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Enabling a Flexible Grid with Increased Penetration of DER: Techno-economic Analysis of Metal Hydride Thermochemical Energy Storage Integrated with Stirling Engine for Grid Energy Storage Applications

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CAPEX	Capital Expenses
CSP	Concentrated Solar Power
ENG	Expanded Natural Graphite
ΔH	Enthalpy of reaction
HTMH	High Temperature Metal Hydride
LCOS	Levelized Cost of Storage
LTMH	Low Temperature Metal Hydride
MH TES	Metal Hydride Thermal Energy Storage
OPEX	Operational Expenses
PCU	Power Conversion Unit
SRNL	Savannah River National Laboratory
TES	Thermal Energy Storage

1.0 Executive Summary

This report summarizes the results of a techno-economic assessment of the capital and operational expenses for 3 scenarios utilizing a TES/Stirling engine system which is charged by an electric heater to provide grid power and energy storage. While there are several integration possibilities and material choices that could be utilized in such systems, three difference scenarios were chosen for this assessment to reflect an anticipated deployment of the technology where each might require different TES system configurations. Additionally, an enhanced version of the HTMH is considered to demonstrate the expected impact on costs with further technology development. The predicted capital and operational LCOS for the system configurations range from \$0.0198/kWhr$_e$ - \$0.0734/kWhr$_e$ which compare positively to the LCOS for lithium ion battery storage ranging from \$0.087/kWhr$_e$ – \$0.329/kWhr$_e$. The key drivers for cost improvements to the system are material property enhancements in the HTMH primarily related to reducing the costs associated with the HTMH vessel and heat exchangers. This analysis demonstrates the potential benefits and flexibility of integrating a Stirling engine with a metal hydride-based TES system and suggests that the MH TES technology, at its current level of development, provides a highly competitive alternative to lithium ion batteries for large scale grid energy storage applications.

2.0 Introduction

It is well known that thermal energy storage (TES) integrated with a Stirling engine provides a promising pathway to produce dispatchable power from concentrated solar power (CSP) dish systems. [1-4] Herein, we have analyzed the techno-economic feasibility of leveraging a metal hydride-based TES system with a Stirling engine to provide a low-cost alternative to lithium ion batteries for residential, microgrids, and grid storage applications. Large scale energy storage solutions are becoming imperative as increased quantities of intermittent renewable energy technologies are deployed. Further fueling the immediate need for innovative solutions for large scale energy storage, California governor Jerry Brown recently signed a bill with the goal of becoming 100% CO_2 free in the electric grid by 2045. In order to meet these goals and the targets outlined in the Paris agreement, a substantial amount of grid storage will need to be deployed. SRNL has recently developed a new class of high temperature metal hydride-based TES materials which provide the necessary operational temperatures to pair with a high efficiency Stirling engine power conversion unit (PCU). The newly developed TES materials have advantages in being made from low-cost, highly abundant elements which operate at high temperatures (600-750 °C). These materials have advantages over latent and sensible heat materials such as molten salts due to their non-corrosive nature, significantly higher energy densities, and ability to store thermal energy nearly indefinitely since the energy is held directly in chemical bonds. The overall system also contains no rare earth and platinum group metals which can hinder the long-term sustainability of a technology. Pairing these materials with a Stirling engine provides a high efficiency conversion pathway capable of accepting various heat inputs to charge the system. The operational lifetime of Stirling engines has also progressed rapidly. In 2016, NASA demonstrated 103,000 hours of continuous operation for two of their Stirling engines without maintenance or a reduction in performance. [5] Furthermore, Kockums has demonstrated up to 18,000 hours of maintenance-free run time on more than 200 Stirling engines and STC also confirmed over 67,000 hours of operation. [6]

A metal hydride-based TES system operates by the transfer of hydrogen between two metal hydride beds. The high temperature metal hydride (HTMH) bed contains a material which has a high enthalpy (heat of reaction) and a reasonable equilibrium pressure (≤ 60 bar) at the desired operational temperature. The low temperature metal hydride (LTMH) has a low enthalpy and a matching equilibrium pressure at a lower operational temperature. The equilibrium pressure for a metal hydride material is the pressure at which the rate of hydrogen uptake (exothermic) and release (endothermic) is equivalent. The equilibrium pressure for a reversible metal hydride is reduced with decreasing temperature and elevated with increasing temperature. To store heat, hydrogen is released by the addition of heat to the HTMH material. The temperature will then increase, raising the pressure in the system above the equilibrium pressure of the LTMH material and causing hydrogen to react with the LTMH. The lower grade heat produced in the LTMH material is rejected to maintain a lower temperature and lower equilibrium pressure in the LTMH bed. To release the stored thermal energy, the temperature of the LTMH bed is increased to release hydrogen which then reacts with the HTMH bed to generate a large amount of heat due to the larger enthalpy of that reaction. Figure 1 below illustrates the fundamental concept for metal hydride-based TES operation.

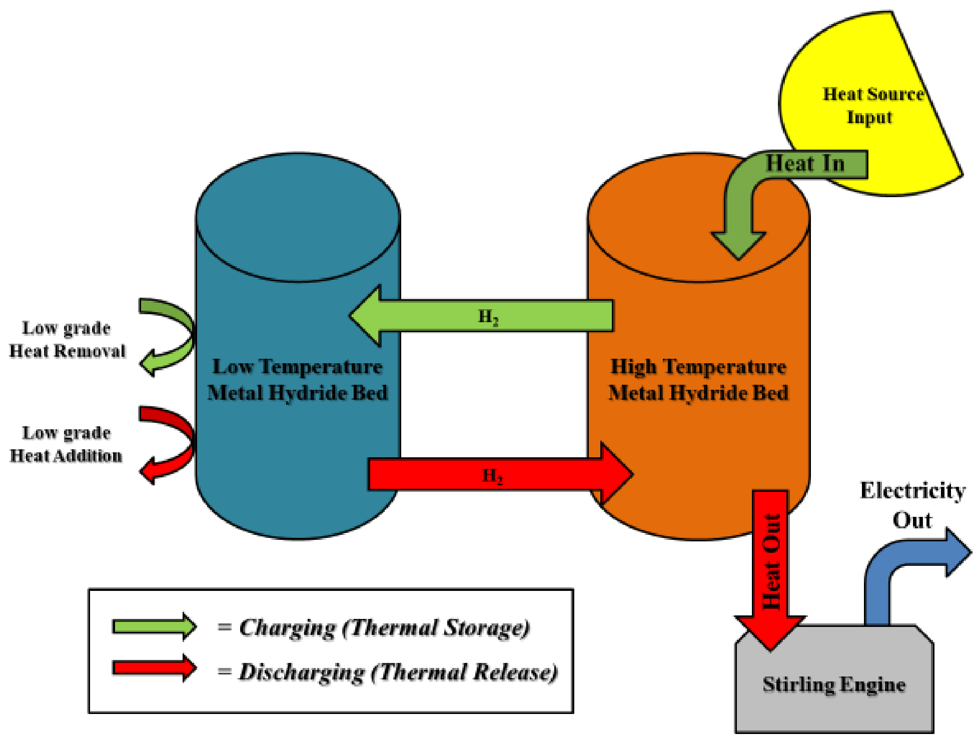

Figure 1: Illustration of the operation of a metal hydride-based TES system integrated with a Stirling Engine. (Components are not to scale).

Herein, a cost assessment of the capital and operational expenses is carried out on a TES/Stirling engine system which is charged by an electric heater. There are a number of integration possibilities and material choices which could be utilized in such a system. Three difference scenarios were chosen, based on previous knowledge of the subject, which each employ a different TES system configuration. Additionally, an enhanced version of the HTMH is considered to demonstrate the expected impact on costs with further technology development.

