The Current Obstacles of Thermoelectric Semiconductor Technology from Efficiency, Performance, and the Environment

A Research Paper submitted to the Department of Engineering and Society

Presented to the Faculty of the School of Engineering and Applied Science

University of Virginia • Charlottesville, Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science, School of Engineering

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Spring 2023

On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

From basic comfort to food storage and super-computers, society has found a constant need for thermal management which has gradually led to the development of semiconductor based thermoelectric technology. Despite being capable of converting electric current into temperature differentials, it isn’t often applied in the most common applications for heating and cooling, like air conditioning. Instead, thermoelectric technology is found in smaller scale heating/cooling applications with stricter constraints or it is used for thermoelectric generation. Thermoelectric technology has it’s own set of strengths and weaknesses that aren’t entirely ideal for replacing many larger cooling systems for several reasons, but the technology has many unique properties that make it applicable for cooling for more specific needs while also having applications outside of just cooling. To understand why there is such a narrow field of applications for thermoelectric technology, it is necessary to examine other technologies that set a foundation for, compete with, or rely on thermoelectrics while also evaluating the influence that society has played in the development and integration of these technologies.

Many forms of technology started with a high overhead cost or an unwieldy design and were mainly used in specific situations that truly required it, but those technologies, given enough reason for development, can be refined enough to become commonplace and usable in many situations. Thermoelectric technology is still relatively new, but due to the shared application for cooling, thermolectric devices can be compared with compressor cooling systems which are commonly used in air conditioning units. According to the US Energy Information Administration, data from 2020 showed that about 88% of households in the United States had some form of air conditioning. (U.S Energy Information Administration, 2022), but it took over a century since some of its earliest prototypes to reach this point. One of the first compressor based air conditioning designs was made by John Gorrie in the 1840s when he proposed a design for air conditioning with the intent that it would help combat diseases such as malaria (Roth, 1936). For multiple reasons, this design failed to gain commercial success and it wasn’t until the early 1900s that Willis Carrier was assigned with the task of reducing humidity to improve the performance of printers during the lithography process. The cooling coils reduced humidity by condensing water vapor, but the cold air was also found to be comforting. This idea of comfort cooling was explored and further developed to gradually expand into public settings, like movie theatres, and then brought into homes (Shah, 2019). Especially with other factors, like energy efficiency legislation, it is clear that society has a heavy influence on the development of technology. Air conditioning went through many stages of development, driven to resolve several different problems in society, so it would make sense that thermoelectric technology has, or will require, a significant amount of societal influence for its use and development.

Although thermoelectric technology has been possible since the discovery of the Peltier effect in 1834, thermoelectrics have failed to see widespread use in comparison to other forms of cooling, like compressor based systems. The existing and future applications, experiments, and developments regarding Thermoelectric technology can be found by looking through literature and reports. It is necessary to understand this technology to analyze and compare it with the technology that is used more prevalently, while also determining which applications benefit more from thermoelectrics. This information can be used to foresee the technological closure for thermoelectrics through the Social Construction of Technology.

The Need for Thermal Management

Thermal management is commonly a main design goal, such as for a room heater or an air conditioning unit. Many times these devices are designed to meet specific standards, such as the temperature ranges assigned by the US Food and Drug Association. These require food to be refrigerated under 40 degrees fahrenheit or 4 degrees Celsius to slow bacteria growth (FDA, 2021). Alternatively, the food could be heated and held at a temperature above 140 degrees Fahrenheit or 60 degrees Celsius (FDA, 2022). These FDA guidelines are meant for regulating food for human consumption, but there are also more strict regulations, such as for the storage of vaccines. Many of these immunobiologics are sensitive enough to require storage within a small range of temperatures, such that it is cold enough to maintain potency, but not so cold that it damages the contents or compromises the materials for properly containing it (CDC, 2022). Applications in which thermal management is the primary goal have a clear need for a dedicated heating or cooling system, but it is still found in many other products, hidden from the user.

Proper thermal management is especially necessary in many electronics since the normal operation can generate byproduct heat than can damage or destroy components. For this purpose, engineers may need to include other devices to manage this heat, but there are many different options that can be explored. Many designs could be fine with a passive solution, such as simply improving ventilation to improve air flow or by attaching a heat sink which effectively increases the surface area for dissipating heat. Even for complex devices, passive cooling can be highly effective, such as cell phones and other mobile devices. This is necessary for both the structural and functional integrity of the device, but also for the performance, since the electronics are more power efficient and reliable at lower temperatures (Xie et al, 2013). Passive cooling is not enough for all designs though, and may require additional energy input to effectively dissipate byproduct heat. Active cooling methods are most commonly seen using in combination with passive techniques, like including a fan on top of a heat sink. For additional thermal output, more complex systems would need to be implemented. Active cooling is where Thermoelectric cooling modules have some potention, but compressor cooling systems are one of the oldest and the most common form of active cooling found in designs.

