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# THERMOELECTRIC MATERIALS FOR BODY HEAT-POWERED WEARABLE ELECTRONICS

## INTRODUCTION

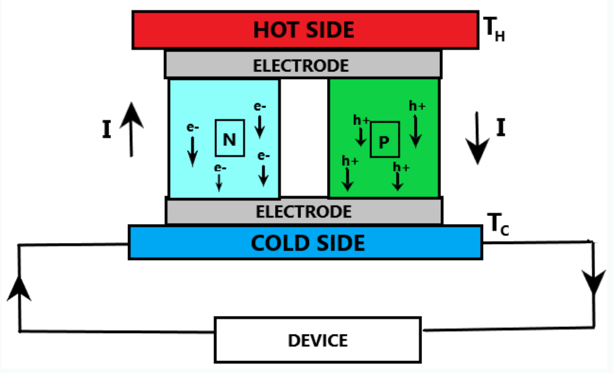
Combatting **global warming** is the core motivation behind this research. **Wasted heat is a missed opportunity** for energy and it is everywhere. From car exhausts to power stations and from laptops to body heat. **Over 60% of primary energy from fossil fuels is wasted as heat** [1].
**Body-heat is a renewable and sustainable energy resource.** The challenge is to find materials that could exploit the temperature difference between us and our environment for energy generation.

## OBJECTIVE

To find thermoelectric materials that can power wearable electronic devices with the body temperature gradient, using material data and an online simulation.

**Wearable technology** offers huge benefits to the medical world, like tracking patient data or improving quality of life. The Covid-19 pandemic has sparked even more interest in wearable technology, specifically for continuous monitoring of patient health (outside of a hospital, thus socially distanced). However, the battery size used in these wearable devices determines their operating times, limiting their potential for long term monitoring.

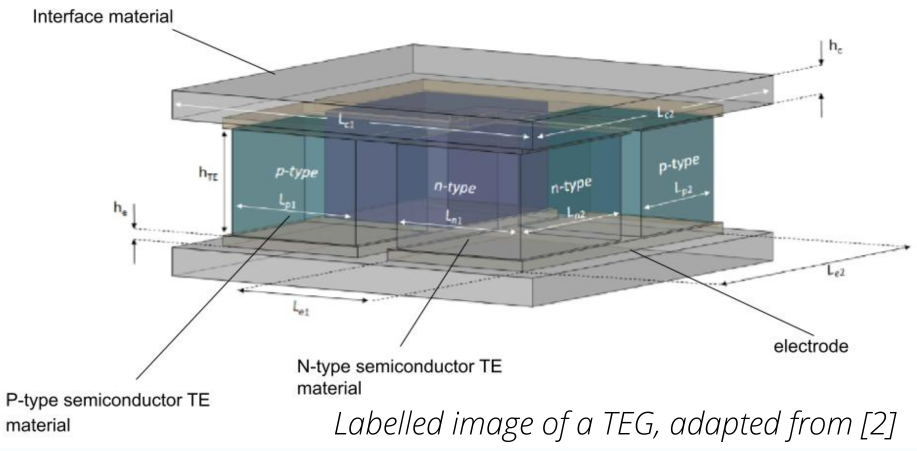
## THEORY OF TEGs



A TEG (thermoelectric generator) works because of the **Seebeck effect** - when a *temperature difference induces a potential difference.* The hot side gives kinetic energy to charge carries in a thermoelectric (TE) material so they travel to the cold side, creating a charge imbalance and thus, a potential difference.

A TEG consists of **legs** that are **p- and n-type thermoelectric semiconductors**. P-type have holes for charge carries and n-type have electrons for charge carriers. Each **pair of legs is called a couple**.

A good thermoelectric material needs a **high electrical conductivity** (σ) and a **low thermal conductivity** (κ).

