

Power Generation via a Thermoelectric Generator Driven by a Reversible Exothermic Reaction

by
Renuka Bhatt

A THESIS

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Abstract approved: _____

Nick AuYeung

Solar thermal energy can be stored and later converted to electrical energy using a combination of thermochemical energy storage (TCES) and a thermoelectric generator (TEG). This TEG and TCES combination illustrates a potential route for clean electricity storage from renewable energy. TCES allows for thermal energy from the sun to be stored as chemical energy that can then be utilized to generate electrical energy through a TEG device at a later time. While there are many methods of TCES, this paper presents a storage through a reusable porous matrix impregnated with CaCl_2 . The dehydration and hydration of CaCl_2 within the matrix material provides a reversible thermochemical reaction for TCES. The dehydration of CaCl_2 hexahydrate within the matrix material stores thermal energy; while, the hydration of anhydrous CaCl_2 within the matrix material provides a heat input for the TEG device. The TEG principle of operation is based upon the Seebeck effect; a phenomenon that converts a temperature difference into a voltage difference to create power. Thus, the thermochemical reaction between CaCl_2 and water creates a hot side for a temperature difference with the ambient cool side. In general, the Seebeck effect is inherently a weak thermoelectric effect; and it is for this reason that the TEG efficiency is very low as compared to a photovoltaic and battery storage system. Nevertheless, the TEG and TCES combination poses a cheaper and more scalable storage system that could still compete with the PV and battery storage system. In terms of cost analysis, TEGs are cheaper within low peak power but high storage capacity settings; this advantage makes the TEG and TCES combination comparable to that of the PV and battery storage system. Experimental investigation illustrated that the matrix material produced 0.6mW/g of power; this was then maintained for about 17 min before dropping to a negligible temperature difference. While this illustrates the low overall energy efficiency of a TEG and TCES storage system, the economic motivation behind this method is presented. With a long solar collection time, a high storage capacity, and a low TEG peak power, the TEG/TCES storage system could be beneficial. Within further investigations, utilizing a heat sink, exploring the cold side of the TEG, and considering a more insulated experimental set up could be beneficial for this proof of concept.

Key Words: energy storage, solar thermochemical, thermoelectric generator

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Honors Baccalaureate of Science in Chemical Engineering project of Renuka Bhatt presented on May 20, 2021

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I understand that my project will become part of the permanent collection of Oregon State University, Honors College. My signature below authorizes release of my project to any reader upon request.

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Introduction:

Over the years, energy storage has started to become a more necessary capability to supply electricity sourced from renewables on-demand. Energy storage can play a pivotal role in supplying energy when the demand becomes larger than the supply if the primary energy source is intermittent. This can increase the share and utilization of renewable sources of energy as it makes them more cost effective.

Photovoltaic systems inherently have existing limitations in that the electricity generated can only be produced during the day and during specific weather conditions. For example, dust accumulation and cloud coverage can severely impact the power production from a solar panel as they act as barriers from the sun and heat. With over-supply issues during the day, and under-supply issues at night, this limitation results in an irregular power generation as there are large gaps between the supply and demand of electrical power¹. Furthermore, photovoltaics require maintenance and cleaning as degradation can affect the efficiency of the system. However, coupling battery storage with a PV system helps to integrate the energy source to the grid; this diminishes over-voltage issues as well as balances the generation and consumption of electrical power to meet the supply and demand. Even with this, supplementary energy storage systems are being investigated. Thus, this introduces the combination of thermochemical energy storage (TCES) with thermoelectric power generation for storage and electricity production (Figure 1). Thermoelectric generation can be advantageous over conventional power generation as it does not require routine maintenance, are considered a reliable source of energy, and they have a high scalability (they can be applied to any sized heat source). The addition of thermochemical energy storage is a possible heat input for the TEG device. Thus, this illustrates the motivation to investigate the TEG and TCES energy system. When comparing the TEG/TCES system to the PV/battery system, the former requires an additional step for energy storage. The TCES is utilized for the storing and charging of thermal energy, and the TEG functions as the discharge of energy as it converts from thermal to electrical. On the other hand, the PV works to convert solar energy directly into electrical energy, and the battery stores and discharges this energy.

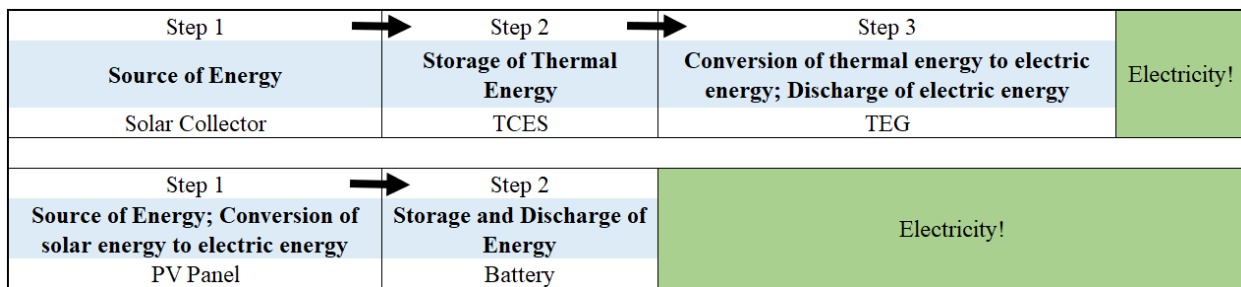


Figure 1: The TEG/TCES system is illustrated; the PV/Battery System is also demonstrated.

Nevertheless, a major barrier for the PV and battery system is the high cost of battery storage. Some batteries also have a low-energy density and a short lifetime (this can vary based on how

¹ I. Ranaweera, O.-M. Midtgård, Optimization of operational cost for a grid-supporting PV system with battery storage, Renewable Energy. (2015). (accessed April 27, 2021).

they are charged and discharged); this makes this energy storage less beneficial for grid storage¹. While, the cost of the PV panels and TEGs are comparable, the cost of a TEG can depend on the available temperature difference. A recent study showed that an increase in the temperature difference resulted in a lower payback time as well as a lower cost per kW. Figure 2 illustrates how the cost and payback period of the TEG system decreases as the temperature difference increases. For example, when comparing a TEG temperature difference of 50 °C to a temperature difference of 200 °C, the cost per kW of a TEG decreases from \$80,000/kW to less than \$10,000/kW. This decrease in costs makes the TEG system more attractive when combined with the TCES storage system.

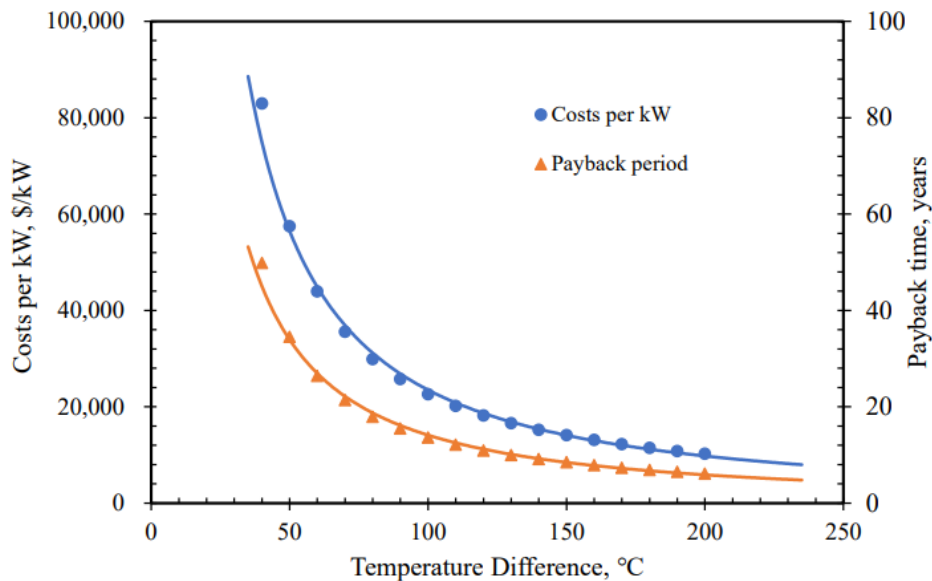


Figure 2: This figure illustrates that the cost per kW and the payback period depend upon the temperature difference of the TEG.²

There are many different methods of thermal energy storage. Currently, Google is pursuing the Google X Malta project, which features storage of renewable energy in the form of molten salt (Figure 3). Within this energy storage concept, Malta is collecting renewable energy that is gathered from wind or solar farms. They collect this energy by converting the electricity into thermal energy through a temperature difference. Regarding the temperature difference, the heat is stored within the molten salt; while, the cold is stored within a chilled liquid. This energy can then be stored for up to 200 hours before being utilized³. To use the stored energy, the temperature difference is then converted back into electrical energy and distributed as electricity. Ideally, this temperature difference would produce power. Such a concept would be extremely beneficial as it would negate the need for fossil fuels and other sources of energy that may not be as environmentally friendly. Since this energy project can be extremely useful; similar methods

² K. Li, G. Garrison, Y. Zhu, R. Horne, S. Petty, Cost Estimation of Thermoelectric Generators, Stanford University. (2020). <https://pangea.stanford.edu/ERE/db/GeoConf/papers/SGW/2021/Li1.pdf> (accessed May 1, 2021).

of thermochemical energy storage are being developed due to its ability to store energy indefinitely.

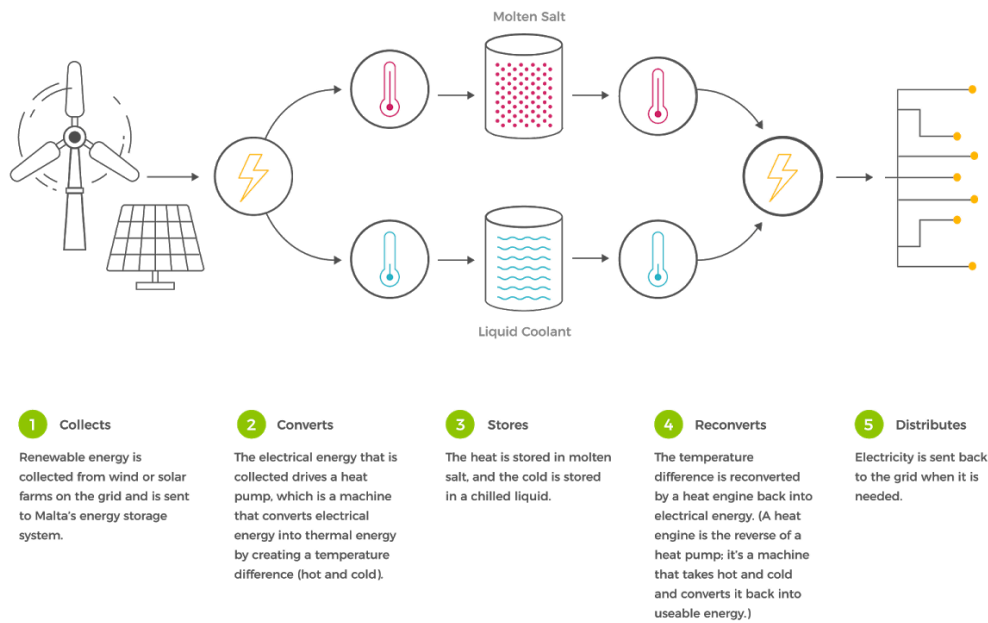


Figure 3: The Malta Electro-Thermal Energy Storage cycle is shown above. This process illustrates the key features of the system from start to finish. ³

NASA is also investigating another method for energy storage through the use of radioisotopes for thermoelectric generators (RTGs). This lightweight power system utilizes heat from the natural radioactive decay of plutonium-238 or plutonium dioxide to generate power/electricity using the Seebeck effect (Figure 4). With this, semiconductor thermocouples are connected electrically in series and thermally in parallel. The temperature difference between the hot plutonium dioxide and the cold environment of space brings about a long-lasting, high energy density heat source that can supply hundreds of watts of power without any moving parts within the system⁴.

