UC Davis Hot Water Storage Tank Optimization

Final Report
ABT 212: Path to Zero Net Energy
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1 Executive Summary

UC Davis's 'Big Shift' project is aimed at eliminating Scope 1 emissions resulting from campus heating systems by moving towards a 100% electric heating and cooling system, employing Heat Recovery Chillers (HRC). Using a single piece of equipment for meeting heating and cooling load allows for significant synergy and optimization potential, but this can only be maximized by utilizing a Thermal Energy Storage System (TES). A TES allows for storage of excess heat in periods of low demand which can be supplied in periods of high demand. Moreover, it allows for demand response which can shift HRC operation out of high-cost hours and into low-cost hours, achieving substantial savings in annual operational costs.

This study analyzed how different tank sizes would impact the capital expenditure and savings potential for UC Davis' TES system. By running a rule-based simulation on heat recovery and demand response for 2 MGal, 3.5 MGal and 5 MGal tank sizes, we calculated potential annual savings of \$182,000, \$242,000, and \$285,000 respectively. Through vendor outreach, a budgetary capital estimate for each tank size was found to be \$3,750,000, \$5,850,000, and \$7,020,000 respectively. Based on this the simple payback period for the TES was estimated to be 17, 20, and 20 years respectively. By applying a 40% rebate from the Inflation Reduction Act (IRA) for TES systems and one demand response incentive program like a September 2022 event, this payback period can decrease to as low as 7.5 years for the 5 MGal Tank. The study concluded that the campus should install a 5 MGal tank to maximize the savings potential and allowance for future growth.

2 Project background

UC Davis' Facilities is currently completing a "BIG SHIFT", with the goal of achieving net zero emissions by 2025. Achieving this ambitious goal will necessitate an increase in energy efficiency and a transition to renewable sources of energy. UC Davis Facilities is moving toward this goal is by changing the heating system on campus, transitioning from steam generation with natural gas boilers to making hot water with heat recovery chillers; with this system, UCD Facilities is both increasing the energy efficiency of the heating system while eliminating carbon emissions accompanied with burning natural gas. The newly proposed system can be seen in diagram form in Appendix B.

A key component in the heating system's transition is a hot water storage tank, or Thermal Energy Storage (TES) tank. This TES tank will store heat extracted from the campus cooling system as well as a geo-exchange system and use this stored heat for heating during costly, peak electricity hours, which is also the time when electricity tends to have the greatest carbon footprint. The use of this TES tank will increase the overall flexibility and reliability of the system while simultaneously decreasing operation costs in the campus' heating system.

Figure 1 displays UC Davis's heating and cooling demand for a typical April day. Heating and cooling load peaks happen at different times of the day; the heat recovery chillers produce hot and cold water simultaneously. A TES system can store excess heat in periods of high cooling demand to supply the heat when there is a high heating demand.