Compressor based cooling systems work by cycling a chemical refrigerant between its gaseous and liquid state through pressure. This chemical refrigerant must have a boiling point that is below the temperature of the environment that it is removing thermal energy from (*Basics*, n.d.). As a liquid, the refrigerant is able to absorb thermal energy from its environment until it has all expanded into a gas. At this point, the refrigerant is moved another location to dissipate the heat and cool the gas back to a liquid. This liquid refrigerant is moved back to the target cooling environment to repeat the process (U.S. Office of Energy Efficiency & Renewable Energy, n.d). The many moving parts within a compressor system are liable to breaking or degrading through normal use while also generating noise. The chemical refrigerant is a mandatory component that may contribute to greenhouse gas emissions if released/leaked. These refrigerants must be evaluated and classified using the "ozone-depletion potential, global warming potential (GWP), flammability, toxicity, local air quality, ecosystem effects, and occupational and consumer health/safety" (Environmental Protection Agency, 2022) and future refrigerants would need to be developed with these properties in mind.

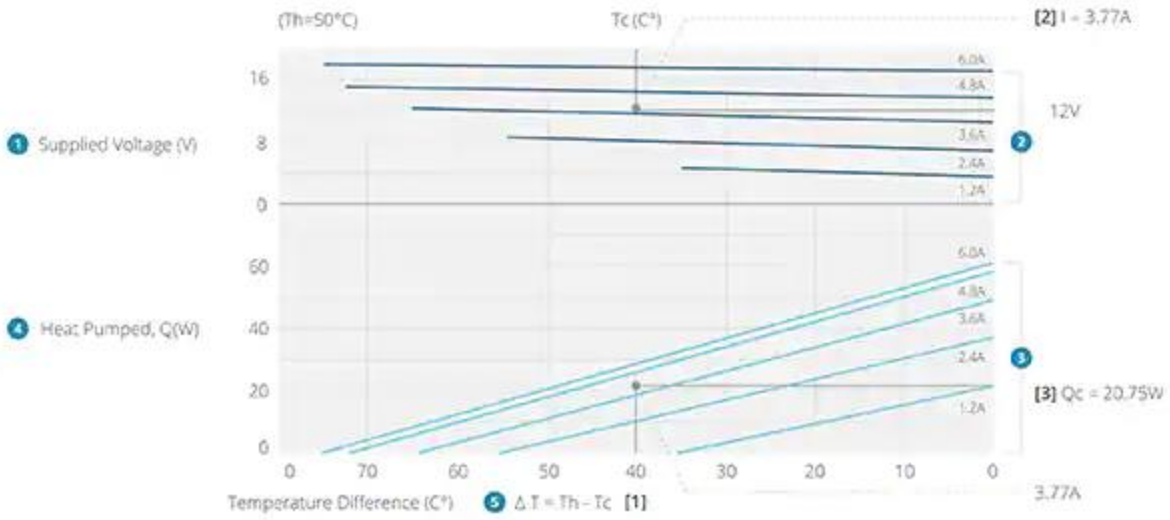
Thermoelectric cooling devices, however, operate on fundamentally different principles. Rather than manipulating the physical state of unique chemicals, thermoelectric coolers use the Peltier effect, which use a series of alternating semiconductors to create a temperature differential between two sides that is related to the electric current provided. This method of operation allows for devices using thermoelectric cooling to have the potential of using no moving parts and generating no noise along with the additional perks of being physically small and not requiring a refrigerant (U.S. Office of Energy Efficiency & Renewable Energy, n.d). The Peltier effect can also be reversed and create an electric current when a temperature differential is created. According to Baru and Bhatia (2020), these devices are dependable since their operation does not require moving parts while also being versatile with its application for energy generation in environments with otherwise unusable byproduct heat. With the benefits of thermoelectric cooling reflecting the opposite of the drawbacks for compressor systems, it isn't immediately clear why thermoelectric technology is not nearly as prevalent.