³ Our Solution, Malta Inc. (2018). <https://www.maltainc.com/our-solution> (accessed March 11, 2021).

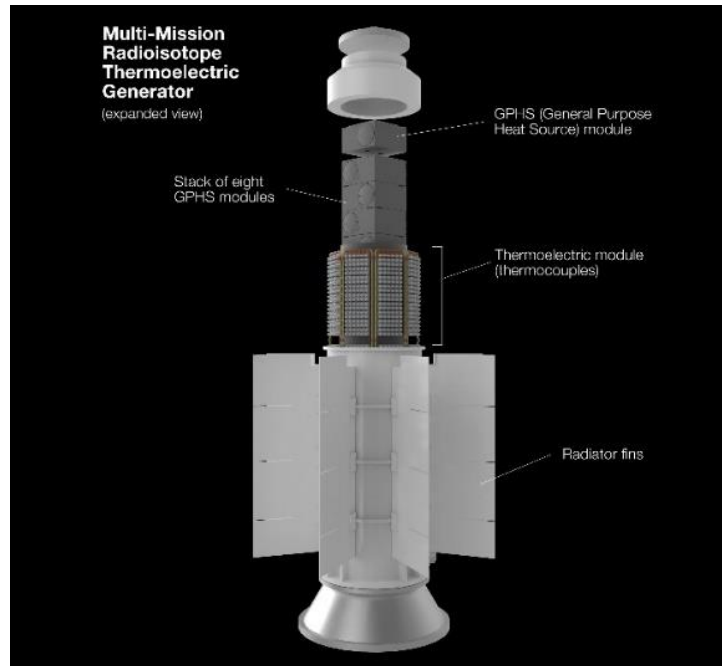
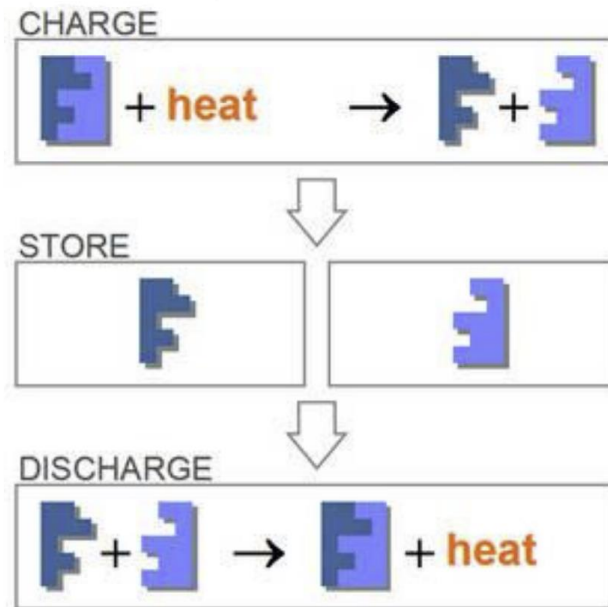


Figure 4: A pulled-apart view of the radioisotope thermoelectric generator is shown above. The main components of the system are fully labeled.⁴

Thermochemical energy storage is another heating method that is being discussed as it provides higher storage densities and lower thermal losses. This makes this storage extremely beneficial for low temperature and long storage as well as high storage density. Thus, a combination of TCES with thermoelectric generation offers an opportunity for conserving renewable energy sources. Within this storage, a reversible chemical reaction would store energy as the products of the reaction and the heat are stored separately; when the reverse reaction occurs, this stored energy can be recaptured (Figure 5). The heat and the products are stored separately because the intermolecular bonding between the chemical material pairs are broken and separated into their own reactive components; this is considered desorption. When the reactive components are recombined through the reversible reaction, the stored heat energy can be recovered and utilized; this is considered sorption⁵.

⁴ Power Systems, NASA. (2020). <https://rps.nasa.gov/power-and-thermal-systems/power-systems/> (accessed March 11, 2021).

⁵ S. Kalaiselvam, R. Parameshwaran, Advances in thermal energy storage (TES) systems, Thermochemical Energy Storage. (2014) 127–130. doi:<https://www.sciencedirect.com/science/article/pii/B9781782420880500018#!>



Source: ECN, the Netherlands

Figure 5: This figure illustrates the principle behind thermochemical energy storage. As the reaction occurs, the heat and products are stored separately. When the reverse reaction occurs, and the reactive components are recombined the stored heat is reutilized⁶.

Determining an appropriate reversible chemical reaction can allow for a high storage capacity to be achieved. Some beneficial salt hydrates that could be utilized within thermochemical energy storage are magnesium sulfate, lithium chloride, lithium bromide, and sodium chloride. Another appropriate salt hydrate for a reversible chemical reaction would be calcium chloride with water. This dehydration of the CaCl_2 hydrate has shown to be extremely beneficial for TCES applications due to its high thermal conductivity, low toxicity and flammability, and easy accessibility. Additionally, these hydrate reactions can be stored within a highly porous matrix material such that thermal performance of the storage system can be enhanced⁵. Through adsorption, the reactant will be embedded within the porous material with the water. Then during desorption, the reactive chemical (e.g. CaCl_2) stays within the matrix material; while, the water is removed. Finally, through adsorption of water within the matrix material, an exothermic reaction occurs, and heat is released. Thermochemical energy storage schemes are typically developed for heating applications rather than cooling applications as it is easier to trap heat energy from a solar collector. Additionally, it has been found that combining the thermochemical energy storage with seasonal thermal energy storage (TES) systems can be beneficial. This is because the thermal energy from the sun can be stored as chemical potential through TCES⁵. When the energy is not needed, it can be stored indefinitely in chemical bonds; however, when it needs to be utilized, the reverse reaction allows for the chemical bonds to recombine and release energy.

⁶ Cuypers, R.; Hoegaerts, C., More Effective use of Renewables including compact Thermal Storage (MERITS). In RHC Conference, Dublin, 2013.

Through thermochemical energy storage, a salt hydrate (in this case CaCl_2) would be stored within a porous material. The porous material (impregnated with CaCl_2) would then be dehydrated due to solar concentration or heating using surplus renewable electricity. Thus, this theory is tested through the use of a solar concentrator, an evacuated tube, as well as scales to determine the weight difference. The idea is that the porous material (impregnated with CaCl_2) is weighed prior to being scattered within the evacuated tube. As shown in Figure 6, the evacuated tube is then placed above the solar concentrator such that the water will evaporate from the matrix material and the weight of the melamine will decrease. A previous literary article was able to successfully execute this concept when dehydrating salts through solar thermal energy⁷.

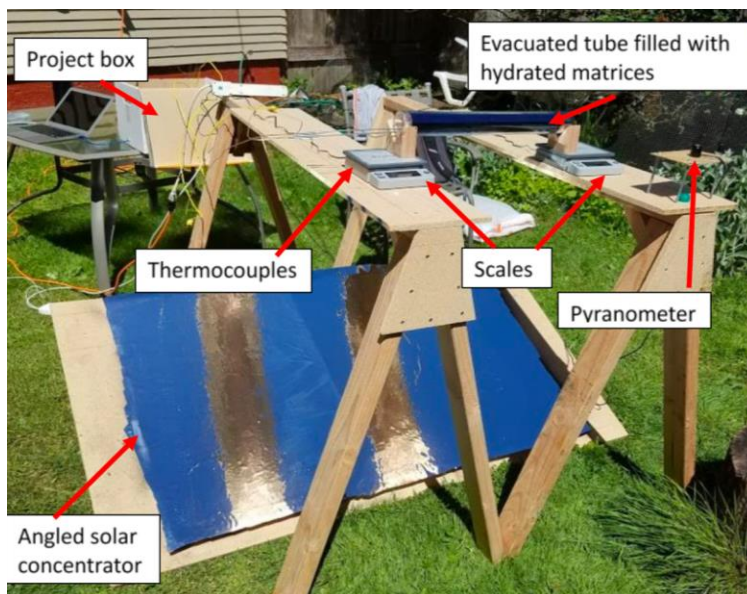


Figure 6: The set up to dehydrate the CaCl_2 soaked melamine through a solar concentrator. The main components of the system are fully labeled.⁷

With the solar concentrator, the temperature will effectively increase allowing more water molecules to leave the material. The angle of the concentrator allows for more sunlight to be reflected onto the evacuated tube and allows for the light to hit the porous material (impregnated with CaCl_2) much more intensely. Therefore, with calcium chloride's ability to store energy when transitioning between hydrate states, the solar concentrator is that much more beneficial (Figure 7). From direct sunlight, the CaCl_2 within the porous material can be dehydrated from the tetrahydrate to the dihydrate state. This is because this transition in stable hydrate states can only occur at low temperatures ($45\text{ }^\circ\text{C}$). On the other hand, the solar concentrator can dehydrate the CaCl_2 within the porous material from the tetrahydrate state to the monohydrate state. This is because the solar concentrator directs the sunlight such that the rays of light bend to focus on the matrix material. Without concentrated solar power, the evacuated tube holding the porous material (impregnated with CaCl_2) reaches about $100\text{ }^\circ\text{C}$. While this surpasses the dihydrate state of the CaCl_2 , it does not reach the monohydrate state at $175\text{ }^\circ\text{C}$. Thus, the addition of the solar

⁷ G. Drake *et al.*, "Development of a small-scale solar thermochemical energy storage system," 2017 IEEE Global Humanitarian Technology Conference (GHTC), San Jose, CA, 2017, pp. 1-8.

concentrator allows the CaCl_2 within the porous material to surpass 175°C and store additional energy. The solar concentrator also allows for the porous material to become reusable as one can simply dehydrate the material to reuse again.