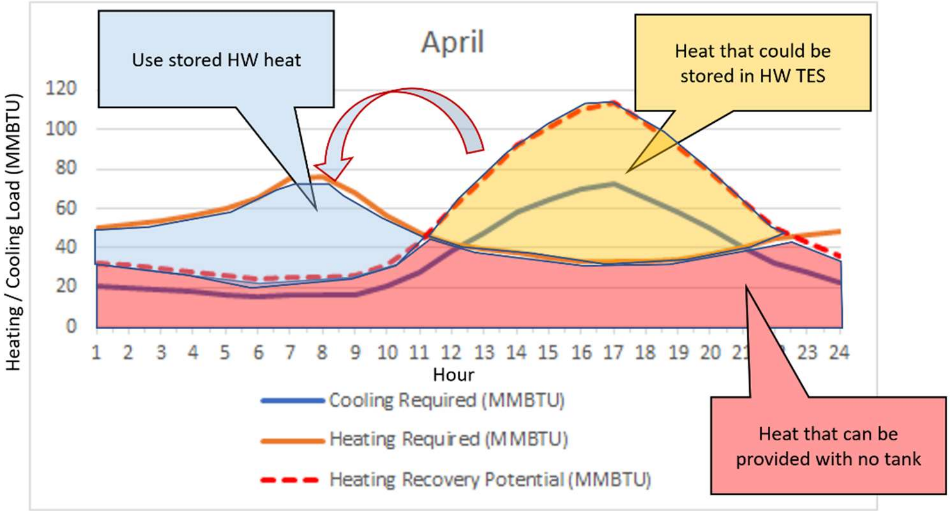

Figure 1: Heat Recovery Potential for a typical April Day

The problem that this study seeks to address is the sizing of the TES. To determine the optimal size of the TES tank, a techno-economic analysis was conducted on the campus' operations with a TES tank installed. Using weather data, campus energy demand profiles, and equipment performance data, a model of the yearly operations was created. In addition, an economic evaluation based on capital and operating costs is incorporated into the analysis, allowing an optimal tank size to be determined.

3 Literature Review

Before diving into the technical aspects of this project, a literature review was conducted to determine the feasibility of the project as well as to develop a sense of scope for our expectations of what is possible to achieve by adding a TES tank to the campus' heating system. An analysis by Li et al. (2022) focused on the economic impact of adding TES tanks of different sizes to a district heating system (Li et al., 2022). A numerical simulation model was used to carry out this analysis. More specifically, the model was applied to the Norwegian University of Science and Technology to optimize the size of a TES tank, with potential sizes ranging from 200 m^3 to 50,000 m^3, which translates to roughly 50,000 - 3,000,000 gallons (Li et al., 2022). The size of 3 MGal is particularly useful to this project because the tank sizes that are being considered range from 2 MGal to 5 MGal. After running the simulation of the campus' district heating system, the simulation showed that increasing the tank size resulted in a peak load shaving of 39% as well as savings up to 1.9 million NOK, which is roughly equivalent to $175,000 USD (Li et al., 2022). This result gives us reason to believe that increasing the size of a TES tank in a district heating system will lead to greater savings and reduced loads during peak hours, which is a key goal of our project. While it does not completely translate to UC Davis' operations, the model provides a similar scenario and a good reference for our expectations on sizing's relationship to economic and energy savings.

We also studied previously used methodologies to simulate TES systems and optimize system size. Knudsen el al (2021) discusses a modeling approach to optimize the sizing, operation, and integration of a TES system operating on industrial waste heat. The study uses dynamic simulation and model predictive control methods to model the system performance. Stalinski and Duquette (2021) presented a method for optimally sizing hot water storage tanks operating on short-term intermittent charge/discharge cycles. The proposed method combines a numerical analysis with a cost optimization model. Due to the use of specialized software such as Modelica, Dymola and TRNSYS, the methodologies outlined by these studies could not be adopted directly, but they aided us in understanding the underlying concepts to size a TES tank.

Finally, to understand and set up a framework of energy justice in this project, we used the University of Michigan's Energy Equity Report. From this report, this project examined distributional, procedural, and structural energy justice, to identify multiple efforts that UC Davis could take to promote procedural and distributional justice, detailed later (*Energy Equity Project*, 2022) . Krieger et al. (2016) was also examined to understand the benefits of energy storage and demand response for regions in California, with the specific goal of emissions reductions for health benefits in environmentally burdened communities; this study presented an environmental justice framework to view the importance of the project through. Reduction of electricity generation not only reduces global greenhouse gases but also reduces local criteria pollutants in local communities often overburdened by these pollutants. While cost is the main restraint for this project, the benefits of reduced emissions should be included in future projects.