Thermoelectric Limitations in Thermal Management

Thermoelectric devices create a temperature differential between two sides when an electric current is applied. It is important to emphasize that this is a temperature differential rather a given rate of thermal energy transfer. At any given electrical current, there will be an approximate maximum temperature differential that can be generated between the two sides. To create a larger temperature differential, more electrical energy also needs to be provided. This relationship between electrical energy and thermal output is not linear, but documentation is often provided to assist with product design and an example can be seen in Figure 1.

Figure 1

Example Graph for Controlling a TEC Module from Electrical Parameters to Thermal Output



Note. This graph was from Smoot, J. (2018, February 6). *Choosing and Using Advanced Peltier Modules for Thermoelectric Cooling*. Digi-Key Electronics. Retrieved March 15, 2023, from https://www.digikey.com/en/articles/choosing-using-advanced-peltier-modules-thermoelectric-cooling

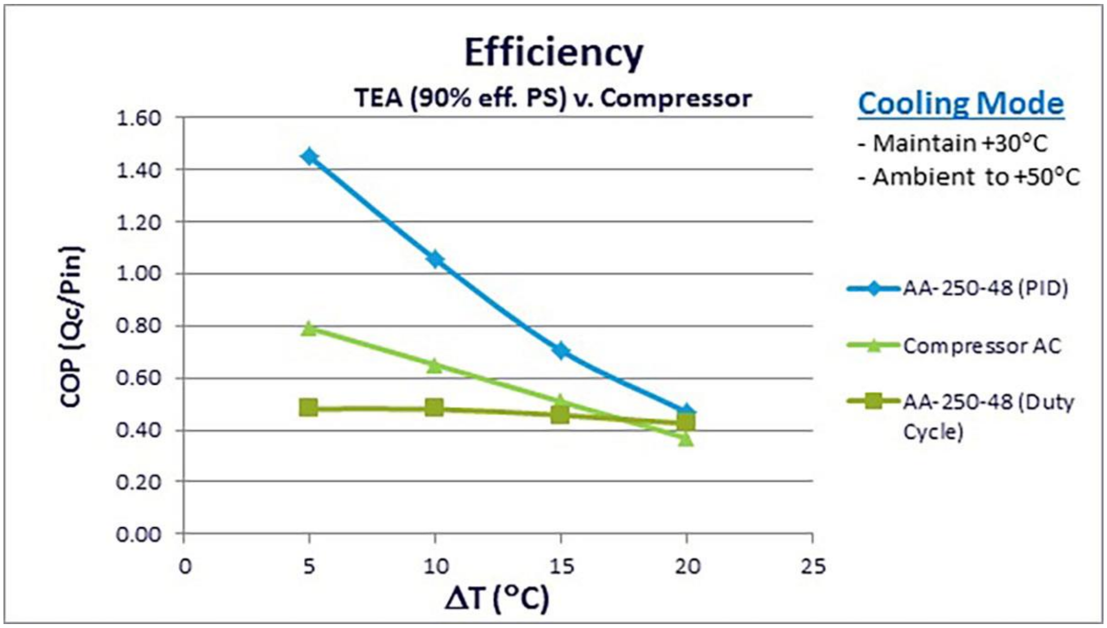
Figure 1. Example graph useful for controlling a thermoelectric cooling module with electric current and voltage for a rate of thermal transfer and temperature differential (Smoot, 2018)

Although design is slightly streamlined using aforementioned documentation, there are also other properties to be aware of. The electrical resistance is also variable, dependent on the hot side temperature. Although the variable resistance may be listed at given temperatures, the variability paired with the thermal output correlating with the current makes operating thermoelectric modules more difficult, often requiring a form of current source rather than a more simplistic voltage source. These devices are certainly capable of maintaining a stable temperature, given that the temperature differential will be maintained given a constant current, but modulating the current can also prove difficult (*HFAN-08.2.0*, 2004). Electrical devices like motors are commonly controlled by pulse width modulation (PWM), but a simple control algorithms like On-Off or Proportial, Integral, Derivative algorithms are not actually as efficient. A manually tuned fuzzy logic control algorithm has been shown to be most effective for reaching and maintaining a stable temperature (Indiketiya, 2021). Also, an unfiltered PWM signal is thermally inefficient since the generated heat is less efficient at higher currents and may require additional hardware to filter it, like by filtering the PWM signal through an inductor for an more stable average current (*Peltier Element Efficiency*). Even more hardware is likely to be required in a complete design because, despite fundamentally not requiring any moving parts to perform cooling, the device still needs to dissipate its byproduct heat. This means that it would require other components, like a heat sink and fan, or in some cases, a liquid cooling system could remove heat while maintaining a more compact design.