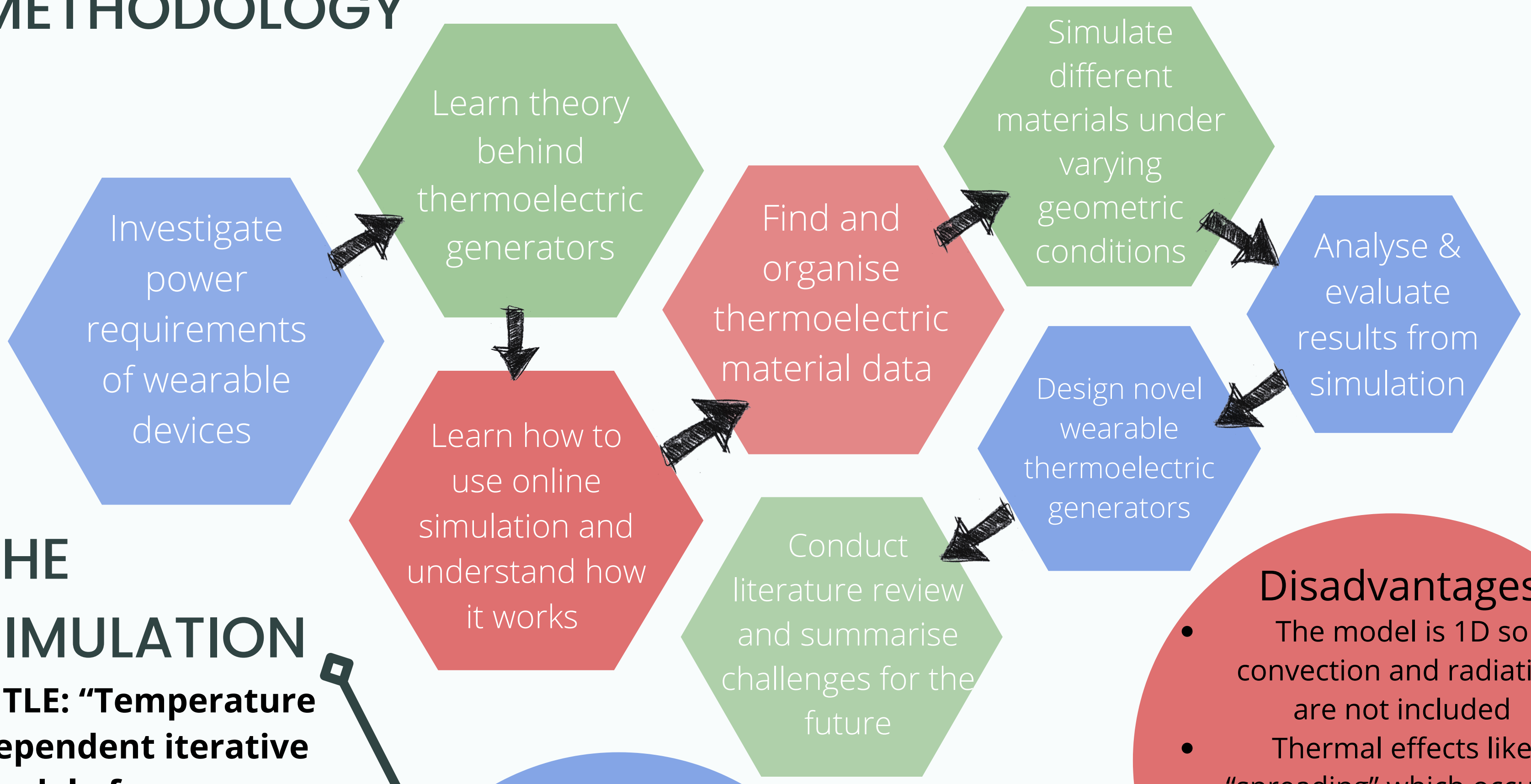


*Labelled image of a TEG, adapted from [2]*

**Figure of merit, ZT**
A high ZT value indicates a high performing thermoelectric material

**Fill factor, F**
F is the ratio of total surface area of couples to surface area of module. F is less than or equal to 1.