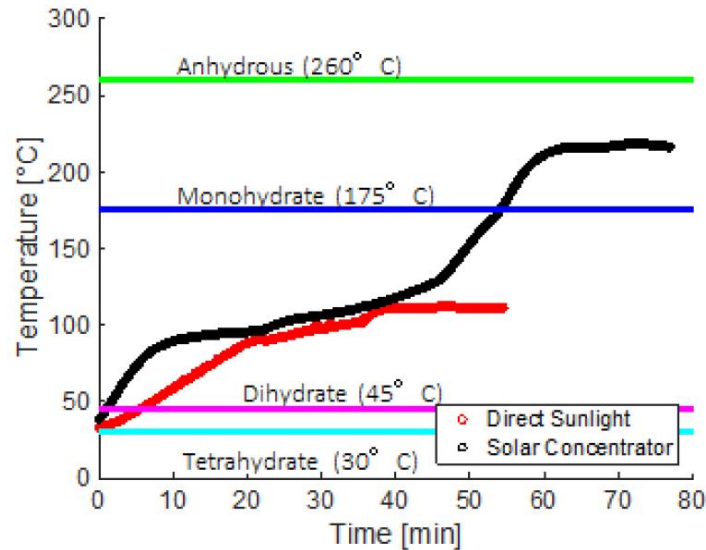


Figure 7: The temperature vs. time graph illustrates which hydrate molecules evaporate at each temperature. As the temperature increases, the tetrahydrate, the dihydrate, and then the monohydrate can evaporate. However, once it reached a certain temperature, it evens out over time as the solar concentrator is unable to reach the anhydrous state.⁷

The use of solar thermoelectric generators (TEGs) could be a suitable energy conversion process as it could convert the thermal energy stored within the TCES to electric energy. With this renewable energy conversion, one would be able to provide on-demand electricity without the use of PV and batteries; this could effectively decrease our dependence upon batteries as the need for energy storage increase. Currently, there are issues with scaling and cost when it comes to utilizing batteries. While it is important to note that TEGs also have this issue, these devices can become competitive in terms of their permanency and longevity, which could minimize routine maintenance in many devices⁸. However, some drawbacks to TEGs could also be their low efficiency when working with smaller temperature differences. Nevertheless, TEGs coupled with TCES could be ideal for distributed, low peak power applications in energy impoverished areas. In addition to this, this combination could be applied within camping stoves and space heaters as well.

Currently, TEG devices can consist of different materials such as bismuth telluride, silicon germanium, and lead telluride. Within this case, the TEG design consists of two silicon germanium substrates with thermocouples (TCs) arranged in between the plates to measure the temperature difference. Therefore, there is a hot side silicate plate and a cold side silicate plate. While there are multiples methods to arrange the TCs, the TEG design in question (Figure 8) is made of TCs arranged horizontally, and the heat flows vertically. The TCs consist of multiple n-type and p-type of semiconducting materials that facilitate the transfer of heat. The TEGs are then connected to an electrical load that to convert the temperature difference into electricity.

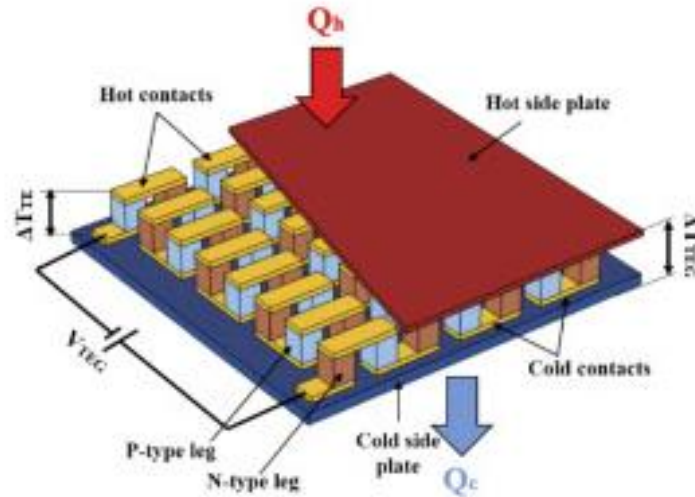


Figure 8: A fully labeled TEG design illustrating the silicon substate plates and the thermocouples arranged in between the plates.⁸

Approach:

By investigating TEG and TCEs together, an energy storage is provided as a heat input to a TEG device. The energy storage is first synthesized through pyrolysis and then utilized to create a temperature difference between the hot and cool side of the TEG. This temperature difference creates a voltage difference which allows for this to be applied in low peak power and high storage capacity systems.

Methods:

The use of melamine provides a non-reactive matrix material for the salt hydrates to be embedded in. This allows for a reversible salt hydrate reaction as the matrix material can provide a beneficial insulator.

Before the utilization of the TEG and the experimental setup, the melamine is first synthesized through pyrolysis to bring about a porous material. With this porous material, an exothermic reaction can occur on the hot side of the TEG. This will provide a temperature difference for the TEG and will allow for power to be produced as the heat is converted to on-demand electricity.

Melamine Synthesis:

To synthesize a non-reactive matrix material, one utilizes melamine foam as it has shown to be extremely porous. This could be beneficial as a porous material typically has a low thermal conductivity which allows it to be a better insulator. Additionally, the use of a porous material will prevent salt agglomeration and enhance reliability. With this in mind, magic erasers are cut

⁸ N. Jaziri, A comprehensive review of Thermoelectric Generators: Technologies and common applications, Energy Report. (2020). <https://www.sciencedirect.com/science/article/pii/S2352484719306997> (accessed March 11, 2021).

into smaller cubes and pyrolyzed within a tube furnace at 620 °C for about five hours (Step 1 of Figure 9). Magic erasers are favorable as they are easily accessible (can be found at a local convenience store) and they are made of melamine foam. This pyrolysis of the magic erasers allows for the production of a matrix material that is enriched in carbon and char. Once pyrolyzed, the activated carbon within the extremely porous magic erasers become a beneficial material for a salt hydrate reaction. By disintegrating the material into its integral parts, the objective of this pyrolysis is to yield a favorable energy product as it also allows for the saturation of a salt hydrate reaction. This porous material is then soaked within a 20% CaCl₂ solution overnight (Step 2 of Figure 9). Once thoroughly soaked, the material is then dehydrated within a muffle furnace at 120 °C; this allows the material to be dehydrated while still being able to retain the CaCl₂ (Step 3 of Figure 9). This process is estimated by weighing the material at every point in the process. This is specifically important before and after soaking the pyrolyzed melamine to approximate how much water was absorbed within the porous material.

By soaking the porous material within this solution, the CaCl₂ is absorbed into the material. CaCl₂ is yet another common material that is inexpensive and easy to obtain. Due to its exothermic reaction with water and freezing point depression, CaCl₂ is typically used as driveway salt during snowy conditions.

Therefore, by soaking the porous material within the CaCl₂ solution and then dehydrating the material such that only the CaCl₂ remains, one is able to produce a matrix material that is impregnated with a reversible salt hydrate reaction.

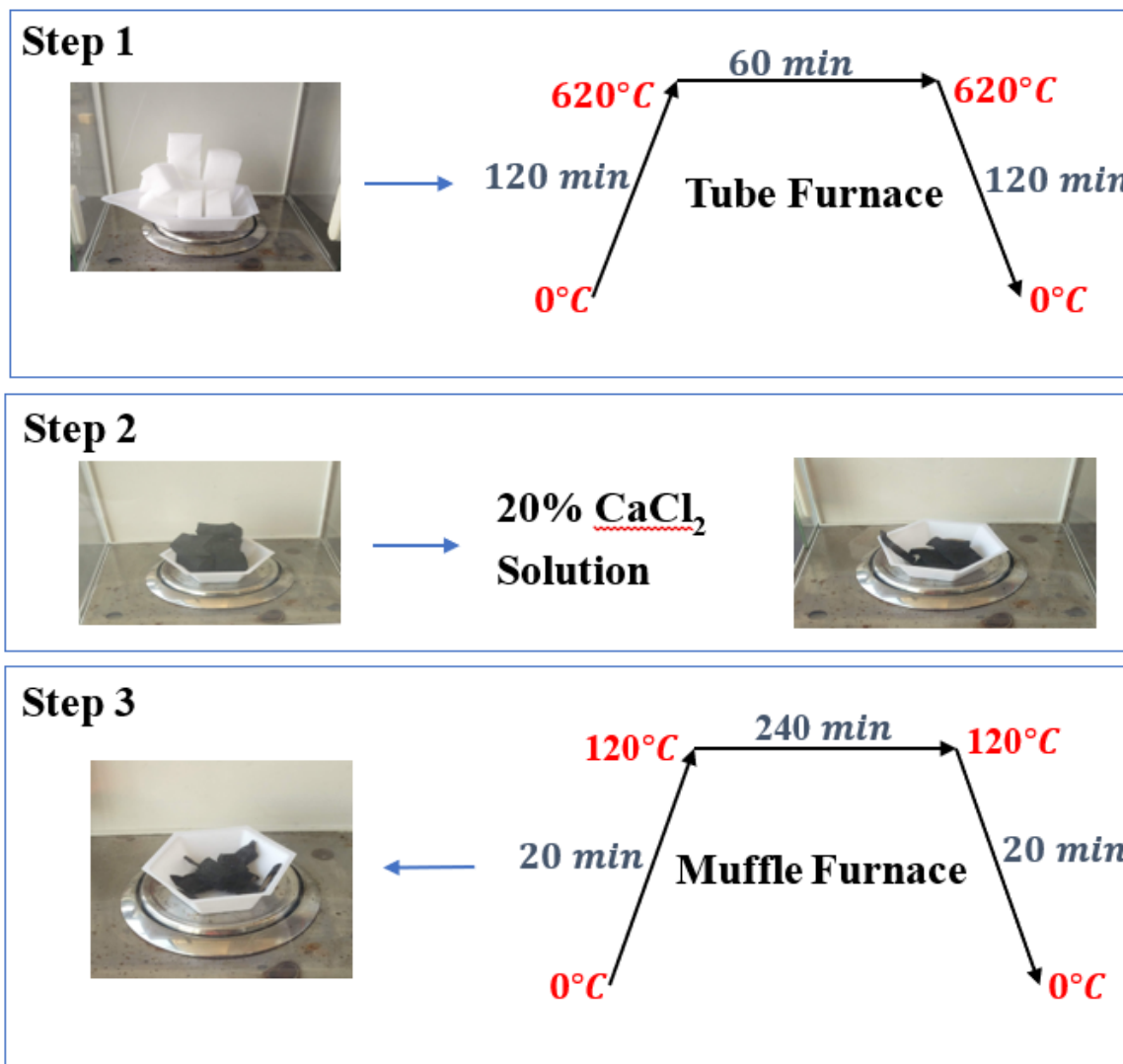


Figure 9: The melamine synthesis is shown above with pictures. Step 1 illustrates weighing before pyrolysis. Step 2 illustrates weighing after pyrolysis and hydration. Step 3 illustrates weighing after dehydration.

Experimental Setup:

A TEG converts the heat into electricity. The melamine chamber is made from aluminum and is placed on top of the hot side of the TEG's. The use of the aluminum material is favorable as it is inexpensive and a good conductor for heat to travel from the chamber toward the TEG.