The previously mentioned thermal output restrictions can still be worked around by stacking thermoelectric modules for greater temperature differentials or by using many thermoelectric devices over a larger area for a greater rate of thermal energy transfer. Stacking thermoelectric modules will draw more energy and typically requires the surface area of the device to reduce for each layer such that the generated heat can be handled by the larger layer of semiconductors. One experiment performed by Kamasi, et al (2015) tested this method of stacking and successfully demonstrated an increased temperature differential, but it was only an increase by about 2 degrees Celsius by adding an extra layer. The use of more thermoelectric devices will cost more money and use more electricity while also contradicting one of the primary benefits of being small. This increased cost for the size of a Thermoelectric system quickly accumulates in comparison to alternative cooling systems like compressors, which are able to scale larger with greater thermal output for lower costs (U.S. Office of Energy Efficiency & Renewable Energy, n.d). Using some of the most efficiently designed thermoelectric systems could still consume more power than an equivalent compressor cooling system. Modern compressors, under maximum load conditions, would "use 30% to 35% less power", but thermoelectric coolers can achieve efficiency "25% to over 90%" greater than compressors at lower temperature differentials (*Electronic*, 2016). Efficiency of Thermoelectric devices appears to decline much more rapidly with greater temperature differentials than compressors, as seen in Figure 2.

Figure 2

Efficiency of Thermoelectric and Compressor Coolers at Different Temperature Differentials



Note. This graph was from *Electronic Enclosure Cooling Thermoelectric vs. Compressor-Based Air Conditioners*. Laird Thermal Systems. (2016, April). Retrieved March 15, 2023, from https://lairdthermal.com/thermal-technical-library/white-papers/electronic-enclosure-cooling-thermoelectric-vs-compressor-based-air

Although this greater efficiency is possible, overall device efficiency depends on implementation and not all environments may be able to operate a thermoelectric cooler at its most ideal conditions. Similar to how compressors can improve with better refrigerants, thermoelectric technology has greater potential in the future with the discovering of thermoelectric materials with a greater conversion efficiency (Francis, 2005). One of the currently most used thermoelectric materials is bismuth-telluride, but there are clear concerns regarding the conversion efficiency, use of relatively scarce earth materials, high device costs, and potential negative impacts on the environment. Overall, however, the benefits from the use of thermoelectrics are estimated to outweigh the environmental costs of production by a notable margin and “also shows the comparable ecofriend potential of this platform vis-a-vis electricity from two widely used renewable sources - solar and wind” since one of the primary costs was their “large electricity consumption for their processing” (Iyer & Pilla, 2020).

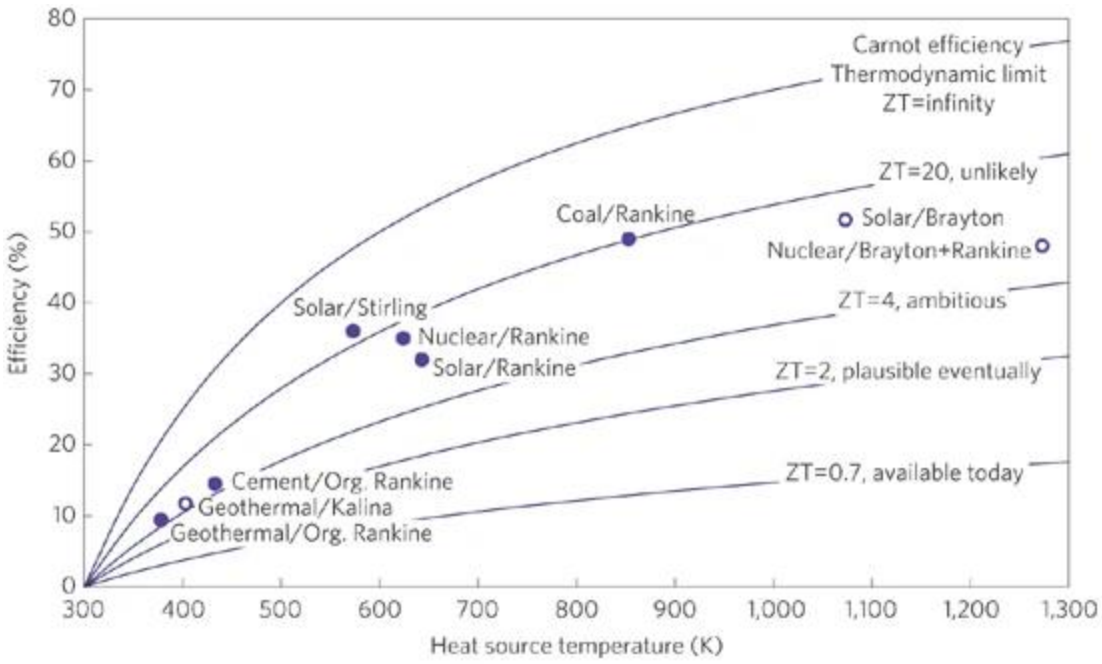
Thermoelectric devices, when used for thermal management, are usually used for the cooling functionality, since the heat generated from these devices are typically just a byproduct and there are many different ways to perform heating with dedicated hardware. This dedicated hardware isn’t always a necessary cost if the device is designed to be used as both a heating and a cooling system. A Peltier based thermoelectric cooling system can perform both heating and cooling with the same hardware by simply switching the direction of the current or the polarity of the voltage across each peltier module (Smoot, 2018). This flexibility of the hardware, in addition to thermal stability, is one of the few strengths that thermoelectric technology consistently has over the other options for thermal management, but there are other applications that it can be used for.