## METHODOLOGY



Investigate power requirements of wearable devices

Learn theory behind thermoelectric generators

Learn how to use online simulation and understand how it works

Find and organise thermoelectric material data

Simulate different materials under varying geometric conditions

Analyse & evaluate results from simulation

Design novel wearable thermoelectric generators

Conduct literature review and summarise challenges for the future

## THE SIMULATION

**TITLE: "Temperature dependent iterative model of thermoelectric generator including thermal losses in passive elements" [2]**

### Advantages

- Validated by 2 commercial thermoelectric devices
- Accurate with standard models
- Other approximation-based methods strongly overestimate the power output.

### Disadvantages

- The model is 1D so convection and radiation are not included
- Thermal effects like "spreading" which occur in curved shapes & thin films are also not included. These can cause severe distortions in results.

## TYPES OF TE MATERIALS

**Inorganic**
- ✓ Relatively, they are very high performing at low temperatures
- ✗ Bulk inorganic materials are rigid
- ✗ Contain toxic and rare earth elements [3]
- ✓ Thin-film inorganic TE materials combined with nanostructure manipulation can be flexible

**Organic**
- ✓ Low thermal conductivity, low density, low cost, low environmental impacts, good mechanical flexibility [3]
- ✓ They do not contain any toxic elements
- ✗ Lower ZTs compared to those of inorganic TE materials
- ✗ Mostly p-type because n-type organics are unstable in air

**Hybrid**
- ✓ Conjoins the benefits of inorganic and organic TE materials
- ✓ Allows for high performance inorganic TE materials to be deposited onto lowly thermally conductive and flexible organic materials
- ✗ They still contain toxic and rare inorganic elements
- ✗ No research has been done on their lifecycle performance [3]

## RESULTS: Material patterns

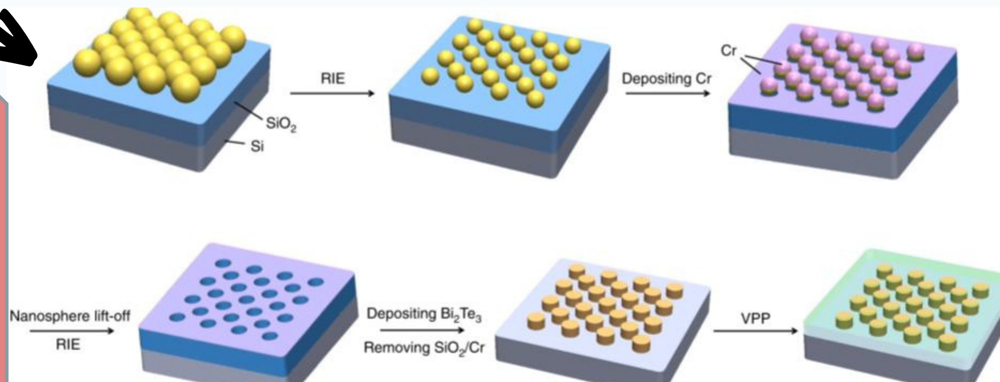
A set of simulations to compare how different thermoelectric and interface materials perform. Here is a summary of my findings:

*Ag2S-based alloy twisted into various shapes [4]*

Highest performing *inorganic TE pair*: **n-type Ag2S0.5Se0.45Te0.05** (a flexible film) and **p-type Mg0.97Zn0.03Ag0.9Sb0.95** (MgAgSb based alloys were introduced as a substitute for Bi2Te3 based alloys due to scarcity of Te).

Highest performing *hybrid TE pair*: **n-type Bi2Te3/SWCNT** (flexible and has ZT of 0.89) and **p-type Bi2Te3/PEDOT** (fabricated synthesizing PEDOT within Bi2Te3 nanoparticle arrays).

Highest performing *organic TE pair*: **n-type TBDOPV:N-DMBI-H** (high electrical conductivity because lots of atoms lie in same plane) and **p-type PEDOT:Tos** (PEDOT is known for its environmental stability and solution processability [6]).