Insulation around the experimental setup and thermal paste between the TEG and the melamine chamber are additional measures that are taken to ensure that the temperature difference is felt upon the TEG (Figure 10). While the bulk of the experimental setup surrounds the hot side of the TEG, the cool side is placed upon the lab table as the temperature of the lab is already at a cool 22°C.

To determine the CaCl₂ to water ratio, multiple tests were run where the temperature was measured for a specific weight for CaCl₂ to water. Through these tests, it was determined that a 1:1 ratio of grams of CaCl₂ to milliliters of water would produce the highest possible temperature

within the salt hydrate reaction. Following this, there were a few hypotheses regarding the most efficient method of water addition into the melamine chamber. An experiment was run where the melamine- CaCl_2 matrix sits on the base of the melamine chamber and a sponge soaked with water sits on top of the matrix. Ideally, the matrix is then hydrated as the water from the sponge gravitates into the porous matrix to react with the CaCl_2 . This experiment was also run where the matrix material sits on top of the soaked sponge; here the water within the sponge would move towards the matrix through capillary action. However, both these methods were shown to be inadequate as the sponge itself was already porous enough such that the water would not leave.

Additional experiments were then run where the melamine- CaCl_2 matrix material is hydrated from above by a water dispenser. At first, a measured amount of water was poured into the melamine chamber by hand; however, issues arose with this method. This is because some areas of the matrix material would become hydrated before others. This was illustrated through the TEGs as there would be spikes in power when areas of the matrix material would just be coming in contact with the water. Furthermore, by pouring the water into the chamber by hand, the water would not be dispensed at a steady rate; thus, this also caused spikes in power. A final experiment was run where the water was simply dispensed above the matrix material in the form of a spray mist. This would allow the entire melamine chamber to be covered with the mist being dispensed. A spray mist also allowed the water to be dispensed at a steady rate as compared to simply pouring it in. This also ensured that melamine- CaCl_2 matrix material reacts fully as the water was distributed evenly. Through this, it was determined that the most effective option would be to dispense the water from the top via a spray mist (As shown in Figure 10).

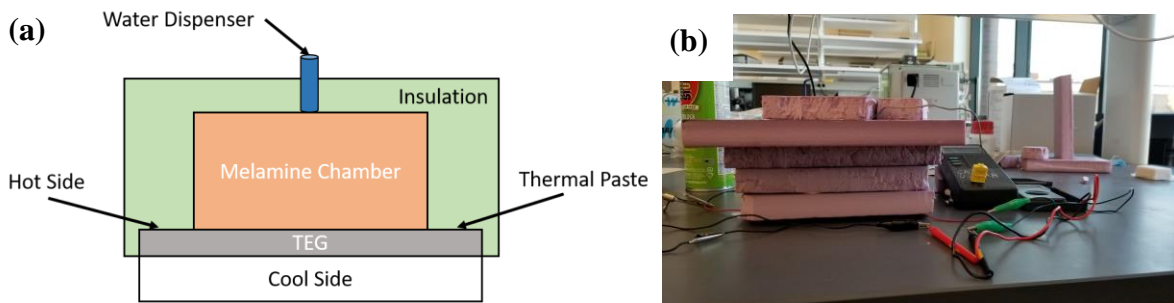


Figure 10: (a) A diagram of the TEG-melamine chamber is shown as well as (b) the physical set up from the lab.

Multiple experiments were run within this set-up. Prior to soaking the porous matrix in the CaCl_2 solution, the material weighed about 23.3g. After dehydrating the now melamine- CaCl_2 matrix, the material weighed about 58.3g. Through this, about 35g of CaCl_2 was absorbed into the matrix material. By hydrating the melamine- CaCl_2 matrix material with 35 mL of water, an exothermic reaction was produced and a temperature difference between the hot and cool side of the TEG was generated. Additional experiments were also run with pure CaCl_2 to better measure the TEG efficiency. With the pure CaCl_2 trial, 10g of pure CaCl_2 was hydrated with 10mL of water. When comparing the weight of the melamine- CaCl_2 matrix after dehydration to the experiments run with CaCl_2 , the matrix contained about 3.5 times the amount of CaCl_2 within the material as compared to the pure CaCl_2 experiment. While the temperature differences cannot be directly

compared between the two experiments, the conversion efficiency of stored chemical energy to electrical energy can still be calculated for each case.

Below the melamine chamber and thermal paste, four TEGs were connected in series to an ammeter and a 9.6 Ohm resistor (Figure 11). This circuit design rests on the lab desk such that the cool side of the TEGs sit at ambient temperature (22 °C). The experimental set up rests on top of the hot side of the TEG such that a temperature difference can be generated.

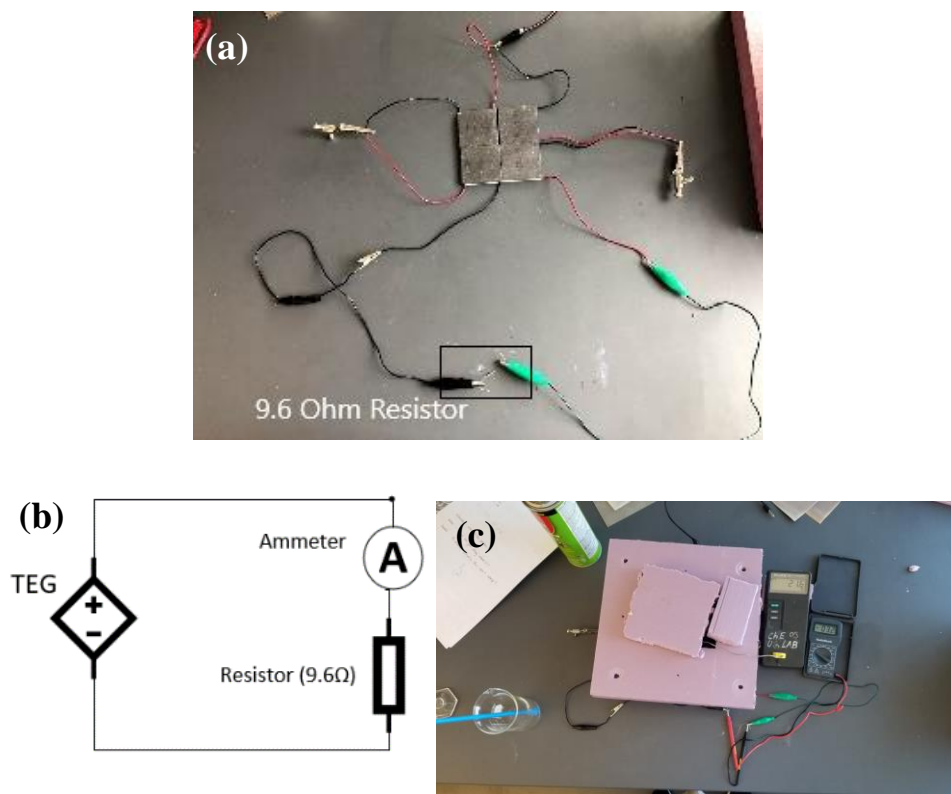


Figure 11: (a) illustrates the physical circuit that is connect to the TEGs in lab. (b) The circuit diagram is shown with all the main components fully labeled. (c) A top view of the physical setup with the circuit is shown; the TEG is below the insulation.

Results:

The maximum temperature of the melamine- CaCl_2 matrix came out to be 51.1°C ; this occurred 180 seconds into experiment. The maximum temperature of the pure CaCl_2 came out to be 49.3°C ; this temperature was reached 44 seconds into the experiment (Figure 12). Since the weight of the melamine- CaCl_2 matrix material experiments differed from the weight of the pure CaCl_2 experiments, the temperature differences cannot be compared. Therefore, even though the similar peak temperatures between both experiments were reached, a conclusion cannot be made until further experimental investigation. While the melamine- CaCl_2 matrix material took longer for it to reach its peak temperature, the decline of this maximum lasted much longer than the decline of the maximum temperature of pure CaCl_2 . The fast cooling rate of the pure CaCl_2 is most likely due to the fast convection and conduction heat loss. On the other hand, the porous matrix material enhanced the thermal performance of the CaCl_2 and water reaction. Due to this,

the temperature difference between the TEG was sustained for longer for the melamine-CaCl₂ matrix (relative to pure CaCl₂).

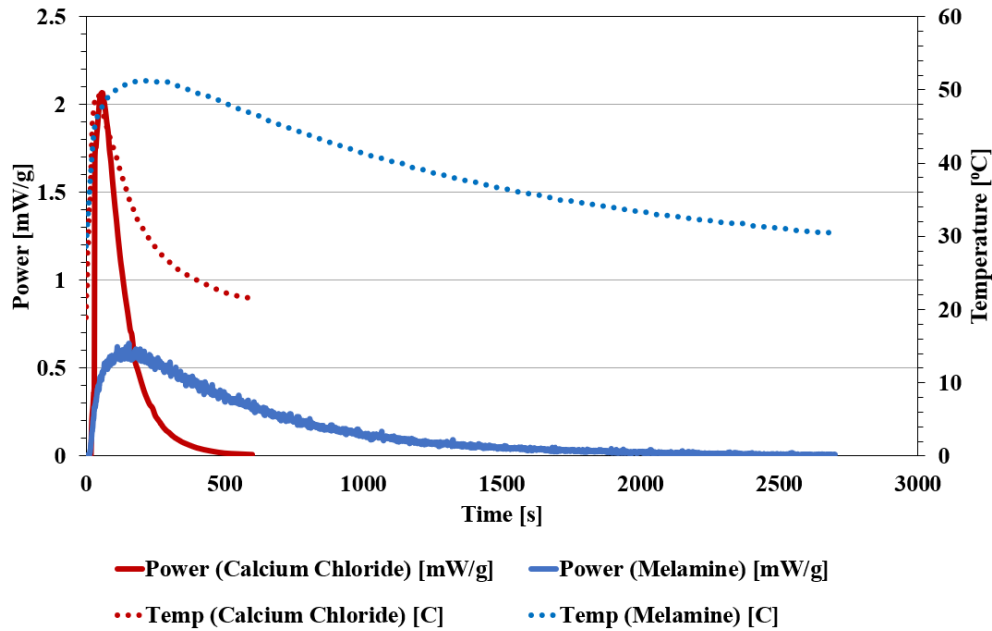


Figure 12: Comparing the overall power and temperature peaks of pure CaCl₂ to the overall power and temperature peaks of the melamine-CaCl₂ matrix. The dotted lines follow the y-axis on the right while the solid lines follow the y-axis on the left.