3.0 Cost Analysis

A techno-economic analysis to evaluate the capital expenses and operational expenses of a metal hydride TES system coupled with a Stirling engine in an electrically charged scenario was carried out. The TES system was based on HTMH materials, recently developed by SRNL, operating at a temperature of 750 °C and coupled with three different LTMH configurations. Two different HTMH material scenarios were evaluated and are designated HTMH 1 and HTMH 2. HTMH 1 is a known and thoroughly evaluated material in which all material properties are based on experimental measurements. HTMH 2 is based on another experimentally evaluated material with a practically achievable enhancement in the hydrogen capacity versus current experimental results. Current experimental hydrogen capacity for HTMH 2 is 1.7 wt. % while the theoretical hydrogen capacity is 3.69 wt. %. A hydrogen capacity of 2.7 wt. % was utilized for this analysis and is meant to represent a near term advancement in the TES technology with additional research and development. LTMH 1 and LTMH 2 in this cost assessment represent TiFe and Na_3AlH_6, respectively. The material properties utilized for the analysis and shown in Table 1 are from experimentally acquired data by SRNL and other literature reports. The HTMH and LTMH material cost has been assessed assuming the cost of the precursors on a multi-ton scale with an additional 20% added for manufacturing costs as shown in Table 2. LTMH 2 (Na_3AlH_6) cost estimates have been previously reported as 2.5-3.5 $/kg. [7,8] In this analysis, the TES system (HTMH coupled with LTMH) is designed for each Stirling unit (30 kW_e), assuming thermal to electric conversion efficiency of 40% and thermal energy storage times of 6 and 12 hours. Operational parameters are given in Table 3. System charging is assumed to take course over a 6-hour period. A resistive electric heater is assumed as the heat input source for this analysis, but the system could be heated by any thermal input which can provide high temperatures. The cost analysis is performed on individual systems where each TES system is coupled with one 30 kW_e Stirling engine. The modular nature of these systems allows for storage capacity to be scaled as desired by deploying more units.

Table 1: TES material properties used in cost analysis

	Density (kg/m^3)	ΔH (kJ/mol H_2)	Hydrogen capacity (wt. %)	Thermal conductivity (W/m•K)
HTMH 1	1900	96	1.7	6.5
HTMH 2	1700	110	2.7	3.5

LTMH 1 (TiFe)	2500	28	1.9	7
LTMH 2 (Na_3AlH_6)	1000	47	2.5	7

Table 2: HTMH and LTMH material economic properties

	Raw material cost ($/kg)	**Additional Processing Cost Assumption**	**Total Cost ($/kg)**
HTMH 1	$1.70	20%	$2.90
HTMH 2	$1.50	20%	$1.80
LTMH 1 (TiFe)	$5.00	20%	$6.00
LTMH 2 (Na_3AlH_6)	$2.50	20%	$3.00

Table 3: Stirling engine operational parameters

Stirling Engine Output Rate (kW_e)	30
Stirling Engine Efficiency (%)	40
Thermal Energy Input Rate (kW_{th})	75
Total Engine Output ($kWhr_e$) (12 hrs.)	360
Total Engine Output ($kWhr_e$) (6 hrs.)	180
Total Thermal Energy Required ($kWhr_{th}$) (12 hrs.)	900
Total Thermal Energy Required ($kWhr_{th}$) (6 hrs.)	450

3.1 Scenario 1

In the first scenario, the costs associated with coupling HTMH 1 and HTMH 2 with LTMH 1were assessed. Additionally, a storage capacity of 12 hours and 6 hours was evaluated with an expected operational lifetime of 25 and 40 years. All calculations below assume a 6-hour charging time. LTMH 1 represents TiFe which can operate at temperature between 30 and 80°C for the pairing with the HTMH 1 and HTMH 2. The higher density and lower enthalpy of reaction of LTMH 1 allows for cost reductions related to vessel size reductions and a reduced amount of excess HTMH required to shuttle the hydrogen back to the HTMH during discharge. Currently calculations do not consider waste heat recovery from the Stirling engine to drive the LTMH reversibility. Tables 4-7 below give a cost breakdown of the system components and an estimated operational expense per year based on the potential upkeep of each system. The capital expenses (CAPEX) are a summation of the primary components costs with an additional balance of plant (BOP) cost added to address the costs of tubing, supports, control panel electronics, and safety devices. Operational expenses (OPEX) are related to the replacement of seals and other parts on the Stirling engine (Service and maintenance) as well as upkeep that may be required for the TES system. All system component costs were rounded to the nearest \$100 (except for hydrogen which was rounded to the nearest \$10). SS 347 was assumed as the construction material for the HTMH vessel and heat exchangers. Sodium heat pipes were assumed for the HTMH heat exchangers and an ethylene glycol radiator heat exchanger assumed for the LTMH vessel. The LTMH vessel and construction material is assumed to be aluminum. Vessel thicknesses were estimated based on the yield strength of the material used at the highest operational temperature. A safety factor of 3 was employed in these cases. Tables 4 and 5 provide a cost breakdown and overall percentage of cost for HTMH 1 and HTMH 2 coupled with LTMH 1 over 40 years, respectively, with 12 and 6 hours of storage. Tables 6 and 7 provide the same cost analysis over a 25-year system lifetime. As expected, the levelized cost of storage (LCOS) is slightly higher with 6 hours of storage when compared to 12 hours of storage in all cases. This is primarily a result of the constant capital expenses for the Stirling engine and many BOP items.

Table 4: Cost analysis for HTMH 1 + LTMH 1 integrated with Stirling engine over a 40-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 1 + LTMH 1 with 12 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$10,000	6.63%
LTMH Material	$20,900	13.85%
HTMH Heat Exchanger	$20,100	13.32%
LTMH Heat Exchanger	$3,100	2.05%
Cost of Hydrogen	$260	0.17%
HTMH Vessel	$29,300	19.42%
LTMH Vessel	$4,700	3.12%
Heater Cost	$1,700	1.13%
Stirling Engine Cost	$14,000	9.28%
Insulation / System Casing	$4,200	2.78%
Balance of Plant	$7,600	5.04%
Total System Cost (CAPEX)	**$115,860**	**76.80%**
Operational hours (hrs/yr)	4380	
Lifetime operational hours	175200	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	5256000	
Service Cost ($/yr)	$874	
Service Cost (OPEX)	**$35,000**	**23.20%**
Total Cost (OPEX + CAPEX)	**$150,860**	
LCOS ($/$kWhr_e$)	**$0.0287**	

HTMH 1 + LTMH 1 with 6 hours TES over 40 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$5,000	5.87%
LTMH Material	$10,400	12.22%
HTMH Heat Exchanger	$10,100	11.86%
LTMH Heat Exchanger	$1,600	1.88%
Cost of Hydrogen	$130	0.15%
HTMH Vessel	$14,700	17.27%
LTMH Vessel	$2,400	2.82%
Heater Cost	$900	1.06%
Stirling Engine Cost	$14,000	16.45%
Insulation / System Casing	$2,800	3.29%
Balance of Plant	$6,200	7.28%
Total System Cost (CAPEX)	$68,230	80.15%
Operational hours (hrs/yr)	2190	
Lifetime operational hours	87600	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	2628000	
Service Cost ($/yr)	$423	
Service Cost (OPEX)	$16,900	11.20%
Total Cost (OPEX + CAPEX)	$85,130	
LCOS ($/$kWhr_e$)	$0.0324	

Table 5: Cost analysis for HTMH 2 + LTMH 1 integrated with Stirling engine over a 40-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 2 + LTMH 1 with 12 hours TES over 40 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$4,400	4.12%
LTMH Material	$17,900	16.77%
HTMH Heat Exchanger	$12,900	12.09%
LTMH Heat Exchanger	$2,700	2.53%
Cost of Hydrogen	$210	0.20%
HTMH Vessel	$9,400	8.81%
LTMH Vessel	$2,000	1.87%
Heater Cost	$1,700	1.59%
Stirling Engine Cost	$14,000	13.12%
Insulation / System Casing	$2,500	2.34%
Balance of Plant	$4,700	4.40%
Total System Cost (CAPEX)	$72,410	67.86%
Operational hours (hrs/yr)	4380	
Lifetime operational hours	175200	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	5256000	
Service Cost ($/yr)	$857	
Service Cost (OPEX)	$34,300	32.14%
Total Cost (OPEX + CAPEX)	$106,710	
LCOS ($/$kWhr_e$)	$0.0203	