4 Methodology

Before optimizing the sizing for the TES tank, potential options for what sizes are physically possible were determined. After completing a site visit and communicating with UC Davis Facilities, it was determined that the tank needs to be 55' in height to match the size of the chilled-water storage tank. The site that will be available for the TES tank is shown below in Figure 2, outlined with a dotted red line. The white circle in Figure 2 is the 5 MGal cold water storage tank, with a diameter of roughly 130', and is close to the maximum size that would fit within the site. Furthermore, because the height of the new TES tank needs to remain the same as or less than the chilled-water storage tank any increase in volume would have to be accommodated by an increase in diameter. Additionally, after correspondence with TES tank vendors, we determined that the tank needs to be steel welded, as opposed to steel bolted, due to a longer lifespan, zero leakage tolerance, and good performance in high seismic zones. As a result of the space constraints and correspondence with vendors concerning the availability of tank sizes, we determined to further explore TES tanks with volumes of 2 Mgal, 3.5 Mgal, and 5Mgal.

Figure 2. Future TES Tank Site

To create a model that is representative of the demand that UC Davis' campus will experience, we needed to first collect data as the foundation of the said model. There were 3 key types of data that we collected to produce an accurate model. The first data set that we collected was UC Davis demand data for 2022; this data included the actual heat demand, chilled water production, and heat recovery potential for each hour during 2022. The next key data set that we collected was the hourly electricity rates for 2022, showing us when electricity is expensive or cheap, allowing us to model load shifting. (Both the campus demand and electricity rates were supplied to us by UC Davis Facilities). The last set of data that we collected was actual weather data for 2022; this weather data was key for determining the temperature of the water being circulated in the heating and cooling system, giving us insight into temperature delta in supply and return water. All of this collected data helped us determine when to charge and discharge the TES tank to maximize the efficiency of the heating system and minimize the operating costs. The study's models were built on hourly load data for UC Davis heating and cooling systems for 2022. The analysis was designed to meet 100% heating and cooling load met through electricity i.e. HRC use. This approach assumes that during the winter, geo-exchange is used to supply heat to the chilled water system.

A baseline cost was estimated using this 100% electrification approach, where either the heating or cooling was the controlling factor in terms of electricity consumption. The electricity consumption for each hour was calculated by dividing the heating and cooling load by their respective Coefficients of Performance ($COP_H = 3.25$ and $COP_C = 2.5$), using Equation 1.

Equation 1

$$Electricity\ consumption = \frac{Thermal\ Load}{COP}$$

Either the heating or the cooling load was higher in terms of electricity consumption for each hour, which was taken as the controlling electricity consumption and used subsequently to calculate costs. These hourly costs were summed over the year to calculate yearly costs using Equation 2.

Equation 2

$$\sum_{h=1}^{8760} hourly\ electricity\ price \times\ electricity\ consumption$$

After establishing a baseline cost, 2 simulations were undertaken to estimate the load flexibility and demand response potential of different tank sizes: 2 MGal, 3.5 MGal, and 5 MGal.

The first model in the study analyzed the potential to store excess heat whenever available and to supply this stored energy when required for each hour of the year. Differential heat was determined by taking the difference between heat generated by Heat Recovery Chillers and the campus heating demand at that hour.

The second model extends the first model by introducing demand response. The model analyzes each hour of the year and selects the hours when the electricity price is over the 90th percentile. All heating demand is then shifted out of these hours and shifted to the cheapest hours within the previous 24 hours. The model then calculates the new heating demand based on these shifted loads in order to determine the new heat recovery potential. This is then used to ultimately model charge/discharge cycles of the tank. The complete rule-based algorithm for this simulation is outlined in Figure 3.