While the temperature between both methods were relatively similar, the power that resulted in the temperature differences were drastically different. The pure CaCl₂ trial produced about 2.07mW/g of power within the first min of the experiment; while the melamine-CaCl₂ matrix material produced about 0.64mW/g of power within 155 seconds of the trial. Within the pure CaCl₂ trial, there was a large spike in power produced from the very start of the experiment. However, almost immediately, the power dropped. This illustrates that the temperature difference produced a voltage difference and created power. Nevertheless, since the temperature difference was for such a short amount of time, the power produced dropped almost immediately. In contrast, the power produced from the melamine-CaCl₂ matrix did not spike even with the large temperature difference between the hot and cold side of the TEG. Since it took longer for the temperature difference to occur within the matrix, it also took longer to produce its peak power. Unlike the pure CaCl₂, the power produced from the matrix material was sustained for longer; the power produced gradually decreased as the temperature difference decreased.

Discussion:

The melamine-CaCl₂ matrix trial was run for about 45 min. Based upon the amount of melamine used (53.8g), and the ratio of CaCl₂ salt to matrix material (1.50), about 87,575J of total energy was expected to be released. However, about 21.6J of total energy was actually released during this time. Regarding the pure CaCl₂, this experiment ran for about 20 min. Through this, 10,000J of energy was expected to be released; in reality, about 2.5J of energy was released during this

time. This brought about a TEG efficiency of 0.025% (Table 1). This low TEG efficiency contributed to the low voltage differences despite the larger temperature difference within the experiments. Thus, while the TEG efficiency was extremely low, this experimental setup demonstrated the proof of concept for a TEG and TCES combination.

Table 1: This table compares the total experimental and expected energy between the pure CaCl₂ and the matrix material. It also illustrates the TEG efficiency based upon the energy.

	Pure CaCl ₂	Matrix Material
Total Energy [J]	2.50	21.6
Expected [J]	10000	87575.1
TEG Efficiency	2.50E-04	2.47E-04
TEG Efficiency [%]	0.025	0.025

Theoretically, when the cool side of a TEG is measured at ambient temperature and when the hot side measures at 50°C, the voltage output at this temperature difference is at 0.5V (Figure 13). Regarding the pure CaCl₂ experiment, when the trial reached its peak temperature of 49.3°C, a maximum voltage of 0.43V was measured between all four TEGs in series. This illustrates that the pure CaCl₂ produced ¼ of the specified voltage. While this is very low compared to the TEG specification, it also shows the potential voltage that TEG could have produced had the temperature difference stayed constant.

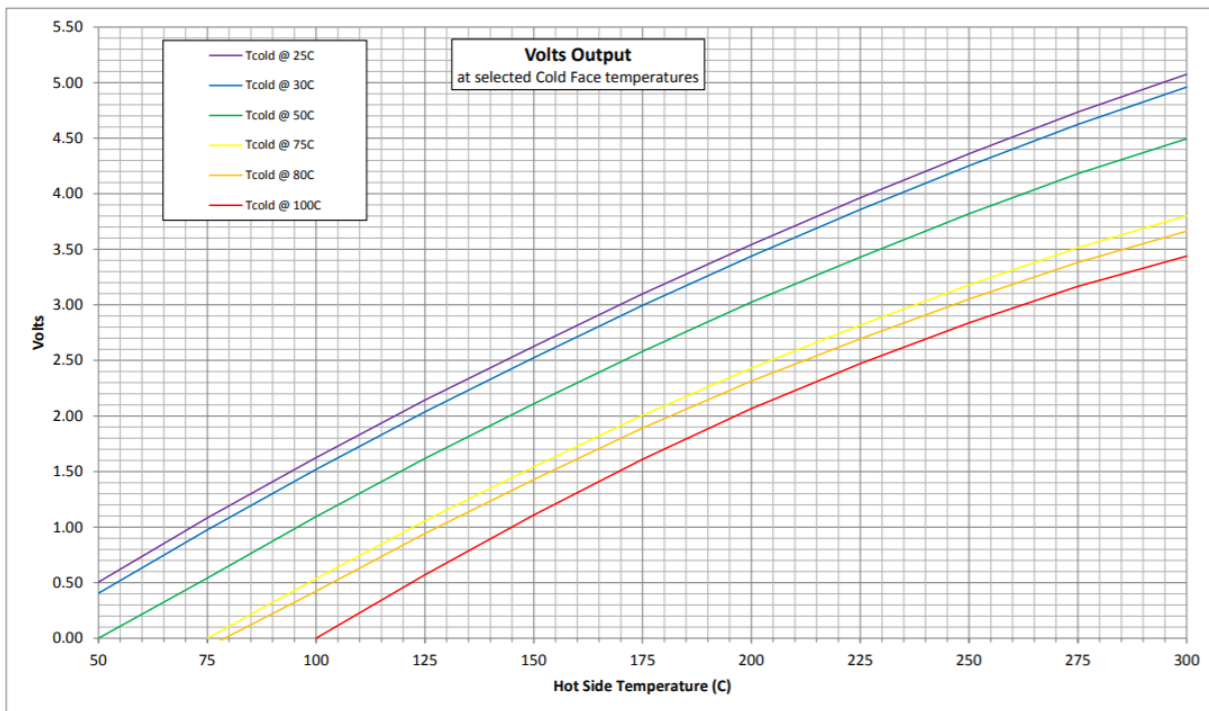


Figure 13: This illustrates the voltage output of a singular TEG based upon its hot and cool temperatures. ⁹

⁹TEG Specification Sheet, Seebeck Thermoelectric Generator. (2014). https://customthermoelectric.com/media/wysiwyg/TEG_spec_sheets/1261G-7L31-04CQ_20140514_spec_sht.pdf.

In both the melamine-CaCl₂ matrix method and the pure CaCl₂ method, the peak temperature and the power produced was for a very short period of time. This is most likely because the temperature difference between the hot and cold side of the TEG did not last for a long enough period of time. This could be due to lack of insulation or a lack of a heat sink to help transfer the heat. While the cold sink temperature was recorded prior to the experiment, it was not measured continuously. Therefore, it would be beneficial to investigate how the cold sink temperature varied. Within the pure CaCl₂ method, a larger peak amount of power was produced with a short peak temperature difference. On the other hand, the melamine-CaCl₂ matrix produced a larger total amount of power and a longer peak temperature difference. The larger total power is because the power produced was able to remain steady for a longer period of time. Thus, the total amount of power produced during the experiment was larger. The porous matrix contributed to the longer peak temperature difference as the porosity improved the thermal performance of the hydrate reaction.

Technoeconomic Analysis

When comparing the TEG and TCES system to PV and battery storage, both have advantages and disadvantages in terms of efficiency and cost. Regarding the TEG and TCES combination, some basic assumptions are made to when estimating and understanding the efficiency of the system (Table 2).

*Table 2: The basic assumptions regarding the ZT efficiency and comparing it to a PV and battery system are listed below.*¹⁰

Basic assumptions
No device or system heat losses
No device or system electrical losses
ZT is constant over a temperature range

The TEG efficiency is based upon the thermoelectric figure of merit (ZT) where thermal conductivity, electric resistivity, and the Seebeck coefficient of a material are taken into account. A high efficiency of a material can be achieved through a large temperature difference and a large ZT. However, TEGs are limited as a high heat source temperature still has a low ZT; this limits the plausible applications that TEGs can be beneficial in as the efficiency improves very slowly. The majority of thermoelectric materials within TEGs have a maximum ZT of 1 (even with a large heat source temperature); this brings about a maximum efficiency of 6% (depending on the TEG material as well). When compared to heat engines that are currently being utilized, a TEGs efficiency barely reaches 1/6th the maximum Carnot efficiency. Additionally, a large increase with the TEGs ZT is highly unlikely within the foreseeable future⁹. Due to this, it is unlikely that TEGs can contribute to large scale systems. On the other hand, TEGs could be favorable within small scale systems. This is because typical conversion systems can become less efficient as they are scaled down in size (Figure 14). At the mW power level, TEGs can deliver a reasonable efficiency that can match the efficiency of mechanical engines. It is important to note that Figure 14 simply demonstrates this concept. This is because the crossover

¹⁰ From Vining, *Nature Materials*, Vol. 8, 2009

point varies upon the thermoelectric applications and materials. Nevertheless, the illustration illustrates that TEGs could be impactful within lower peak power levels.

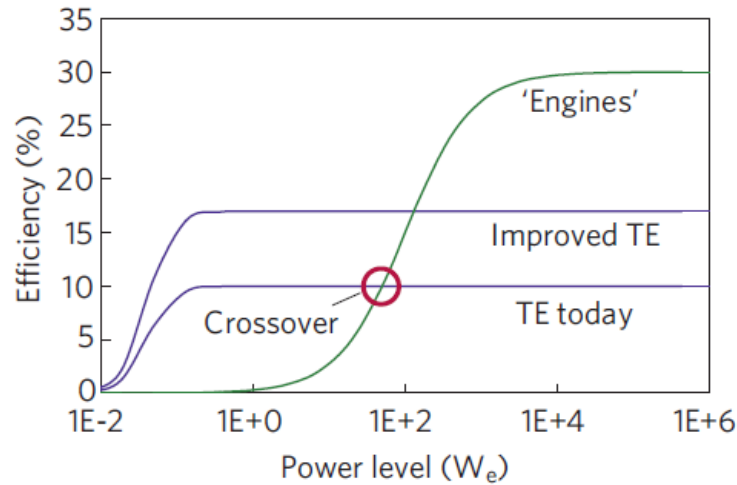


Figure 14: This illustrates the power level against the efficiency of thermoelectrics. The crossover efficiency as compared to heat engines are shown to show the potential applications regarding a TEG¹⁰.

In terms of conversion efficiency, a solar photovoltaic is about 20% efficient when converting thermal energy to electrical energy. However, when the electric energy is stored, the discharge efficiency of the battery can be as high as 80%. These energy efficiencies can then be compared to the TEG and TCES system (Table 3). From the sun, a solar collector (or evacuated tube) can be assumed to capture 80% of the thermal energy. When storing the thermal energy, the TCES can be about 75% efficient. However, the TEGs ability to convert thermal energy into electric energy is at best 6% efficient.

Table 3: This table illustrates how the capital costs were determined for each system; the efficiencies between each aspect in the process were also discussed within the calculations¹¹.

	Solar	Storage	Discharge
TEG and TCES System	Solar collector $\left(\frac{\$}{kWh_{th}}\right)$ Efficiency: 80%	TCES $\left(\frac{\$}{kWh_{th}}\right)$ Efficiency: 75% ¹²	TEG $\left(\frac{\$}{kWh_e}\right)$ Conversion from kWh_{th} to kWh_e Efficiency: 6%
PV and Battery System	Solar PV Cell $\left(\frac{\$}{kWh_e}\right)$ Conversion from kWh_{th} to kWh_e Efficiency: 20%	Battery $\left(\frac{\$}{kWh_{th}}\right)$ Efficiency: 90%	

¹¹ N. AuYeung, R. Bhatt, G. Drake, (637c) Thermochemical Energy Storage Integration with Thermoelectric Power Generation, AIChE Academy. (2019). (accessed April 25, 2021).