Applications of Semiconductor based Thermoelectric Generators

Most methods of generating electricity from heat are indirect, requiring additional hardware overhead and losing a lot of efficiency. Burning coal is one of the more common examples of converting heat to electricity and tend to operate at around 33% efficiency through a network of boilers, turbines, and many other large components, while also greatly contribute to climate change while consuming a limited resource (U.S. Office of Fossil Energy and Carbon Management, n.d). Although there are many ways to generate electricity, thermoelectric materials are one of the few capable of performing a direct conversion, but this doesn’t mean that it is more efficient. For large scale systems, thermoelectrics fail to compare, even with the best material available, which is unworkably expensive and restrictive but has a thermal efficiency value around 3.5, it still doesnt come close to the existing large scale power plants (Vining, 2009). A graph displaying the required efficiency to compare with heat engines can be found in Figure 3.

Figure 3

Required efficiency for Thermoelectric materials to generate electricity to compare with existing heat engines



Note. This graph was from Vining, C. (2009, February) An inconvenient truth about thermoelectrics. *Nature Mater* 8, 83–85. https://doi.org/10.1038/nmat2361

Although it doesn't seem realistic to apply Thermoelectric semiconductors for generating heat on a large scale, it may be possible to apply it at smaller scales. Mechanical heat engines lose efficiency at smaller thermal power thresholds and are thus not applicable in situations like making use of waste heat, such as from vehicles, which may be where thermoelectrics can be used instead (Vining, 2009). They can also be applied to the roadways to use use the heat absorbed by the pavement. According to an experiment by Jiang et al (2017), thermoelectrics can be used with this waste heat without modifying existing pavement materials and can combat issues like the Urban Heat Island effect in a productive manner. This experiment currently shows that it would primarily be cost effective in “tropical and subtropical regions where the radiation intensity and the average annual temperature is high” (Jiang et al, 2017). The analysis from this experiment is hopeful for further improvement as the materials improve, but it does neglect some factors, like road maintenance and deterioration of the material performance over time. This application towards roadways, estimates were calculated with figures on the scale of a “road of 1 km in length and 10 meter in width” (Jiang et al, 2017), but that may not be realistic to obtain all of the required thermoelectric semiconductors. In regards to an experiment for thermoelectric generation from waste heat in water, it was found that most thermoelectric modules are manufactured primarily for the temperature ranges optimal for refrigeration tasks rather than for thermoelectric generation. Not all available thermoelectric modules are usable in situations in which the thermoelectric generation makes use of higher temperatures and are likely to make up a significant portion of the cost of any project that they are included in. These devices also declined in performance over time, seeing a “very significant increases in electrical resistivity (15-27%) occurred during the test period of 76000 hours” (Rowe et al, 1997). This source was making use of arguably older technologies and materials, but it still displayed several limitations with some applications, like the long-term reliability of costly, limited materials which may further prevent use in large scale projects.