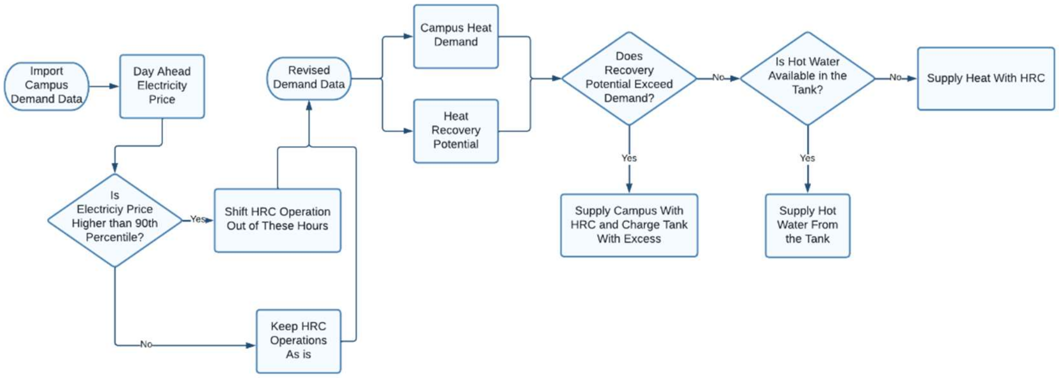

Figure 3: Rule-based algorithm for modelling TES operation

After modeling heat recovery and demand response, we acquired quotations for the tank's capital expenses. To accurately estimate the optimal tank size, the project determined capital and installation expenses for 3 ranges of TES tanks. An internet search was completed for vendors who build insulated, steel-welded or concrete tanks, with a determined height of 55' ranging from 2-5 MGal. In the search, 7 vendors were contacted through phone calls, emails, and website inquiries; 6 vendors returned contact, and 4 vendors provided final quotes. The quotes included procurement and installation costs for the 3 tank sizes. After quotes were collected, the cost per gallon was calculated using the total overall cost of each tank, which included tank and installation costs.

Once we had capital expenses for each size of, we examined the payback period for the lowest-priced tank for each size. The payback period was determined using vendor quotations and savings estimated from our simulations. After assessing the overall savings associated with each tank, some adjustments were made to account for external economic incentives. Because the operating costs are based on electricity prices, which will increase over time, this means that the savings will be greater over time. Assuming a 2.5% annual increase in electricity price, the operating costs can be recalculated to account for this change. In addition, there are other key economic incentives that will make this project economically viable. One incentive that has a dramatic impact on the payback period is the 40% tax credit resulting from the Inflation Reduction Act (*26 USC 48: Energy Credit*); this code allows for a range of tax deductions for energy storage, with tax credits totaling up to 40% if the installation meets sourcing and labor requirements (*Inflation Reduction Act Guidebook*, 2022). By reducing the capital costs by 40%, the resulting payback period is also reduced by this amount. Furthermore, because the tanks allow for load shifting, it is possible to take advantage of monetary demand response incentives put out by CAISO. In 2022, UC Davis was able to take advantage of demand response programs using the 5 MGal cold water storage tank and generated $270,000 from incentives in just one week. Using $270,000 as a baseline for a 5 MGal tank, and adjusting these savings based on relative tank size, the possible demand response incentives are added to the total annual savings for each tank.

To address equity in this project, 3 different dimensions of environmental justice were examined: structural, distributive, and procedural. An examination of structural and distributive environmental justice examined how these contracts are decided, and if the contracts go to minority-owned businesses or socially conscious vendors. None of the 4 vendors were minority-owned, and of these 4 vendors that provided a quote, only 1 company, (CBI—a part of McDermott International Ltd), mentioned company values and actions that promote environmental justice in communities. These values included sections from the UN's Sustainable Development Goals (No Poverty, Quality Education, Decent Work & Economic Growth, and Reduced Inequalities), and the company's actions included installing solar energy and rainwater collectors in disadvantaged communities across the globe (McDermott, 2023; United Nations, 2023) . Another way this project looked at distributive and then procedural environmental justice was to examine how the savings benefits from the heating system could be distributed to disadvantaged communities. UC Davis could champion procedural and distributive justice, utilizing the spirit and framework of "Justice 40", a Biden Administration initiative that requires certain new programs to have 40% of the benefits go to disadvantaged communities (*Justice40 Initiative*, 2021). While the UC Davis campus is insular and the TES may not benefit disadvantaged communities, the funds saved from the installation could be earmarked for sustainable programs, specifically UC Davis' UN Sustainable Development Goals Programs.

5 Results & Discussion

For the baseline estimate, considering 100% heating and cooling demand fulfilment via HRC operation the annual cost of electricity was estimated to be $7.2 million.