¹² N. AuYeung, P. Kreider, Solar Thermochemical Energy Storage, CEP Publications. (2017). (accessed May 2, 2021).

With these efficiencies in mind, the total system cost between the TEG/TCES storage and the PV/battery storage was compared in terms of the storage capacity. As determined previously, the TEG and TCES storage system can be impactful within low peak power but high storage capacity settings. This brought up the question: at what peak power and what storage capacity does the TEG/TCES storage system become most impactful? Thus, this was determined by varying the storage capacity and peak power against the total system cost. The storage capacity ranged from 0.1 kWh_e to 10 kWh_e. By working backwards from discharge to solar (Table 3), the amount of thermal energy needed to be collected from the solar collector was first determined. With a 60-hour collection time of solar energy, the cost of the solar collector was calculated with the varied storage capacity. With the energy from the CaCl₂ material, the cost of the TCES was then calculated. Finally, the TEG cost was determined by assuming a 6% efficiency and utilizing a varied peak power (from 10W to 300W). The total system cost was then computed by summing the cost of the solar collector, TCES, and TEG. With the varied storage capacity and the varied TEG cost (from the different peak power costs), the system cost was able to be compared to the PV/battery system. A maximum power rating of 200W, and a storage capacity of 9 kWh_e, brought about a similar system cost to that of the PV/lithium ion battery (Figure 15). By comparing the storage capacity as well as the TEG peak power, a range could be determined that would illustrate the impact of the TEG/TCES system. Through this, the TCES/TEG system has a comparable cost when the peak power ranges from 300W to 10W and the storage capacity ranges from 0.1 kWh_e to 10 kWh_e; this range illustrated a lower system cost when compared to the PV/lithium ion battery system. This power range would be optimal for appliances that consume less than 300W of power. To put this into perspective, a ceiling fan consumes 70W of power, a typical incandescent lightbulb consumes 100W, and an 82-inch LED TV consumes 295W of power¹³. Therefore, with a large storage capacity, a TEG/TCES system has the potential to power these types of applications. This comparison illustrated the optimal window that the TEG and TCES storage system would be beneficial.

¹³ H. Murata and T. Onoda, "Estimation of power consumption for household electric appliances," Proceedings of the 9th International Conference on Neural Information Processing, 2002. ICONIP '02., 2002, pp. 2299-2303 vol.5, doi: 10.1109/ICONIP.2002.1201903.

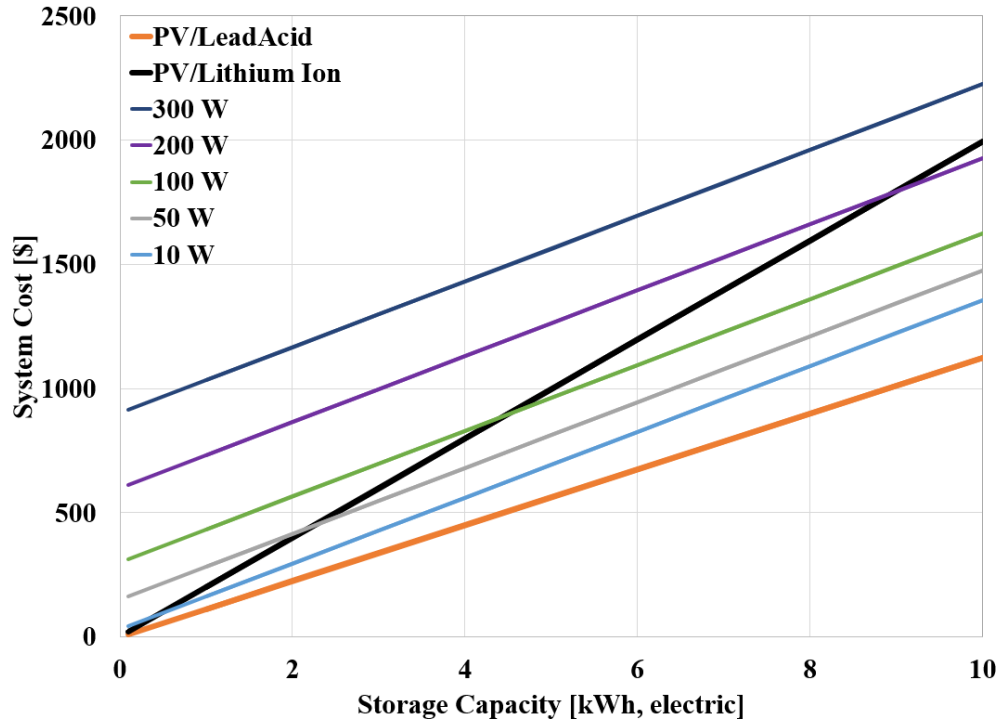


Figure 15: The $\$/kWh_e$ vs Storage Capacity is compared between the TEG/TCES system as well as the PV/Battery system. Within the TEG/TCES system, the TEGs peak power is varied such that the system cost varies. The following assumptions were made when comparing the specific systems: Battery Efficiency: 80%; Lead Acid Battery: $\$50/kWh_e$; Lithium Ion Battery: $\$137/kWh_e$, PV efficiency: 20%, PV Power Rate: $\$3000/kW$; TEG Power Rate: $\$3/W$; TEG Peak Power Range: 300W to 10W; TEG efficiency: 6%; $CaCl_2$ Salt: $\$0.30/kWh_m$; TCES efficiency: 75%; Solar Collection Time: 60hr; Solar Concentrator Efficiency: 80%; Solar Concentrator: $\$272/kWh_e$, Solar Energy Conversion: $1.0 kW/m^2$, Storage Capacity Range: 0.1 kWh_e to 10 kWh_e .

With this window determined, the specific costs within the TEG/TCES system were investigated. When comparing the costs of the specific sections of the TEG/TCES system, the cost of the solar collector largely outweighed the cost of the TEG and the TCES combined. Assuming a 1 kWh_e storage capacity and an 8-hour collection time, the cost of the solar collector was about $\$944$. Comparing this to the cost of the TEG ($\$300$) and the cost of the TCES ($\$6.67$), the solar collector accounted for a large amount of the total system cost (Figure 16). This is most likely due to the large power rate of the solar collector. At a rate of $\$272/kW$, the cost of the solar collector increases rapidly as the power increases. Therefore, if the cost of the solar collector can be minimized, then the TEG/TCES system cost can be that much more impactful as the system cost can largely decrease. It was determined that the solar collector cost varies largely by the solar collection time. If the collection time increases, then the solar collector cost decreases significantly (Figure 17). Thus, this collection time can be adjusted by collecting thermal energy at various times. Thermal collection at night, during cloudy days, or even at moments where the system is not being utilized, the collection time can increase to impact the cost of the solar collector. When the time collected increases from 8 hours to 35 hours (in a 5 kWh_e storage capacity), the system cost decreases from about $\$5,000$ to a little over $\$1,000$. Thus, as the thermal time collected increases, the cost of the solar collector decreases drastically. This difference is demonstrating a potential decreased cost of the TEG/TCES system.

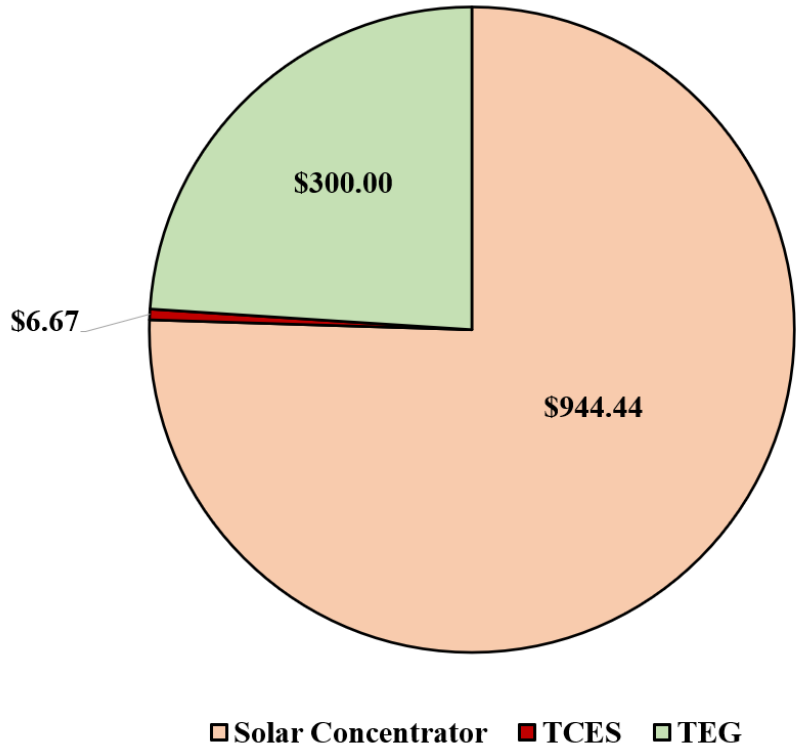


Figure 16: This pie chart illustrates the cost of each specific section within the TEG/TCES system. Regarding this data, the following assumptions were made: TEG Power Rate: \$3/W; TEG Peak Power: 100W; TEG efficiency: 6%; CaCl₂ Salt: \$0.30/kWh_{th}; TCES efficiency: 75%; Solar Collection Time: 8hr; Solar Concentrator Efficiency: 80%; Solar Concentrator: \$272/kW_e, Solar Energy Conversion: 1.0 kW/m², Storage Capacity: 1 kWh_e.