Fabrication procedure for Bi2Te3/PEDOT hybrid [5]

## RESULTS: Geometric patterns

A set of simulations to exhibit how changing the geometric parameters of the thermoelectric generator effect the output voltage. Here are the trends I found:

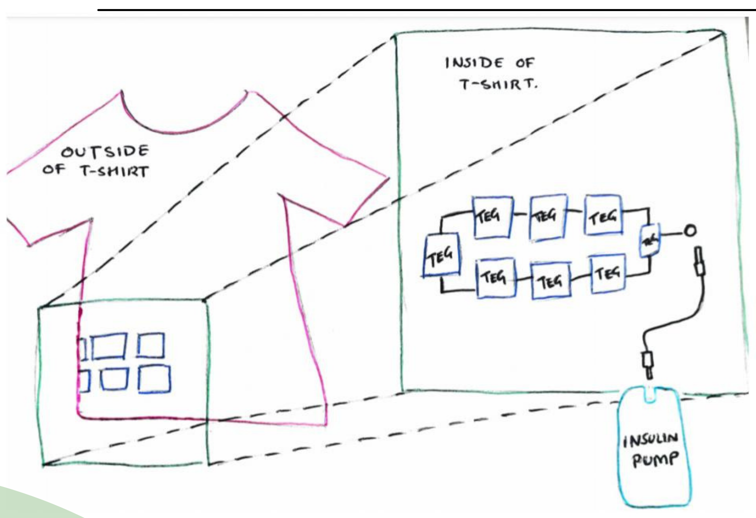
When the fill factor (F) remains constant and as the size of the module and number of couples increases, the output voltage increases

Voltage remains constant when the leg sizes and module sizes vary but keeping the fill factor (F) and number of couples (n) the same.

As the number of couples increases (n) and hence the fill factor (F) increases, the output voltage increases proportionally to F, all whilst the module size stays the same.

When the number of couples (n) is increased but the fill factor (F) and the module size stay the same, the voltage increases proportionally to the couple number. But, for the fill factor to stay the same, the sizes of the couples have to change accordingly.

## NOVEL TEG DESIGN



Using the hybrids: **n-type Bi2Te3/SWCNT and p-type Bi2Te3/PEDOT**, each module size = 50 x 50 mm2, F = 0.627 and the leg sizes = 2.8 x 2.8 mm2. One module produced 0.4V, therefore 7.5 modules are needed to produce the 3V for an insulin pump.

PROs
- Easy to manufacture
- Removeable connector between pump and wearable TEG

CONs
- Clothing must be tight fitting
- Practicalities, like washing clothes, present challenges
- Large amount of TE material needed, Bi and Te are rare - expensive

## LITERATURE REVIEW

These researchers developed a novel packaging solution for TEGs, using high performing inorganic bulk TE materials that are embedded in a **stretchable elastomer** [7]. The liquid interconnects also allow for **self-healing ability.** The final results produced a ZT~0.35 at F=0.06.

*Image of packaged TEG demonstrating flexibility [7]*

*Image of yarn legs embroidered into spacer fabric [8]*

Researchers describe a new **3D fabric-based**, wearable TEG. It was fabricated by alternately **weaving p- and n-type organic thermoelectric composite coated yarns** into a spacer fabric substrate. The yarns were connected electrically in series using conductive paint. Results showed that the prototype generates a low thermovoltage of ~800 μV and an output power of ~2.6 nW at ΔT = 66 K. [8]

## CURRENT LIMITATIONS

- Organic material enhancement is limited by the fact that the **electrical charge carrier transport is not fully understood.**
- The material encapsulating the TEG can cause **degradation of efficiency** if it is too heavy. Future exploration into aerogels and polymers is needed.

- Limited understanding of **filler affects** at interfaces is inhibiting optimised filler selection. Research into **how fillers effect charge carrier transport at interfaces** would enable better engineering of fillers to boost electrical performance
- 2D flat TEGs cause difficulties for wearability because they use **temperature gradients parallel to skin.** Weaving yarns wrapped in thin film TE materials in the perpendicular direction is a potential solution.
- Thermal contact resistance is made worse by **air gaps** between the TEG and skin surface.

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