The modelled yearly TES operation from our primary simulation, based on Heat Recovery only, is shown in Figure 4. During the winter months, there is no significant storage due to the non-availability of surplus heat. Whereas, during the summer, there is an excess of surplus heat, where the tank is full and there is very little energy supply from the tank. Tank operation is most profound during the spring and fall months, when the diurnal swing of the day is at its most extreme (Figure 4). Going into a higher resolution within this window, Figure 5 shows a 48-hr duration in March. Again, charging and discharging here is driven by the diurnal swing in temperatures at Davis.

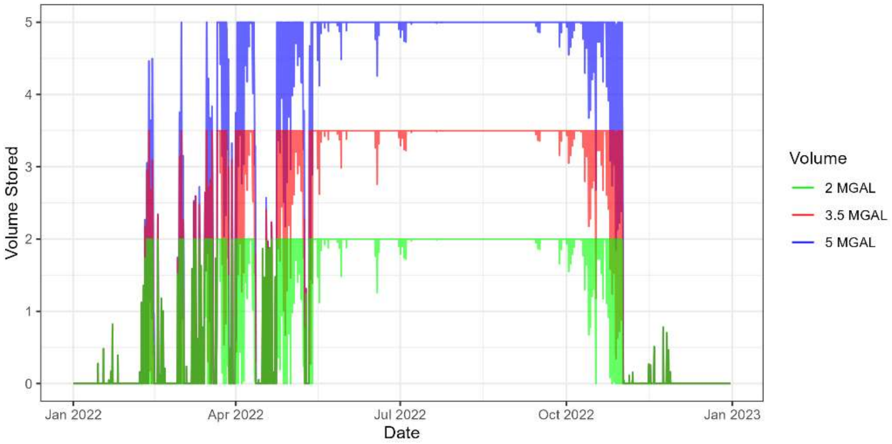

Figure 4 Yearly Operation Model for 3 TES Sizes – Heat Recovery Only

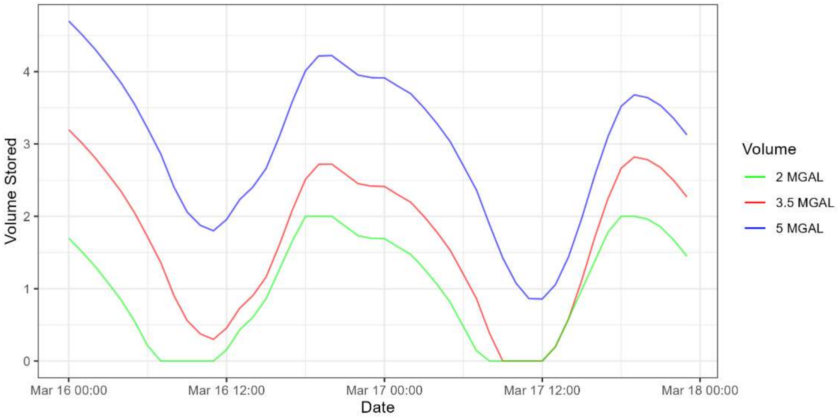

Figure 5 Maximum TES Tank Utilization

Moving on to our second simulation, Figure 6 shows the yearly operational model of different tank sizes if demand response is used to augment the heat recovery. Here, the most striking contrast to the first model the during the winter months (November and December) when we see a significant increase in the energy supplied from the tank where earlier it was non-existent. This is due to the load shifting in these months when electricity prices are higher.

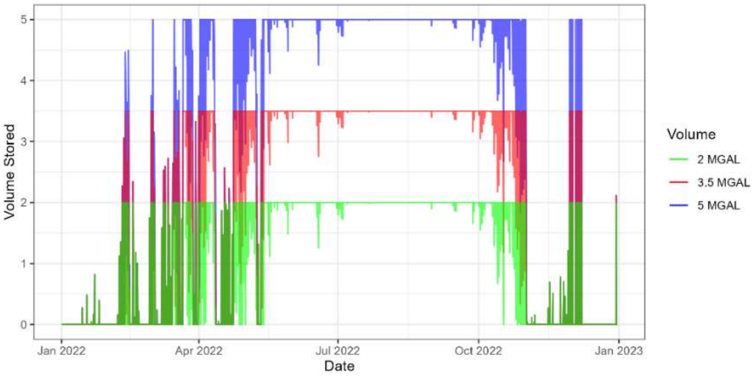

Figure 6 Yearly Operational Model for 3 TES Sizes – Heat Recovery & Demand Response