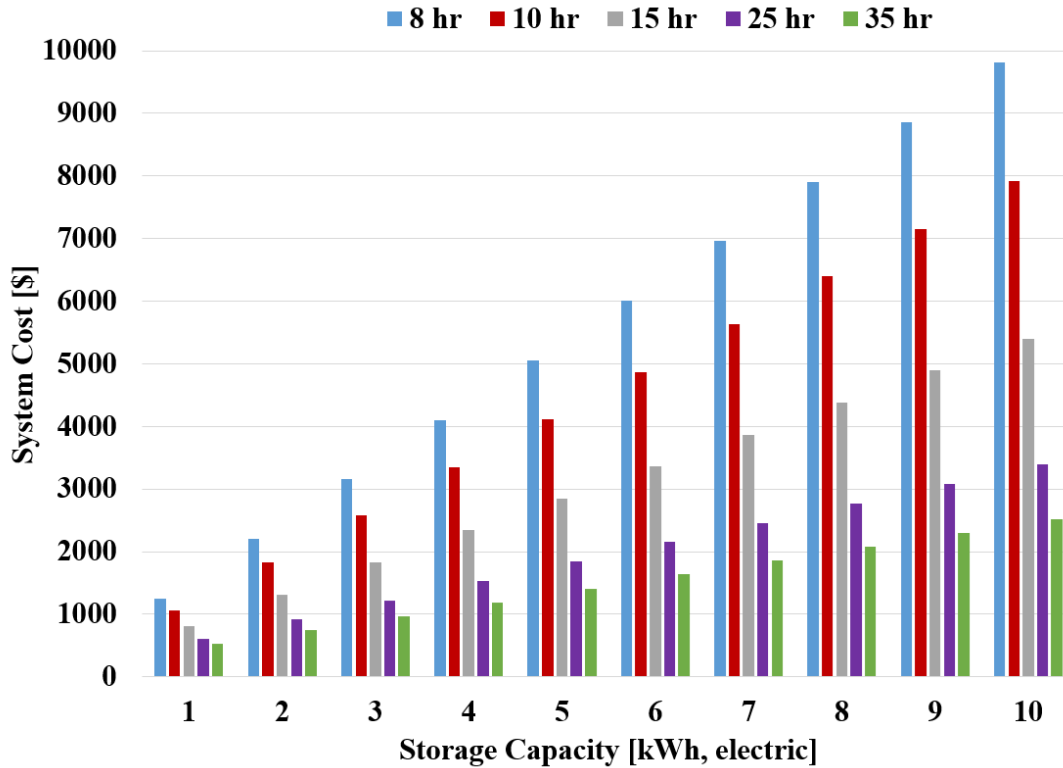


Figure 17: This bar graph illustrates how the system cost changes with the increased time collection. The system cost is plotted against the storage capacity. Regarding this data, the following assumptions were made: TEG Power Rate: \$3/W; TEG Peak Power Range: 100W; TEG efficiency: 6%; CaCl₂ Salt: \$0.30/ kWh_{th}; TCES efficiency: 75%; Solar Collection Time Range: 8hr to 35hr; Solar Concentrator Efficiency: 80%; Solar Concentrator: \$272/kW_e, Solar Energy Conversion: 1.0 kW/m², Storage Capacity Range: 0.1 kWh_e to 10 kWh_e.

Since the solar collector was the largest cost, other heating methods would be worth investigating to pair with the TEG/TCES system. With this in mind, the system cost of just the TEG and TCES was compared to just the battery storage (the storage capacity was varied at the same rate). Here the total cost of the system was calculated in the same way; however, the cost of the solar collector was excluded (the cost of the PV was also excluded for the battery system). With the solar collector cost omitted, the system cost of the TEG/TCES was much more comparable to the system cost of the PV/battery storage system (Figure 18). When the solar collector was included within the system cost, the TEG/TCES system was only comparable to the PV/Lithium Ion battery. However, when the cost of the solar collector was excluded, the TEG/TCES system cost is comparable to both the Lead acid battery as well as the Lithium ion battery. Regarding the PV/lithium ion battery system, the TEG/TCES system has a comparable cost when the peak power ranges from 450W to 10W (and the storage capacity ranges from 0.1 kWh_e to 10 kWh_e). The lack of the solar collector increased the window where the TEG/TCES system is comparable to the Lithium ion battery storage. When considering the PV/lead acid battery system, the inclusion of the cost of the solar collector made the TEG/TCES system incomparable. However, the TEG/TCES system had a comparable cost to the lead acid battery storage when the peak power ranged from 140W to 10W (and the storage capacity ranges from 0.1 kWh_e to 10 kWh_e). This illustrates that an alternative heating method could make the

TEG/TCES storage system that much more impactful. Thus, it could be beneficial to investigate resistive heating as an alternative heating method as the cost per kWh is low.

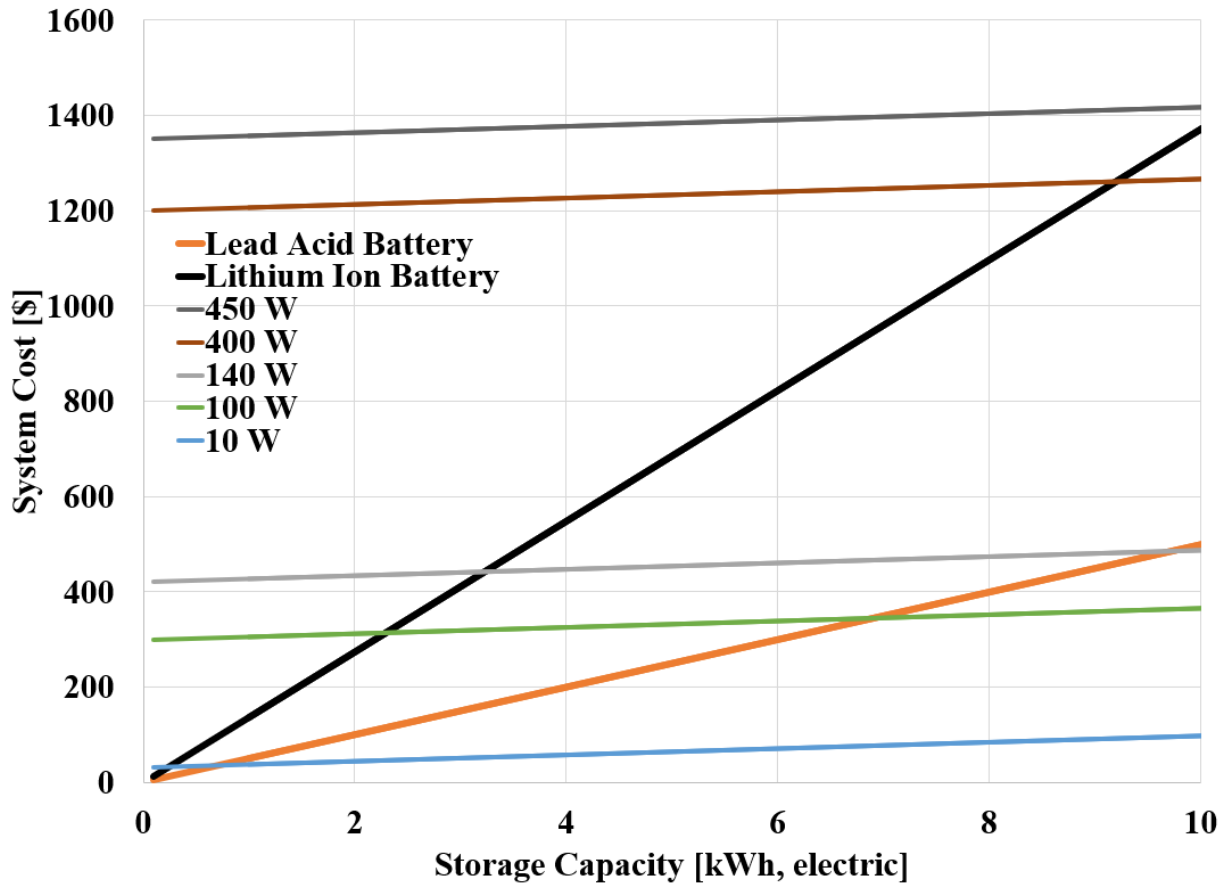


Figure 18: The $\$/kWh_e$ vs Storage Capacity is compared between the TEG/TCES storage system as well as the Battery storage system. Within the TEG/TCES system, the TEGs peak power is varied such that the system cost varies. The following assumptions were made when comparing the specific systems: Battery Efficiency: 80%; Lead Acid Battery: $\$/kWh_e$; Lithium Ion Battery: $\$/kWh_e$; TEG Power Rate: $\$/W$; TEG Peak Power Range: 300W to 10W; TEG efficiency: 6%; $CaCl_2$ Salt: $\$/kWh_{th}$; TCES efficiency: 75%; Storage Capacity Range: 0.1 kWh_e to 10 kWh_e .

Conclusion:

This work illustrates proof of concept that power can be generated via a thermoelectric generator and a reversible chemical reaction. The TEG and TCES storage system were found to be most suitable within low peak power but high storage capacity settings. Within these system settings, the system cost of the TEG/TCES became comparable to the cost of the PV/battery system. While the solar collector cost was high during low collection times, this cost decreased significantly as the collection time increased. Through this, the TEG/TCES system cost could be more comparable to the PV/battery system cost. Nevertheless, it could be meaningful to investigate cheaper thermal collection systems. Resistive heating with the TEG/TCES system could also be a beneficial route towards clean and affordable energy storage. Thus, time of use and battery storage versus time of use and the TEG/TCES system could also have comparable

costs. Future work will investigate utilizing a heat sink, exploring the cold side of the TEG (as in make it colder than ambient temperature), and considering a more insulated experimental set up. If the temperature difference between the Hot and Cold side of the TEG increased, then more power could be produced. One way to do this would be to improve the insulation around the TEG and melamine chamber. Then if the TEG would be able to detect the temperature difference, more power could be produced. This would involve one to design a more efficient module for the TEG and melamine chamber to work with each other. Another way to produce a larger temperature difference would be to make the Cold side of the TEG colder. This would involve working with colder temperature, perhaps utilizing an endothermic reaction, or even working with a circulating ice bath to keep the cold side at a cold enough temperature. Through this experimental investigation, the proof of concept of a TEG and TCES combination was demonstrated as well as possible applications this system could be applied to. A technoeconomic analysis also presented possible peak power and storage capacity windows where the TEG/TCES system could be beneficial. These windows could be useful within low peak power and high storage capacity applications. When considering the market for the TEG and TCES combination, it could be beneficial within low peak power demands in distributed settings. This system could be marketed towards camping or wood stoves , and to charge electronic devices.

Contributions:

I would like to thank Dr. Nick AuYeung for his patience, support, and mentoring. Thank you to Griffin Drake, and Chuan Hao Tan for their assistance in the experimental investigation, and analysis of the results.

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Appendix

Technoeconomic Analysis Calculations

Solar collector											
Energy Storage coming out of TEG [kWh,e]	1	2	3	4	5	6	7	8	9	10	0.1
Efficiency of TEG	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Coming out of TCES [kWh,th]	16.67	33.33	50.00	66.67	83.33	100.00	116.67	133.33	150.00	166.67	1.67
TCES efficiency	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Coming out of Solar Collector [kWh,th]	22.22	44.44	66.67	88.89	111.11	133.33	155.56	177.78	200.00	222.22	2.22
Efficiency of Soalr Concentrator	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Solar Energy Needed [kWh,th]	27.78	55.56	83.33	111.11	138.89	166.67	194.44	222.22	250.00	277.78	2.78
Collection Time [hr]	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00	60.00
Solar Energy Conversion [kW/m2]	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00
Area Needed [m2]	0.46	0.93	1.39	1.85	2.31	2.78	3.24	3.70	4.17	4.63	0.02
Solar Concentrator [\$ /kW]	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272	\$ 272
Cost of Solar Concentrator [\$]	\$ 126	\$ 252	\$ 378	\$ 504	\$ 630	\$ 756	\$ 881	\$ 1,007	\$ 1,133	\$ 1,259	\$ 13
TCES											
Coming out of Solar Collector [kWh,th]	22.22	44.44	66.67	88.89	111.11	133.33	155.56	177.78	200.00	222.22	2.22
Salt Energy [\$ /kWh,th]	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
Cost of TCES [\$]	6.67	13.33	20.00	26.67	33.33	40.00	46.67	53.33	60.00	66.67	0.67
Cost of Solar Concentrator and TCES [\$]	133	265	398	530	663	796	928	1061	1193	1326	13
TEG											
Peak Power [W]	100	100	100	100	100	100	100	100	100	100	100
Power Rate [\$ /W]	3	3	3	3	3	3	3	3	3	3	3
Cost of TEG at this Peak Power [\$]	300	300	300	300	300	300	300	300	300	300	300
Total TEG/TCES System Cost [\$]	433	565	698	830	963	1096	1228	1361	1493	1626	313

Table 4: Determining the cost of the total TEG/TCES system as the storage capacity changes. Highlighted in green, the energy storage varies from 0.1 kWh_e to 10 kWh_e. Based upon this change, the cost of the solar concentrator, TCES, and TEG changes (as highlighted in blue). Regarding the solar concentrator, the collection time is 60 hours for each storage capacity. For the TEG system, the Peak power stays constant at 100W. The row in red is referenced¹⁴. The row in yellow is referenced¹⁵.