Recent Research, Development, and Applications

The energy consumption and scaling of thermoelectric devices is not ideal for large scale applications or for high thermal loads, but not all applications have been explored. The strengths of these devices lie in their versatility and smaller size. Zaferani, et al (2021) listed several of the unique properties and how they can be applied for use in the medical field in their paper. These applications ranged from the stable transport of medical supplies to localized hypothermia for surgery. There was also the inclusion of cryotherapy and treatments in the dermatology field for skin treatment, both of which emphasize the application of cooling a small area, requiring the small size while accepting the high energy and material costs as a tradeoff. They also described the development of flexible and wearable thermoelectric generators is in development and, with the advancement of other technology, like 3D printing, these thermoelectric devices may be applied in more effective ways, potentially tackling inefficiency issues through the design implementations rather than through the development of new materials.

The previously mentioned application for thermoelectric technology in the automobile industry has also been gradually implemented. Initially, it was primarily used as thermocouples/sensors or smaller luxury inclusions, like seat or cup coolers, due to poor efficiency. Nanotechnology improvements have improved efficiency enough for vehicles to consider development for replacing, or at least assisting, larger components. The main ideas focus around the alternator, for generating electricity from the heat of the engine or exhaust pipe heat. The US Department of Energy attempted to sponsor research with the goal of developing technology to improve fuel economy by 10%. Additionally, vehicles are seeking to implement thermoelectric cooling for the air conditioning with less expected maintenance (Fairbanks, 2008).

Conclusion

Thermoelectric technology effectively has two general applications, thermal management and thermoelectric generation, but both are currently limited. Compressor technology has established itself as the primary technology used for large scale comfort cooling and is used for its size and hardware cost scalability and greater efficiency at high load conditions. Thermoelectric technology can be complex to design and has a limited range of operating temperatures, but it is capable of greater efficiency at lower thermal loads while also not requiring a heavily regulated refrigerant. It may take more time to overcome the technological momentum of compressor technology in the comfort cooling market, but it is possible with improvements in the thermoelectric materials for greater efficiency while retaining it's net environmental benefits and preferably lowering device costs.

This material improvement also applies to the thermoelectric generation. Although this application is nearly uncontested, performance results are minimal and likely not worth increased material cost and design complexity, especially in regards to replacing large scale electric generation, like coal or nuclear power plants. These obstacles have resulted in thermoelectric technology being applied mostly in situations that only exploit the unique properties, like small size, versatile hardware, or thermoelectric generation. There are a few situations that are being explored that demonstrate these uses, particularly in higher performance electronics and medical applications, since the cooling is required with a small size while the material and energy costs are acceptable tradeoffs. Thermoelectric generation, however, is seen as more applicable for converting low power waste energy, particularly with the rise of electric vehicles and automation.

The development of thermoelectric technology is heavily restricted by the existing technology. Large scale cooling and electric generation is simply performed better by other methods, but societal pushes for environmental sustainability and some specific applications have led to the exploration and development of thermoelectric technology. Particularly, the absence of required refrigerants and capability of utilizing waste heat makes thermoelectrics a viable option for small scale cooling and energy generation. Applications in the medical field and electronics are capable of using the unique properties of thermoelectric semiconductor materials in spite of high energy and material costs, but still desire improvements before seeing widespread commercialization.

The current status of thermoelectrics displays that the technology is viable, if not more optimal than alternatives, in several situations but are not seeing widespread use. There are a lot of problems that, through the lens of the Social Construct of Technology, can almost all be driven back to have societal causes and solutions. Most technological issues are not simply that the technology doesn’t work better than others, but rather that it is too expensive to research and produce. Sometimes it can actually being a supply issue in regards to the current available devices or the materials required to manufacture them are in limited supply. Much of the research into thermoelectrics have been funded or incentivized by other programs, like the Eco-Energy City Project or contracts awarded by the New Energy and Technology Organization in Japan as mentioned by Rowe et al (1997). It isn’t uncommon that large energy projects receive significant subsidization from government entities for construction, manufacturing, research, and various other aspects, so thermoelectric projects may simply require more assistance to overcome much of the overhead costs and incentivize production. Governments and organizations influence this technology, not only through funding, but also by establishing regulations and standards. Food and medical standards must be met and are two of the largest driving factors for developing thermoelectric cooling. Legislation and programs for cleaner energy are driving development for use of thermoelectric generation to make use of waste energy. Currently, societal influence has primarily pushed thermoelectric technology to be further researched, but it has not yet resulted in many significant changes in manufacturing or construction, so it requires greater societal pushes, like the funding of larger projects or subsidization of manufacturing, so incentivize and accelerate development.

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