Table 1: Savings Potential for each tank size

Tank Size	Heat Recovery	Heat Recovery & Demand Response
2 MGal	134,000	182,000
3.5 MGal	157,000	242,000
5 MGal	165,000	285,000

Based on these models, annual savings from the baseline were calculated as described in Table 1. These results show that savings from heat recovery alone are not highly correlated to the tank size, and the true savings potential lies in demand response. It must be noted here that these savings numbers are under-estimated, as they do not include the potential payouts from demand response incentive programs and incremental savings from optimized operation of overall heating & cooling system.

For the capital expenses of the tank, of the 4 vendors that returned a quote, 3 vendors (UIG, DN, CBI) were similar in cost for each size of tank per gallon, with 1 vendor (UIG) having the lowest cost for all sizes; these companies all provided quotes for tanks with steel roofing. 2 companies provided quotes for steel welded tanks, while DN provided a quote for prestressed cement/steel hybrid tank. Another company (MMI) provided a quote for a steel tank with an aluminum roof, which was significantly lower than steel roofs; however, an aluminum roof may not meet the required specifications of the system and would need to be examined further. Another aspect that was not examined in the vendor process but should be examined in future consulting projects is the possibility of burying the TES tank, which was proposed during a vendor consultation. The quotes received for tank costs were compared to a previous consultation estimate supplied by UC Davis facilities and were similar in costs overall. The information for each tank company and associated costs are listed in Appendix A. For all estimates, as the size of the tank increased, the cost per gallon decreased, with the 5 MGal tank being the most cost-effective Figure 7 displays the cost per gallon across all tanks (the aluminum roof tank was excluded from this estimate due to uncertainty of applicability.) Due to the lack of a seismic survey and ground assessment, ground preparation costs were not included in any of the received quotes or the overall cost estimation.