¹⁴ RYANS SPREADSHEET.

¹⁵ N. AuYeung, R. Bhatt, G. Drake, (637c) Thermochemical Energy Storage Integration with Thermoelectric Power Generation, AIChE Academy. (2019). (accessed April 25, 2021).

Battery											
Energy Storage coming out of Battery [kWh _e]	1	2	3	4	5	6	7	8	9	10	0.1
Battery Efficiency	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
Coming out of PV Panel [kWh _e]	1.25	2.5	3.75	5	6.25	7.5	8.75	10	11.25	12.5	0.125
PV Efficiency	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Solar Energy to PV Panel [kWh _{solar}]	6.25	12.5	18.75	25	31.25	37.5	43.75	50	56.25	62.5	0.625
Collection Time [hr]	60	60	60	60	60	60	60	60	60	60	60
Solar Energy Conversion [kW/m ²]	1	1	1	1	1	1	1	1	1	1	1
Area Needed [m ²]	0.104	0.208	0.313	0.417	0.521	0.625	0.729	0.833	0.938	1.042	0.010
Power from PV [kW]	0.0208	0.0417	0.0625	0.0833	0.1042	0.1250	0.1458	0.1667	0.1875	0.2083	0.0021
PV Power Rate [\$ /kW]	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000	3000
Cost of PV [\$]	62.5	125	187.5	250	312.5	375	437.5	500	562.5	625	6.25
Lead Acid Battery Energy [\$ /kWh _e]	50	50	50	50	50	50	50	50	50	50	50
Lead Acid Battery Cost [\$]	50	100	150	200	250	300	350	400	450	500	5
Total System Cost, Lead Acid Battery [\$]	112.5	225	337.5	450	562.5	675	787.5	900	1012.5	1125	11.25
Lithium Ion Battery Energy [\$ /kWh _e]	137	137	137	137	137	137	137	137	137	137	137
Lithium Ion Battery Cost [\$]	137	274	411	548	685	822	959	1096	1233	1370	13.7
Total System Cost, Lithium Ion Battery [\$]	199.5	399	598.5	798	997.5	1197	1396.5	1596	1795.5	1995	19.95

Table 5: Determining the cost of the PV/battery system as the storage capacity changes. Highlighted in green, the energy storage varies from 0.1 kWh_e to 10 kWh_e (the same varied storage capacity as the TEG/TCES system; this is so the two systems can be compared to each other). Based upon this change, the cost of PV changes and the cost of the battery changes (as highlighted in blue). The PV Power Rate stays constant at \$3/kW throughout the varied storage capacity. Regarding the battery, Lead Acid and Lithium Ion batteries are both considered as possible areas of storage. The lead acid battery is assumed to be \$50/ kWh_e and the lithium ion battery is assumed to be \$137/ kWh_e.

Energy Storage coming out of TEG [kWh _e]													
Cost of Solar Concentrator and TCES [\$]		\$ 133	\$ 265	\$ 398	\$ 530	\$ 663	\$ 796	\$ 928	\$ 1,061	\$ 1,193	\$ 1,326	\$ 13	
TEG Peak Power [W]	TEG Rate [\$ /W]	TEG Cost [\$]	\$ 283	\$ 415	\$ 548	\$ 680	\$ 813	\$ 946	\$ 1,078	\$ 1,211	\$ 1,343	\$ 1,476	\$ 163
50	\$ 3	\$ 150	\$ 163	\$ 295	\$ 428	\$ 560	\$ 693	\$ 826	\$ 958	\$ 1,091	\$ 1,223	\$ 1,356	\$ 43
10	\$ 3	\$ 30	\$ 733	\$ 865	\$ 998	\$ 1,130	\$ 1,263	\$ 1,396	\$ 1,528	\$ 1,661	\$ 1,793	\$ 1,926	\$ 613
200	\$ 3	\$ 600	\$ 1,033	\$ 1,165	\$ 1,298	\$ 1,430	\$ 1,563	\$ 1,696	\$ 1,828	\$ 1,961	\$ 2,093	\$ 2,226	\$ 913
300	\$ 3	\$ 900											

Table 6: Determining the total system cost of the TEG/TCES as the TEG Peak power varies. Highlighted in green, the energy storage varies from 0.1 kWh_e to 10 kWh_e (the same varied storage capacity as the PV/Battery system; this is so the two systems can be compared to each other). Based upon this storage capacity change, the cost of the TCES and the solar concentrator vary. As the TEG peak power varies from 50W to 300W, the cost of the TEG also varies. Thus, the altered TEG cost is summed with the solar concentrator and TCES cost. The TEG power per rate is assumed to be constant at \$3/W (as highlighted in blue).

Energy Storage coming out of TEG [kWh _e]												
Cost of TEG and TCES [\$]		\$ 307	\$ 313	\$ 313	\$ 327	\$ 327	\$ 340	\$ 340	\$ 353	\$ 353	\$ 367	\$ 367
Collecton Time [8 hr]												
Cost of Solar Concentrator [\$]		\$ 944	\$ 1,889	\$ 2,833	\$ 3,778	\$ 4,722	\$ 5,667	\$ 6,611	\$ 7,556	\$ 8,500	\$ 9,444	\$ 94
Total System Cost [\$]		\$ 1,251	\$ 2,202	\$ 3,153	\$ 4,104	\$ 5,056	\$ 6,007	\$ 6,958	\$ 7,909	\$ 8,860	\$ 9,811	\$ 395
Collecton Time [10 hr]												
Cost of Solar Concentrator [\$]		\$ 756	\$ 1,511	\$ 2,267	\$ 3,022	\$ 3,778	\$ 4,533	\$ 5,289	\$ 6,044	\$ 6,800	\$ 7,556	\$ 76
Total System Cost [\$]		\$ 1,062	\$ 1,824	\$ 2,587	\$ 3,349	\$ 4,111	\$ 4,873	\$ 5,636	\$ 6,398	\$ 7,160	\$ 7,922	\$ 376
Collecton Time [15 hr]												
Cost of Solar Concentrator [\$]		\$ 504	\$ 1,007	\$ 1,511	\$ 2,015	\$ 2,519	\$ 3,022	\$ 3,526	\$ 4,030	\$ 4,533	\$ 5,037	\$ 50
Total System Cost [\$]		\$ 810	\$ 1,321	\$ 1,831	\$ 2,341	\$ 2,852	\$ 3,362	\$ 3,873	\$ 4,383	\$ 4,893	\$ 5,404	\$ 351
Collecton Time [25 hr]												
Cost of Solar Concentrator [\$]		\$ 302	\$ 604	\$ 907	\$ 1,209	\$ 1,511	\$ 1,813	\$ 2,116	\$ 2,418	\$ 2,720	\$ 3,022	\$ 30
Total System Cost [\$]		\$ 609	\$ 918	\$ 1,227	\$ 1,536	\$ 1,844	\$ 2,153	\$ 2,462	\$ 2,771	\$ 3,080	\$ 3,389	\$ 331
Collecton Time [35 hr]												
Cost of Solar Concentrator [\$]		\$ 216	\$ 432	\$ 648	\$ 863	\$ 1,079	\$ 1,295	\$ 1,511	\$ 1,727	\$ 1,943	\$ 2,159	\$ 22
Total System Cost [\$]		\$ 523	\$ 745	\$ 968	\$ 1,190	\$ 1,413	\$ 1,635	\$ 1,858	\$ 2,080	\$ 2,303	\$ 2,525	\$ 322

Table 7: Determining the total system cost of the TEG/TCES as the solar collection time varies. Highlighted in green, the energy storage varies from 0.1 kWh_e, to 10 kWh_e. Based upon the storage capacity change, the cost of the TEG and TCES changes. As the solar collection time varies from 8hr to 35 hrs, the cost of the solar concentrator varies (as highlighted in purple). Thus, the altered solar concentrator cost is summed with the TEG and TCES cost

Energy Storage coming out of TEG [kWh _e]			1	2	3	4	5	6	7	8	9	10	0.1
Cost of TCES [\$]			\$ 6.67	\$13.33	\$20.00	\$26.67	\$33.33	\$40.00	\$46.67	\$53.33	\$60.00	\$66.67	\$ 0.67
TEG Peak Power [W]	TEG Rate [\$ /W]	TEG Cost [\$]											
140	\$ 3	\$ 420	\$ 427	\$ 433	\$ 440	\$ 447	\$ 453	\$ 460	\$ 467	\$ 473	\$ 480	\$ 487	\$ 421
10	\$ 3	\$ 30	\$ 37	\$ 43	\$ 50	\$ 57	\$ 63	\$ 70	\$ 77	\$ 83	\$ 90	\$ 97	\$ 31
200	\$ 3	\$ 600	\$ 607	\$ 613	\$ 620	\$ 627	\$ 633	\$ 640	\$ 647	\$ 653	\$ 660	\$ 667	\$ 601
300	\$ 3	\$ 900	\$ 907	\$ 913	\$ 920	\$ 927	\$ 933	\$ 940	\$ 947	\$ 953	\$ 960	\$ 967	\$ 901
400	\$ 3	\$ 1,200	\$1,207	\$1,213	\$1,220	\$1,227	\$1,233	\$1,240	\$1,247	\$1,253	\$1,260	\$1,267	\$1,201
450	\$ 3	\$ 1,350	\$1,357	\$1,363	\$1,370	\$1,377	\$1,383	\$1,390	\$1,397	\$1,403	\$1,410	\$1,417	\$1,351

Table 8: Determining the total system cost of the TEG/TCES as the TEG Peak power varies. Highlighted in green, the energy storage varies from 0.1 kWh_e, to 10 kWh_e. Based upon this storage capacity change, the cost of the TCES and the TEG vary. As the TEG peak power varies from 10W to 450W, the cost of the TEG also varies. Thus, the altered TEG cost is summed with the TCES cost. The TEG power per rate is assumed to be constant at \$3/W (as highlighted in blue).