HTMH 2 + LTMH 1 with 6 hours TES over 40 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$2,200	3.53%
LTMH Material	$9,000	14.45%
HTMH Heat Exchanger	$6,500	10.43%
LTMH Heat Exchanger	$1,400	2.25%
Cost of Hydrogen	$100	0.16%
HTMH Vessel	$4,700	7.54%
LTMH Vessel	$1,000	1.61%
Heater Cost	$900	1.44%
Stirling Engine Cost	$14,000	22.47%
Insulation / System Casing	$1,700	2.73%
Balance of Plant	$4,200	6.74%
Total System Cost (CAPEX)	$45,700	73.35%
Operational hours (hrs/yr)	2190	
Lifetime operational hours	87600	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	2628000	
OPEX / Service Cost ($/yr)	$416	
Service Cost (OPEX)	$16,600	26.65%
Total Cost (OPEX + CAPEX)	$62,300	
LCOS ($/$kWhr_e$)	$0.0237	

Table 6: Cost analysis for HTMH 1 + LTMH 1 integrated with Stirling engine over a 25-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 1 + LTMH 1 with 12 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$10,000	7.26%
LTMH Material	$20,900	15.18%
HTMH Heat Exchanger	$20,100	14.60%
LTMH Heat Exchanger	$3,100	2.25%
Cost of Hydrogen	$260	0.19%
HTMH Vessel	$29,300	21.28%
LTMH Vessel	$4,700	3.41%
Heater Cost	$1,700	1.23%
Stirling Engine Cost	$14,000	10.17%
Insulation / System Casing	$4,200	3.05%
Balance of Plant	$7,600	5.52%
Total System Cost (CAPEX)	$115,860	84.16%
Operational hours (hrs/yr)	4380	
Lifetime operational hours	109500	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	3285000	
Service Cost ($/yr)	$874	
Service Cost (OPEX)	$21,800	15.84%
Total Cost (OPEX + CAPEX)	$137,660	
LCOS ($/$kWhr_e$)	$0.0419	

HTMH 1 + LTMH 1 with 6 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$5,000	6.34%
LTMH Material	$10,400	13.19%
HTMH Heat Exchanger	$10,100	12.81%
LTMH Heat Exchanger	$1,600	2.03%
Cost of Hydrogen	$130	0.16%
HTMH Vessel	$14,700	18.65%
LTMH Vessel	$2,400	3.04%
Heater Cost	$900	1.14%
Stirling Engine Cost	$14,000	17.76%
Insulation / System Casing	$2,800	3.55%
Balance of Plant	$6,200	7.87%
Total System Cost (CAPEX)	$68,230	86.55%
Operational hours (hrs/yr)	2190	
Lifetime operational hours	54750	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	1642500	
Service Cost ($/yr)	$423	
Service Cost (OPEX)	$10,600	13.45%
Total Cost (OPEX + CAPEX)	$78,830	
LCOS ($/$kWhr_e$)	$0.0480	

Table 7: Cost analysis for HTMH 2 + LTMH 1 integrated with Stirling engine over a 25-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 2 + LTMH 1 with 12 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$4,400	4.69%
LTMH Material	$17,900	19.08%
HTMH Heat Exchanger	$12,900	13.75%
LTMH Heat Exchanger	$2,700	2.88%
Cost of Hydrogen	$210	0.22%
HTMH Vessel	$9,400	10.02%
LTMH Vessel	$2,000	2.13%
Heater Cost	$1,700	1.81%
Stirling Engine Cost	$14,000	14.92%
Insulation / System Casing	$2,500	2.66%
Balance of Plant	$4,700	5.01%
Total System Cost (CAPEX)	$72,410	77.19%
Operational hours (hrs/yr)	4380	
Lifetime operational hours	109500	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	3285000	
Service Cost ($/yr)	$857	
Service Cost (OPEX)	$21,400	22.81%
Total Cost (OPEX + CAPEX)	$93,810	
LCOS ($/$kWhr_e$)	$0.0286	

HTMH 2 + LTMH 1 with 6 hours TES over 25 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$2,200	3.92%
LTMH Material	$9,000	16.04%
HTMH Heat Exchanger	$6,500	11.59%
LTMH Heat Exchanger	$1,400	2.50%
Cost of Hydrogen	$100	0.18%
HTMH Vessel	$4,700	8.38%
LTMH Vessel	$1,000	1.78%
Heater Cost	$900	1.60%
Stirling Engine Cost	$14,000	24.96%
Insulation / System Casing	$1,700	3.03%
Balance of Plant	$4,200	7.49%
Total System Cost (CAPEX)	$45,700	81.46%
Operational hours (hrs/yr)	2190	
Lifetime operational hours	54750	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	1642500	
Service Cost ($/yr)	$416	
Service Cost (OPEX)	$10,400	18.54%
Total Cost (OPEX + CAPEX)	$56,100	
LCOS ($/$kWhr_e$)	$0.0342	

When pairing the HTMH 1 with LTMH 1 (TiFe), the high temperature side of the TES system dominates the cost of the overall system. Figure 2 below gives an illustrative breakdown of the cost percentages associated with each section of the overall energy storage unit. The HTMH bed contains a large percentage of the cost and this is directly related to the amount of material needed for the long storage time and the operational pressures of 60 bar needed to access the full capacity of the material. The operational temperatures and pressures required for the HTMH vessel increase the amount material required and manufacturing costs associated with that component. When LTMH 1 is paired with HTMH 2, the reduced volume of the HTMH and operational pressures (30 bar) significantly lower the cost of the HTMH vessel. The reduced thermal conductivity of HTMH 2 compared to HTMH 1 increases the number of heat exchanger surfaces required, but the overall size of the heat exchanger is reduced because of the increased storage density and reduced vessel size. This highlights the primary area of cost reduction in this type of system being the HTMH material properties to reduce the costs associated with the vessel and heat exchanger.