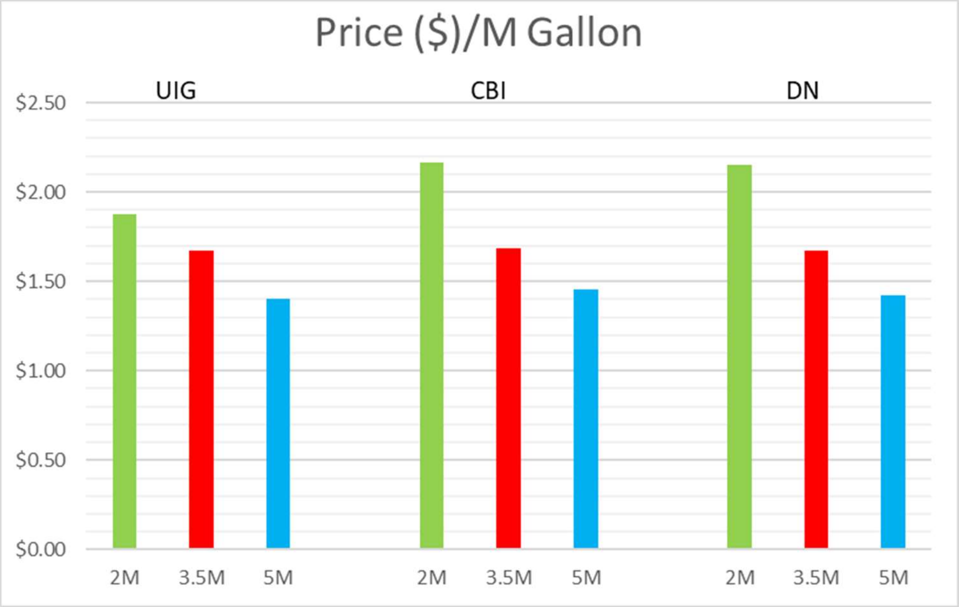

Figure 7 Price of TES Tank Per Gallon

After determining the baseline cost for a completely electrified system with no TES tank as well as the operating and capital costs for each tank size, the payback period for each tank size was calculated. For the 2 MGal, 3.5 MGal, and 5 MGal respectively, the payback periods were 17 years, 20 years, and 20 years, assuming a 2.5% increase in electricity price. These periods are quite long, and resultantly, doing a simple payback period is not sufficient to capture the discounted savings in the long-term future. The unadjusted payback periods calculated solely from the savings coming from the operation costs are seen in Figure 8 below.

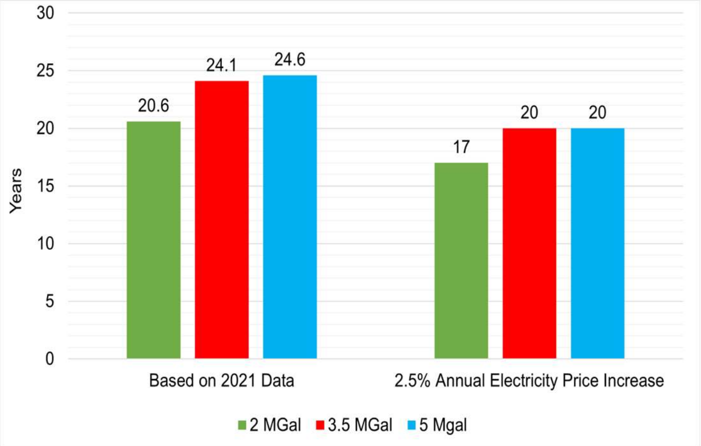

Figure 8 Unadjusted Payback Times

To have an acceptable payback time, we need to apply manual adjustments to account for the external economic incentives such as the 40% reduction in capital from the IRA and the demand response incentives. After these considerations are factored into the payback period, the adjusted payback period for each tank size was recalculated. Based on electricity rate data from 2022, the adjusted payback periods for 2 MGal, 3.5 MGal, and 5 MGal are 6.9 years, 7.5 years, and 7.6 years, respectively. Assuming a 2.5% annual electricity price increase, the adjusted payback periods are 6.5 years, 7.2 years, and 7.2 years, respectively. Because of the relatively short time frame, the electricity price increase does not have a significant impact on annual savings, however, over the 60-year lifespan of the tank, these savings will become more pronounced. The adjusted payback periods can be seen in Figure 9 below.

