved TEG efficiency. **Chapter 4** develops a two-stage TEG with variable leg geometry and dissimilar thermoelectric materials to enhance performance. The study explores the impact of row configuration, exhaust inlet temperature, and coolant flow rate on power output and efficiency, identifying an optimal design for maximizing energy conversion. This study specifically focused on identifying the optimal combination of input factors to maximize the TEG's power output and conversion efficiency, with subsequent economic and environmental considerations planned for future research. **Chapter 5** examines the influence of hybrid nanofluids containing differently shaped nanoparticles, such as graphene, $Al_2O_3$, MWCNT, and $Fe_3O_4$, on the thermal performance of a mini channel heat sink used for TEG cooling. The study evaluates the heat transfer coefficient, Nusselt number, exergy, and Figure of merit to determine the best nanofluid composition for effective heat dissipation and enhanced

TEG power generation. **Chapter 6** analyzes the thermohydraulic performance of various vortex generator geometries in a rectangular channel under different ambient conditions for TEG. It evaluates delta, envelope, and fishtail-shaped vortex generators using Taguchi design of experiments (DOE), ANOVA, and signal-to-noise ratio analysis. Additionally, an artificial neural network (ANN) model is developed to predict performance trends and optimize heat exchanger efficiency. **Chapter 7** investigates a hybrid energy system combining an Evacuated U-tube Solar Water Heater (EUSWH) with a TEG, incorporating fishtail vortex generators for enhanced heat transfer. The study systematically evaluates the effects of solar radiation, water flow rate, and inlet temperature on the thermal and electrical performance of the integrated system, aiming to optimize renewable energy utilization. Finally, **Chapter 8** summarizes the key findings from all studies, highlighting critical parameters influencing TEG performance. It identifies the optimal design configurations and operational conditions for maximizing efficiency and outlines potential future research directions in thermoelectric energy harvesting.

Thus, this thesis aims to improve thermoelectric generator (TEG) performance by examining its three main parts: the hot-side heater, the TEG module, and the cold-side cooler. The research uses new experimental and computer models to achieve this. The study then expands to optimize the entire system and test a practical application in a hybrid solar setup. Although these topics are diverse, they all share the same goal: to find better ways to generate power with TEGs. For example, Chapter 3 tests different vortex generators to improve the hot side of the TEG, Chapter 4 develops a modified and improved TEG, Chapter 5 explores TEG cold side performance enhancement, Chapter 6 optimizes vortex generators from Chapter 3, and Chapter 7 uses the best one from that study in a hybrid system combining a TEG with a solar water heater.