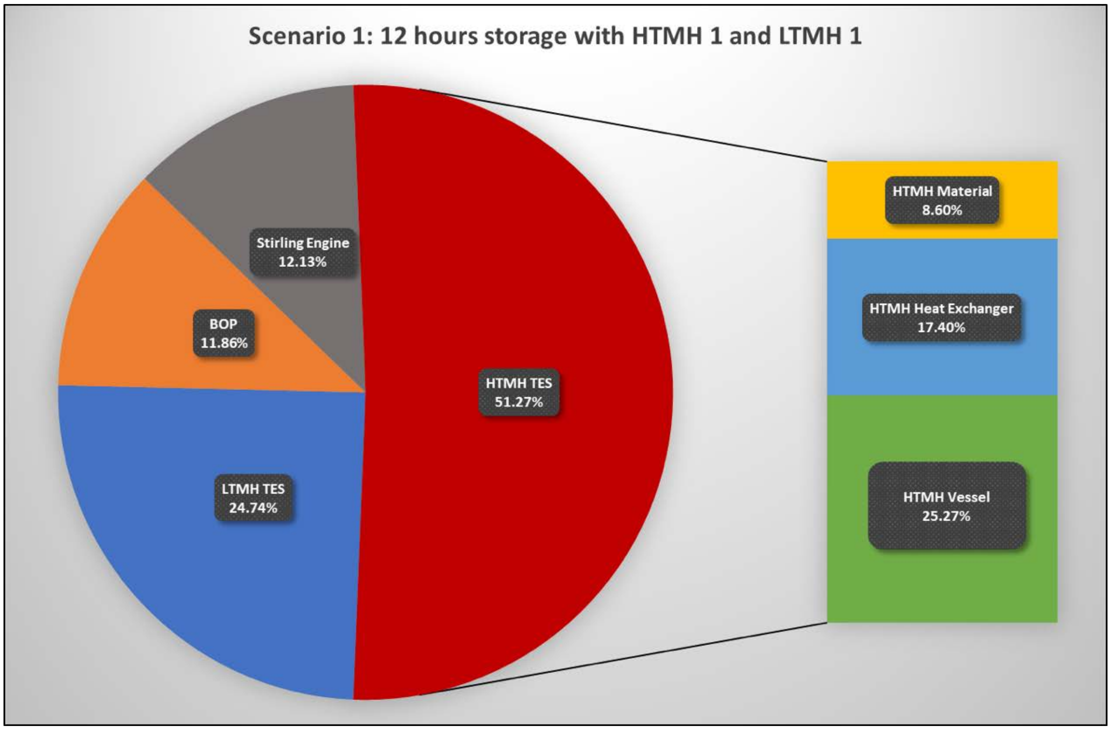

Figure 2: System Cost Breakdown for HTMH 1 + LTMH 1 with 12 hours of TES

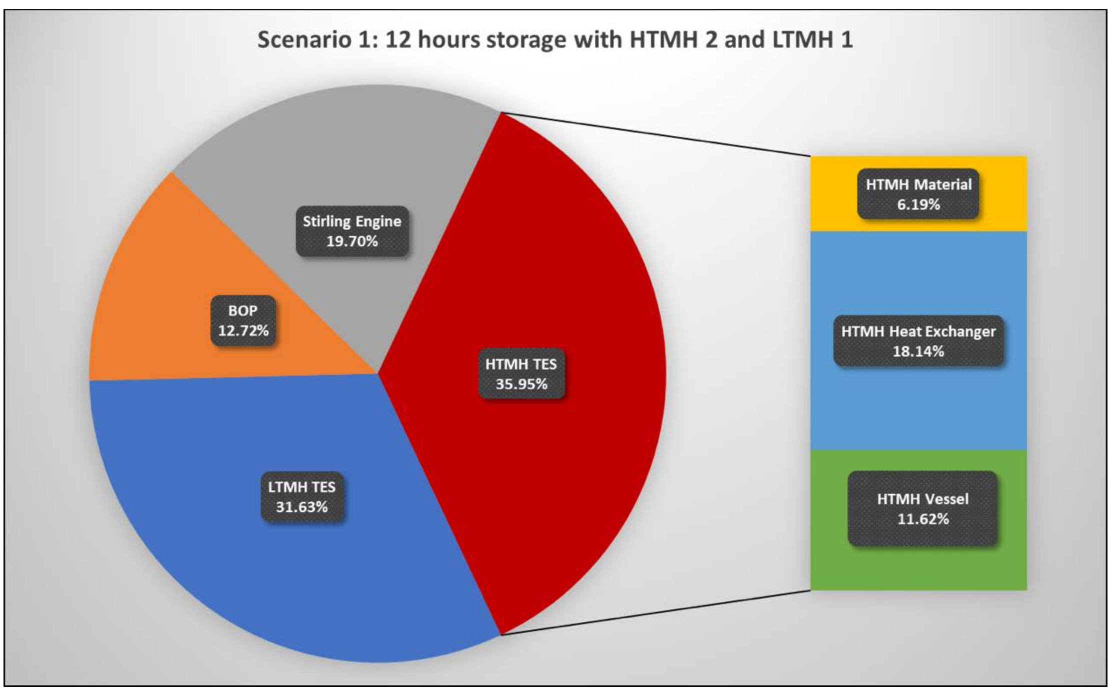

Figure 3: System Cost Breakdown for HTMH 2 + LTMH 1 with 12 hours of TES

3.2 Scenario 2

In scenario 2, a cost analysis is performed for pairing HTMH 1 and HTMH 2 with LTMH 2 (Na_3AlH_6). LTMH 2 operates at a higher temperature (~100-160 °C) to provide the necessary hydrogen pressure to pair with the HTMH. The raw material costs of LTMH 2 are roughly half of LTMH 1 and the hydrogen storage capacity of the material is higher. The result is a reduced volume and mass requirement for LTMH 2 which reduces the costs associated with the LTMH vessel and heat exchanger. On the other hand, the higher operational temperature and enthalpy of reaction increases the vessel and heat exchanger thicknesses required and increases the additional amount of HTMH needed to provide heat to reverse the reaction. Scenario 2 is evaluated as an example of employing a lower cost and higher capacity LTMH material, but the overall system integration is more complex due to the higher operational temperatures required. Tables 8 and 9 compare the systems which pair HTMH 1 and HTMH 2 with LTMH 2, respectively, over a 40-year operational lifetime. Tables 10 and 11 provide the same cost analysis considering a 25-year lifetime. This scenario provides the lowest estimated LCOS of \$0.0198/kWhr$_e$ when pairing HTMH 2 with LTMH 2 over a 40-year lifetime. Figures 4 and 5 give an illustrated cost ratio of each primary system component. When LTMH 2 is paired with HTMH 1 the cost of the HTMH system is estimated at 57.02% of the overall capital cost of the system. By increasing the thermal capacity of the HTMH material (as represented by HTMH 2) the percentage of system cost drops to 42.52% of overall CAPEX. This also drops the LCOS from \$0.0297/kWhr$_e$ to \$0.0198/kWhr$_e$ when assuming a 40-year lifetime. Although there are cost reductions related to HTMH material costs with HTMH 2, the primary cost reductions in the overall system originate from cost reductions in the HTMH vessel and heat exchangers.

Table 8: Cost analysis for HTMH 1 + LTMH 2 integrated with Stirling engine over a 40-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 1 + LTMH 2 with 12 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$11,700	7.49%
LTMH Material	$7,900	5.05%
HTMH Heat Exchanger	$23,300	14.91%
LTMH Heat Exchanger	$5,500	3.52%
Cost of Hydrogen	$300	0.19%
HTMH Vessel	$33,900	21.69%
LTMH Vessel	$9,600	6.14%
Heater Cost	$1,700	1.09%
Stirling Engine Cost	$14,000	8.96%
Insulation / System Casing	$5,000	3.20%
Balance of Plant	$7,900	5.05%
Total System Cost (CAPEX)	**$120,800**	**77.29%**
Operational hours (hrs/yr)	4380	
Lifetime operational hours	175200	
kWhr$_e$ per year	131400	
kWhr$_e$ per lifetime	5256000	
Service Cost ($/yr)	$887	
Service Cost (OPEX)	**$35,500**	**22.71%**
Total Cost OPEX + CAPEX	**$156,300**	
LCOS ($/kWhr$_e$)	**$0.0297**	

HTMH 1 + LTMH 2 with 6 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$5,900	6.69%
LTMH Material	$4,000	4.54%
HTMH Heat Exchanger	$11,700	13.27%
LTMH Heat Exchanger	$2,800	3.18%
Cost of Hydrogen	$150	0.17%
HTMH Vessel	$17,000	19.29%
LTMH Vessel	$4,800	5.45%
Heater Cost	$900	1.02%
Stirling Engine Cost	$14,000	15.88%
Insulation / System Casing	$3,300	3.74%
Balance of Plant	$6,500	7.37%
Total System Cost (CAPEX)	**$71,050**	**80.60%**
Operational hours (hrs/yr)	2190	
Lifetime operational hours	87600	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	2628000	
Service Cost ($/yr)	$427	
Service Cost (OPEX)	**$17,100**	**19.40%**
Total Cost OPEX + CAPEX	**$88,150**	
LCOS ($/$kWhr_e$)	**$0.0335**	

Table 9: Cost analysis for HTMH 2 + LTMH 2 integrated with Stirling engine over a 40-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 2 + LTMH 2 with 12 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$5,000	4.79%
LTMH Material	$6,800	6.52%
HTMH Heat Exchanger	$14,300	13.71%
LTMH Heat Exchanger	$4,900	4.70%
Cost of Hydrogen	$230	0.22%
HTMH Vessel	$10,400	9.97%
LTMH Vessel	$5,000	4.79%
Heater Cost	$1,700	1.63%
Stirling Engine Cost	$14,000	13.42%
Insulation / System Casing	$2,800	2.68%
Balance of Plant	$4,600	4.41%
Total System Cost (CAPEX)	**$69,730**	**66.84%**
Operational hours (hrs/yr)	4380	
Lifetime operational hours	175200	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	5256000	
Service Cost ($/yr)	$864	
Service Cost (OPEX)	**$34,600**	**33.16%**
Total Cost OPEX + CAPEX	**$104,330**	
LCOS ($/$kWhr_e$)	**$0.0198**	

HTMH 2 + LTMH 2 with 6 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$2,500	4.10%
LTMH Material	$3,400	5.57%
HTMH Heat Exchanger	$7,200	11.80%
LTMH Heat Exchanger	$2,500	4.10%
Cost of Hydrogen	$120	0.20%
HTMH Vessel	$5,200	8.52%
LTMH Vessel	$2,500	4.10%
Heater Cost	$900	1.47%
Stirling Engine Cost	$14,000	22.94%
Insulation / System Casing	$1,900	3.11%
Balance of Plant	$4,000	6.56%
Total System Cost (CAPEX)	**$44,220**	**72.47%**
Operational hours (hrs/yr)	2190	
Lifetime operational hours	87600	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	2628000	
Service Cost ($/yr)	$420	
Service Cost (OPEX)	**$16,800**	**27.53%**
Total Cost OPEX + CAPEX	**$61,020**	
LCOS ($/$kWhr_e$)	**$0.0232**	

Table 10: Cost analysis for HTMH 1 + LTMH 2 integrated with Stirling engine over a 25-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 1 + LTMH 2 with 12 hours TES over 25 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$11,700	8.18%
LTMH Material	$7,900	5.52%
HTMH Heat Exchanger	$23,300	16.29%
LTMH Heat Exchanger	$5,500	3.85%
Cost of Hydrogen	$300	0.21%
HTMH Vessel	$33,900	23.71%
LTMH Vessel	$9,600	6.71%
Heater Cost	$1,700	1.19%
Stirling Engine Cost	$14,000	9.79%
Insulation / System Casing	$5,000	3.50%
Balance of Plant	$7,900	5.52%
Total System Cost (CAPEX)	**$120,800**	**84.48%**
Operational hours (hrs/yr)	4380	
Lifetime operational hours	109500	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	3285000	
Service Cost ($/yr)	$887	
Service Cost (OPEX)	**$22,200**	**15.52%**
Total Cost OPEX + CAPEX	**$143,000**	
LCOS ($/$kWhr_e$)	**$0.0435**	

HTMH 1 + LTMH 2 with 6 hours TES over 25 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH 1 Material	$5,900	7.40%
LTMH 2 Material	$4,000	5.02%
HTMH Heat Exchanger	$11,700	14.67%
LTMH Heat Exchanger	$2,800	3.51%
Cost of Hydrogen	$150	0.19%
HTMH Vessel	$17,000	21.32%
LTMH Vessel	$4,800	6.02%
Heater Cost	$900	1.13%
Stirling Engine Cost	$14,000	17.55%
Insulation/ System Casing	$3,300	4.14%
Balance of Plant	$4,500	5.64%
Total System Cost (CAPEX)	**$69,050**	**86.58%**
Operational hours per year	2190	
Lifetime operational hours	54750	
kWhre per year	65700	
kWhre per lifetime	1642500	
OPEX / Service Cost ($/yr)	$427	
OPEX / Service Cost ($/lifetime)	**$10,700**	**13.42%**
Total Cost OPEX + CAPEX	**$79,750**	
LCOS ($/$kWhr_e$)	**$0.0486**	

Table 11: Cost analysis for HTMH 2 + LTMH 2 integrated with Stirling engine over a 25-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 2 + LTMH 2 with 12 hours TES over 25 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH 2 Material	$5,000	5.47%
LTMH 2 Material	$6,800	7.45%
HTMH Heat Exchanger	$14,300	15.66%
LTMH Heat Exchanger	$4,900	5.37%
Cost of Hydrogen	$230	0.25%
HTMH Vessel	$10,400	11.39%
LTMH Vessel	$5,000	5.47%
Heater Cost	$1,700	1.86%
Stirling Engine Cost	$14,000	15.33%
Insulation/ System Casing	$2,800	3.07%
Balance of Plant	$4,600	5.04%
Total System Cost (CAPEX)	$69,730	76.35%
Operational hours per year	4380	
Lifetime operational hours	109500	
kWhre per year	131400	
kWhre per lifetime	3285000	
OPEX / Service Cost ($/yr)	$864	
OPEX / Service Cost ($/lifetime)	$21,600	23.65%
Total Cost OPEX + CAPEX	$91,330	
LCOS ($/kWhr$_e$)	$0.0278	

HTMH 2 + LTMH 2 with 6 hours TES over 25 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH 2 Material	$2,500	4.57%
LTMH 2 Material	$3,400	6.21%
HTMH Heat Exchanger	$7,200	13.16%
LTMH Heat Exchanger	$2,500	4.57%
Cost of Hydrogen	$120	0.22%
HTMH Vessel	$5,200	9.50%
LTMH Vessel	$2,500	4.57%
Heater Cost	$900	1.64%
Stirling Engine Cost	$14,000	25.58%
Insulation/ System Casing	$1,900	3.47%
Balance of Plant	$4,000	7.31%
Total System Cost (CAPEX)	$44,220	80.81%
Operational hours per year	2190	
Lifetime operational hours	54750	
kWhre per year	65700	
kWhre per lifetime	1642500	
OPEX / Service Cost ($/yr)	$420	
OPEX / Service Cost ($/lifetime)	$10,500	19.19%
Total Cost OPEX + CAPEX	$54,720	
LCOS ($/kWhr$_e$)	$0.0333	

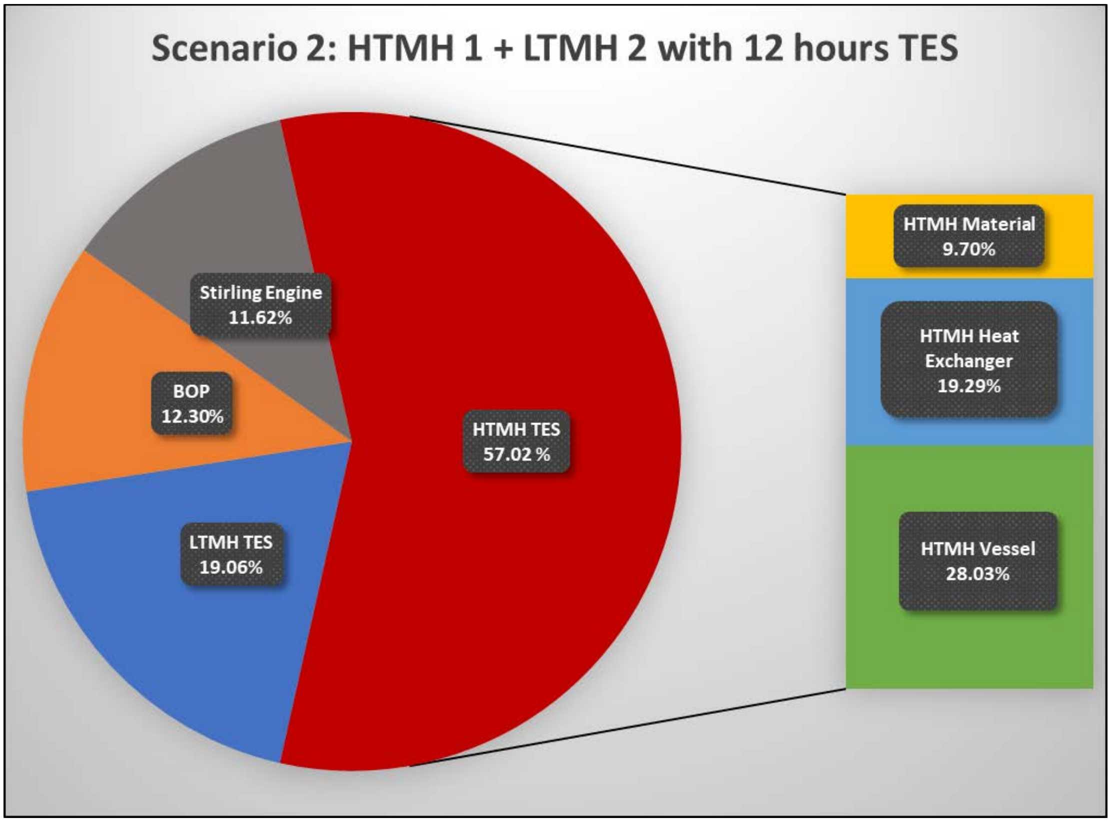

Figure 4: System Cost Breakdown for HTMH 1 + LTMH 2 with 12 hours of TES

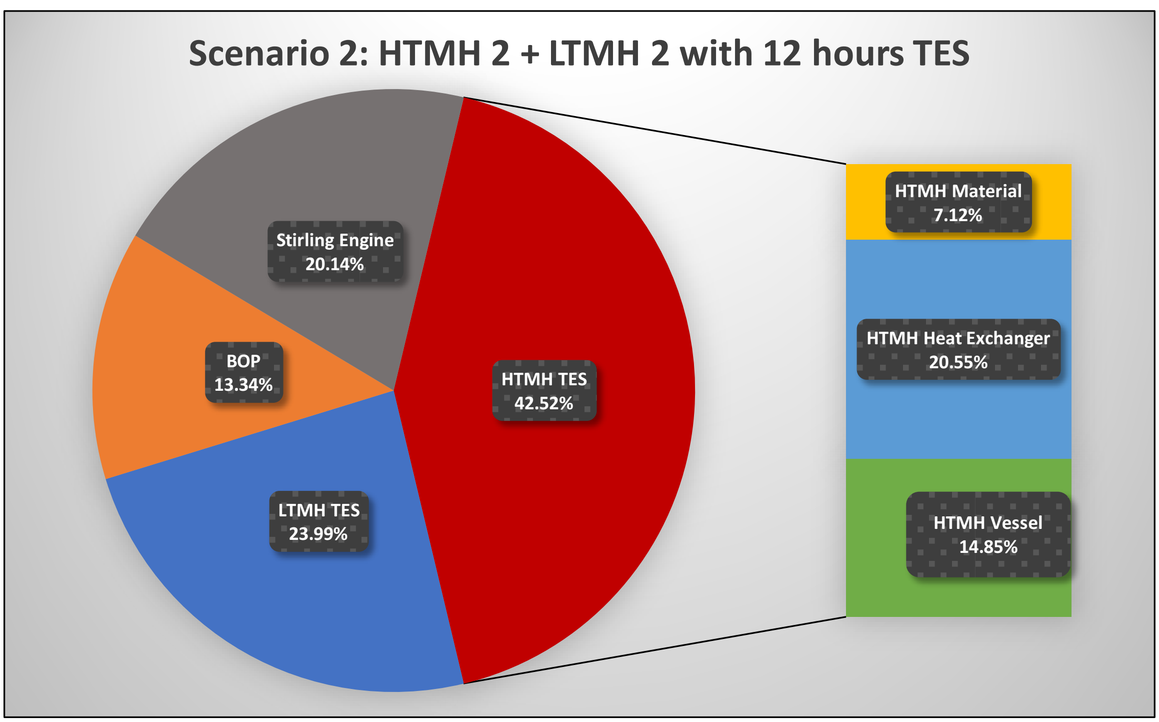

Figure 5: System Cost Breakdown for HTMH 2 + LTMH 2 with 12 hours of TES

3.3 Scenario 3

Scenario 3 considers a slightly different approach to the technology. In this case, the LTMH material is replaced with compressed hydrogen and a high-pressure storage tank. In this configuration, the compressor is used during system charging to pressurize the hydrogen storage tank during desorption of hydrogen from the HTMH. During discharge, the hydrogen flow is controlled by a regulator to flow back to the HTMH material and generate heat to power the Stirling engine. This type of design reduces the complexity of the system since low grade heat is not required during discharge as it is with LTMH 1 and LTMH 2. On the other hand, hydrogen compressors and high-pressure hydrogen tanks (250 bar) are quite expensive. For this scenario, the charging time plays a significant role in the capital cost of the overall system. The size of the electric heater needed to transfer the required heat for storage plays a role in the cost differences over charging, but the size of the compressor needed to store the hydrogen over the allotted period of time is the most influential cost parameter. Tables 12 and 13 provide the cost analysis for HTMH 1 and HTMH 2 paired with compressed hydrogen over a 40-year lifetime. Tables 14 and 15 give the same analysis over 25 years. Figures 6 and 7 give a pie chart breakdown of primary system component costs. It is evident that the HTMH TES system is still a significant portion of the overall of in this scenario, but the compressed hydrogen system contributions are more significant than when paired with LTMH 1 and LTMH 2. Table 16 below provides a comparison of the LCOS with charging time for pairing HTMH 1 and HTMH 2 with compressed hydrogen.

Table 12: Cost analysis for HTMH 1 + compressed hydrogen integrated with Stirling engine over a 40-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 1 + Compressed H_2 with 12 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$7,900	5.21%
HTMH Heat Exchanger	$16,500	10.88%
Compressor Cost	$17,500	11.54%
Hydrogen Storage Tank	$24,500	16.16%
Cost of Hydrogen	$200	0.13%
HTMH Vessel	$24,000	15.83%
Heater Cost	$1,700	1.12%
Stirling Engine Cost	$14,000	9.23%
Insulation / System Casing	$3,400	2.24%
Balance of Plant	$7,700	5.08%
Total System Cost (CAPEX)	$117,400	77.44%
Operational hours (hrs/yr)	4380	
Lifetime operational hours	175200	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	5256000	
Service Cost ($/yr)	$854	
Service Cost (OPEX)	$34,200	22.56%
Total Cost OPEX + CAPEX	$151,600	
LCOS ($/$kWhr_e$)	$0.0288	

HTMH 1 + Compressed H_2 with 6 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$4,000	4.67%
HTMH Heat Exchanger	$8,300	9.70%
Compressor Cost	$8,800	10.28%
Hydrogen Storage Tank	$12,300	14.37%
Cost of Hydrogen	$100	0.12%
HTMH Vessel	$12,000	14.02%
Heater Cost	$900	1.05%
Stirling Engine Cost	$14,000	16.36%
Insulation / System Casing	$2,300	2.69%
Balance of Plant	$6,300	7.36%
Total System Cost (CAPEX)	**$69,000**	**80.61%**
Operational hours (hrs/yr)	2190	
Lifetime operational hours	87600	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	2628000	
Service Cost ($/yr)	$416	
Service Cost (OPEX)	**$16,600**	**19.39%**
Total Cost OPEX + CAPEX	**$85,600**	
LCOS ($/$kWhr_e$)	**$0.0326**	

Table 13: Cost analysis for HTMH 2 + compressed hydrogen integrated with Texel Stirling engine over a 40-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 2 + Compressed H_2 with 12 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$3,800	3.23%
HTMH Heat Exchanger	$11,300	9.61%
Compressor Cost	$15,300	13.01%
Hydrogen Storage Tank	$21,400	18.20%
Cost of Hydrogen	$180	0.15%
HTMH Vessel	$8,300	7.06%
Heater Cost	$1,700	1.45%
Stirling Engine Cost	$14,000	11.91%
Insulation / System Casing	$2,200	1.87%
Balance of Plant	$5,500	4.68%
Total System Cost (CAPEX)	**$83,680**	**71.17%**
Operational hours (hrs/yr)	4380	
Lifetime operational hours	175200	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	5256000	
Service Cost ($/yr)	$848	
Service Cost (OPEX)	**$33,900**	**28.83%**
Total Cost OPEX + CAPEX	**$117,580**	
LCOS ($/$kWhr_e$)	**$0.0224**	

HTMH 2 + Compressed H_2 with 6 hours TES over 40 year lifetime		
System Capital Costs	**Cost (USD)**	**Cost %**
HTMH Material	$1,900	2.79%
HTMH Heat Exchanger	$5,700	8.38%
Compressor Cost	$7,700	11.33%
Hydrogen Storage Tank	$10,700	15.74%
Cost of Hydrogen	$90	0.13%
HTMH Vessel	$4,200	6.18%
Heater Cost	$900	1.32%
Stirling Engine Cost	$14,000	20.59%
Insulation / System Casing	$1,500	2.21%
Balance of Plant	$4,700	6.91%
Total System Cost (CAPEX)	**$51,390**	**75.58%**
Operational hours (hrs/yr)	2190	
Lifetime operational hours	87600	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	2628000	
Service Cost ($/yr)	$414	
Service Cost (OPEX)	**$16,600**	**24.42%**
Total Cost OPEX + CAPEX	**$67,990**	
LCOS ($/$kWhr_e$)	**$0.0259**	

Table 14: Cost analysis for HTMH 1 + compressed hydrogen integrated with Texel Stirling engine over a 25-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 1 + Compressed H_2 with 12 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$7,900	5.69%
HTMH Heat Exchanger	$16,500	11.89%
Compressor Cost	$17,500	12.61%
Hydrogen Storage Tank	$24,500	17.65%
Cost of Hydrogen	$200	0.14%
HTMH Vessel	$24,000	17.29%
Heater Cost	$1,700	1.22%
Stirling Engine Cost	$14,000	10.09%
Insulation / System Casing	$3,400	2.45%
Balance of Plant	$7,700	5.55%
Total System Cost (CAPEX)	$117,400	84.58%
Operational hours (hrs/yr)	4380	
Lifetime operational hours	109500	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	3285000	
Service Cost ($/yr)	$854	
Service Cost (OPEX)	$21,400	15.42%
Total Cost OPEX + CAPEX	$138,800	
LCOS ($/$kWhr_e$)	$0.0423	

HTMH 1 + Compressed H_2 with 6 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$4,000	5.04%
HTMH Heat Exchanger	$8,300	10.45%
Compressor Cost	$8,800	11.08%
Hydrogen Storage Tank	$12,300	15.49%
Cost of Hydrogen	$100	0.13%
HTMH Vessel	$12,000	15.11%
Heater Cost	$900	1.13%
Stirling Engine Cost	$14,000	17.63%
Insulation / System Casing	$2,300	2.90%
Balance of Plant	$6,300	7.93%
Total System Cost (CAPEX)	$69,000	86.90%
Operational hours (hrs/yr)	2190	
Lifetime operational hours	54750	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	1642500	
Service Cost ($/yr)	$416	
Service Cost (OPEX)	$10,400	13.10%
Total Cost OPEX + CAPEX	$79,400	
LCOS ($/$kWhr_e$)	$0.0483	

Table 15: Cost analysis for HTMH 2 + compressed hydrogen integrated with Texel Stirling engine over a 25-year operational lifetime with 12 hours TES (top) and 6 hours TES (bottom)

HTMH 2 + Compressed H_2 with 12 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$3,800	3.62%
HTMH Heat Exchanger	$11,300	10.77%
Compressor Cost	$15,300	14.59%
Hydrogen Storage Tank	$21,400	20.40%
Cost of Hydrogen	$180	0.17%
HTMH Vessel	$8,300	7.91%
Heater Cost	$1,700	1.62%
Stirling Engine Cost	$14,000	13.35%
Insulation / System Casing	$2,200	2.10%
Balance of Plant	$5,500	5.24%
Total System Cost (CAPEX)	$83,680	79.79%
Operational hours (hrs/yr)	4380	
Lifetime operational hours	109500	
$kWhr_e$ per year	131400	
$kWhr_e$ per lifetime	3285000	
Service Cost ($/yr)	$848	
Service Cost (OPEX)	$21,200	20.21%
Total Cost OPEX + CAPEX	$104,880	
LCOS ($/$kWhr_e$)	$0.0319	

HTMH 2 + Compressed H_2 with 6 hours TES over 25 year lifetime		
System Capital Costs	Cost (USD)	Cost %
HTMH Material	$1,900	3.08%
HTMH Heat Exchanger	$5,700	9.24%
Compressor Cost	$7,700	12.48%
Hydrogen Storage Tank	$10,700	17.34%
Cost of Hydrogen	$90	0.15%
HTMH Vessel	$4,200	6.81%
Heater Cost	$900	1.46%
Stirling Engine Cost	$14,000	22.69%
Insulation / System Casing	$1,500	2.43%
Balance of Plant	$4,700	7.62%
Total System Cost (CAPEX)	$51,390	83.30%
Operational hours (hrs/yr)	2190	
Lifetime operational hours	54750	
$kWhr_e$ per year	65700	
$kWhr_e$ per lifetime	1642500	
Service Cost ($/yr)	$414	
Service Cost (OPEX)	$10,300	16.70%
Total Cost OPEX + CAPEX	$61,690	
LCOS ($/$kWhr_e$)	$0.0376	

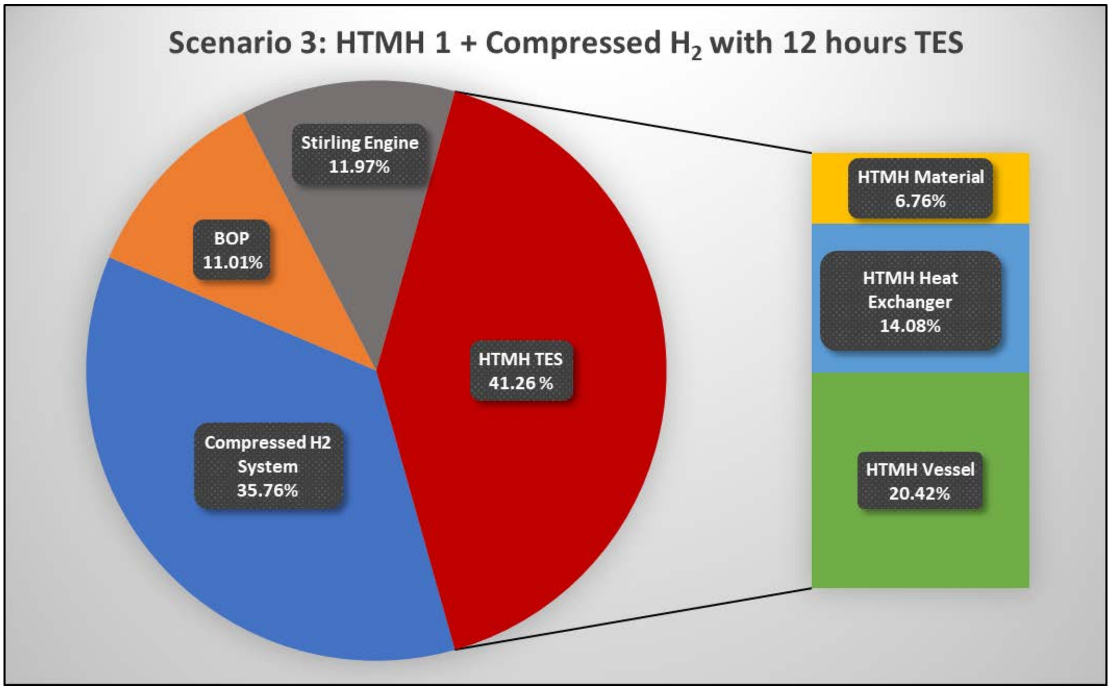

Figure 6: System cost breakdown for HTMH 1 + compressed hydrogen with 12 hours of TES

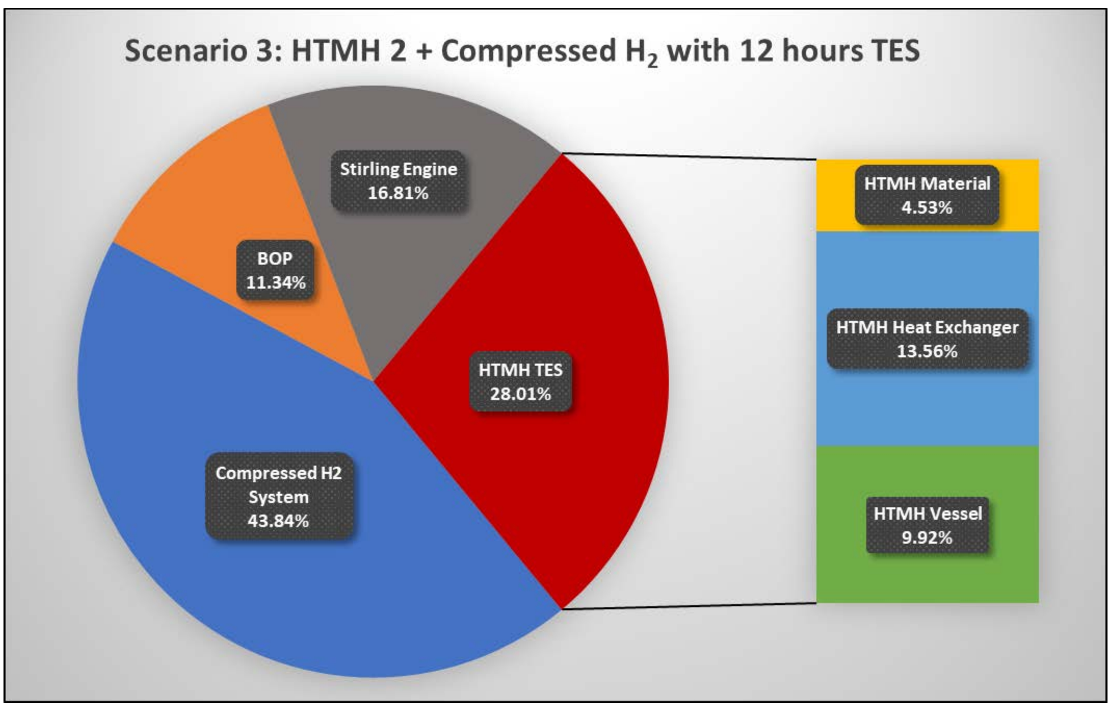

Figure 7: System cost breakdown for HTMH 2 + compressed hydrogen with 12 hours of TES

Table 16: LCOS cost difference for Scenario 3 with charging time

HTMH 1 (25 yr lifetime)	1 hour Charging	6 hour charging	12 hour charging
LCOS	$0.0734	$0.0422	$0.0391

HTMH 2 (25 yr lifetime)	1 hour Charging	6 hour charging	12 hour charging
LCOS	$0.0595	$0.0319	$0.0291

HTMH 1 (40 yr lifetime)	1 hour Charging	6 hour charging	12 hour charging
LCOS	$0.0483	$0.0288	$0.0269

HTMH 2 (40 yr lifetime)	1 hour Charging	6 hour charging	12 hour charging
LCOS	$0.0396	$0.0224	$0.0206

4.0 Conclusions

This analysis demonstrates the potential benefits of integrating a Stirling engine with a metal hydride-based TES system utilized as a grid energy storage technology. When comparing the scenarios in which the HTMH 1 is employed, it is evident that compressed hydrogen storage represents the lowest cost option over a 6-hour charging time. Improvement in the HTMH thermal storage capacity, represented by HTMH 2, shifts the economic advantages to pairing with LTMH 2. If the application of interest requires fast charging times, this also favors using the LTMH 1 or LTMH 2 due to high compressor costs. One aspect not considered in this analysis is the ability to recover waste heat from the Stirling engine to drive LTMH 1 (TiFe). The waste heat from the Stirling engine is approximately 60 °C which allows for the LTMH 1 operation but is only capable of preheating the LTMH 2 (which operates around 130 °C). In all scenarios, the LCOS of 6-hour storage with each Stirling engine is greater than with 12 hours of storage. This is to be expected as increasing the storage capacity only incurs costs associated with the TES system while the Stirling engine capital cost and many BOP items remain constant. This analysis has revealed that the HTMH TES system is the primary area for further cost reductions. Material property enhancements in the HTMH can lead to significant overall system cost reductions primarily related to the cost of the HTMH vessel and heat exchangers. This also suggests that the MH TES technology, at its current level of development, provides a highly competitive alternative to lithium ion batteries for large scale grid energy storage. Lithium ion batteries for grid storage applications have been shown to have a high capital and operational expenses. [9] Detailed techno-economic analysis on lithium ion storage in various applications have been carried out by Lazard et. al. [10] Extracting only the capital and operational expenses predicted in the analyses carried out by Lazard gives a wide range of $0.087/kWhr$_e$ – $0.329/kWhr$_e$ over all the scenarios considered. The predicted capital and operational LCOS predicted herein spans a range of $0.0198/kWhr$_e$ - $0.0734/kWhr$_e$.

Although not captured within this analysis, waste heat from the Stirling engine could be used to provide heated water in residential or micro grid applications. Additionally, alternative sources of heat can be utilized to charge the TES system such as concentrated solar power, natural gas combustion, and biomass combustion. This allows for a versatile system which can be deployed and expanded as needed to provide the desired storage capacity. Additional potential cost reduction methods for large-scale grid energy storage applications are possible as well. One example is to combine the compressed hydrogen storage tank for many units to minimize compressor and BOP items costs. The combination of metal-hydride based thermal energy storage with high efficiency Stirling engines provides a promising pathway to providing low-cost residential, micro grid power and grid energy storage alternatives.

5.0 Assumptions

The techno-economic analysis performed herein assumes an operational lifetime of 25 and 40 years for the entire system. All cost assumptions are based on a production scale of 10,000 units/ year. An operational expense cost of $0.18 per hour of operation was assumed for the upkeep of the Stirling engine which corresponds to a conservative service interval of 3000 hours. Upkeep of the TES system was estimated by the replacement of hydrogen needed due to low rates of permeation over time from the HTMH TES system. The HTMH vessel and heat exchangers were assumed to be constructed of SS 347 and the wall thicknesses were estimated using the yield strength of the material [11] at the operational temperature with a safety factor of 3. All vessels were standardized with a 1-meter diameter and the manufacturing cost associated with production was assumed to be 20%. HTMH heat exchangers were assumed to be sodium heat pipes and were scaled as needed from literature reports. [12] HTMH heat pipes were assumed to be constructed of SS 347 nickel mesh wicks, and sodium metal. A 100% manufacturing cost was added to the cost of the HTMH heat pipes. The LTMH heat exchanger was assumed to be an ethylene glycol cooling loop constructed of aluminum with heat rejection fans. Note that these fans and the ethylene glycol cooling loop would only be operational during charging. The LTMH vessels were also assumed to be constructed of aluminum. All construction material costs were based on current market costs [13], except for SS 347 which was calculated by the cost of the elements in the composition of the material [14] with an additional 20% production cost added. Balance of plant costs were estimated at 10% for 12 hours of storage and 7% for 6 hours of storage. The cost of hydrogen is assumed to be $3.00/kg. The heat to electricity conversion efficiency is assumed to be 40% which is a reasonable estimate based on other Stirling engine systems. [15] The cost of the Stirling engine was provided by TEXEL Energy Storage Inc. as $14,049 at a production scale of 10,000 units per year. Insulation and system casing costs were projected based on the overall size of the HTMH TES system and Stirling engine. Thermal loss was not considered for this analysis. Differences in the LCOS effects based on charging time in scenario 3 are due to changes in the cost of the compressor and electric heater. Cost and sizing implications to the HTMH heat exchanger for the various charging times were not considered. Compressor costs and high-pressure storage tank costs were estimated based on previous reports. [16,17] The compressor costs were scaled based on the quantity of hydrogen which is required to be moved in the allotted charging time. The cost of electricity is not considered in the calculations since this varies significantly depending on the region or time in which the electricity is stored as thermal energy. The cost of electricity can simply be added to the levelized cost of storage (LCOS) to account for this parameter. Additionally, the costs of installation and land were not taken into consideration.

6.0 Recommendations, Path Forward or Future Work

This analysis is meant to be a preliminary evaluation of the capital and operational expenses which could be expected from deploying metal hydride-based TES/Stirling engine systems for large scale energy storage applications. Due to the immature stage of the system development of this technology, it is expected that there is significant opportunity for improvement in comparison to lithium ion battery technology. To further understand the cost parameters and operational performance, a pilot and/or full-scale system should be developed and tested. This would provide the necessary assurance in the technology and address any potential unexpected design features which may be required. Once the scaled system is constructed, operated and evaluated, a more detailed techno-economic analysis can be performed. This analysis highlights the HTMH TES system as the primary component which can be addressed to have the greatest impact on reducing costs. Therefore, future studies should be focuses on the development of a scaled system for evaluation and demonstration as well as continued work on improving HTMH material properties to reduce vessel and heat exchanger costs. Further improvements in hydrogen compressors, storage tanks and system integration also provide a potential pathway for cost reductions. The near-term advancements in energy density with this technology are expected to be much greater than that of lithium ion batteries and other mature energy storage technologies because of the abundance of unexplored material possibilities.

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