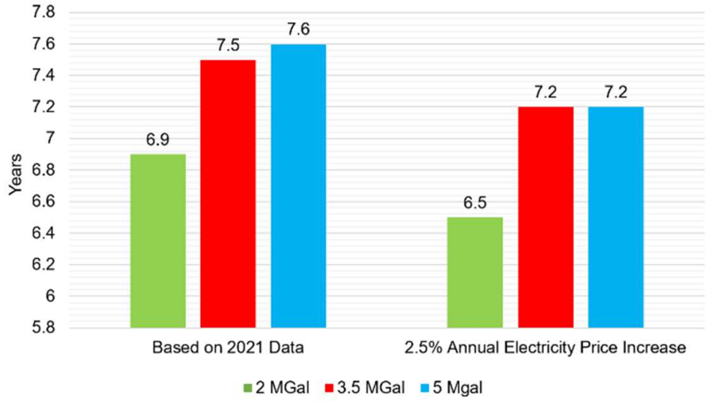

Figure 9 Adjusted Payback Time

Because the payback periods for the tanks are grouped close together, any tank size is viable, however, each tank size has benefits and drawbacks. The 2 MGal tank is the most inexpensive, making the capital investment not an issue. Additionally, the 2 MGal will have the smallest physical footprint allowing for easier site demolition, foundation setting and installation. However, while cheap and easy to install, its energy response capabilities are severely hindered when compared to the larger sizes. The 5 MGal tank has the greatest energy response capabilities and potential to accommodate future growth. This allows for greater potential to shift loads and to take full advantage of demand response incentives. However, the larger size is accompanied by drawbacks when it comes to site demolition, foundation setting, and installation. It additionally is the most expensive in upfront capital costs. The 3.5 MGal tank has a size and cost that is roughly in the middle of the 2M and 5 MGal tanks. The energy response capabilities are similarly in the middle. However, this means that the 3.5 MGal tank doesn't excel at having excellent energy response capabilities or boasting an inexpensive and easy installation and upfront capital cost. It is also crucial to consider that the payback periods are heavily reliant on the IRA incentive and capitalizing on the demand response events to generate savings.

As with any modelling exercise, our analysis had various assumptions and sources of uncertainty. Primarily, the study was based on just one year of data which can introduce unintended uncertainties in the results and can miss any year-on-year changes. Secondly, as the savings are highly sensitive on the price of electricity, any changes to these prices can alter the savings for better or worse. Secondly, costing of system auxiliaries were excluded from the estimate. Thirdly, heat losses from the tank were not taken into account.

Moreover, as the cooling and heating systems get unified under the heat recovery chillers, an isolated analysis of savings from hot water tank does not show an accurate overall picture. In order to reach a more realistic savings number, a combined analysis of the overall space heating system with hot water and cold water storage tank is needed.

Due to the small impact of this project and limited scope, equity implementations were limited. One company was identified as a possible choice due to its public environmental stewardship and community involvement; however, during the bidding process, all these companies should be further examined.

6 Recommendations & Conclusions

Considering the capital expenditure, potential savings, and payback periods, we suggest that the campus should install a 5 MGal tank as it would allow for future growth and maximize the demand response capability of the campus. As our results also highlight, demand response is the key to maximizing savings from TES systems. An alternate strategy to install two small tanks considering capital constraints would result in a higher geographical footprint and higher overall capital costs. At current bid prices, two 2 MGal Tanks would cost more than a single 5 MGal Tank. Moreover, a higher capacity tank would also allow for greater synergy with the chilled water tank, which also has a 5 MGal capacity. Reiterating the payback period, an incremental payback of 03 years for the base case or 0.6 years for the revised case for the 5 MGal tank is negligible considering project lifetime of 60 years. Especially considering the incremental potential it provides for load shifting and demand response.

For future work, to have a better understanding of the savings potential, our analysis could be expanded to conduct simulations on demand response and heat recovery for the combined heating and cooling system. Secondly, the analysis could be expanded to multiple years to identify and exclude anomalies. Thirdly, future campus growth can be added to the model to understand the performance of each tank size. Fourthly, an additional optimization for the reduction of CO_2 emissions from grid purchased electricity can be analyzed based on shifting load out of expensive, high CO2 intensity night-hours to cheap, low CO_2 intensity daytime-hours. Incorporating these aspects into our analysis would provide the UCD Facilities with a holistic view of the TES system sizing dynamics and which tank size to opt for based on multiple selection criteria.

Finally, as previously mentioned, some key ways future construction projects could address equity is through an examination of the contractors and hiring process for construction, followed by re-distribution of potential savings to either disadvantaged communities or programs on campus that support these communities. Another action that could address environmental equity in future projects is to include a social cost of carbon and emissions in project calculations, to accurately assess the environmental impact (or potential avoided impact) of construction projects.

7 Bibliography

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8 Appendices

8.1 Appendix A – Vendor Quotation

Company	**Size of Tank (g)**	**Tank Cost ($)**	**Installation/Other Cost ($)**	**Total ($)**	**Tank Cost/Gal ($/g)**	**Other Cost/Gal ($/g)**	**Total ($/g)**
UIG	2,000,000	2,900,000	850,000	3,750,000	1.45	0.43	1.88
	3,500,000	4,850,000	1,000,000	5,850,000	1.39	0.29	1.67
	5,000,000	5820000	1,200,000	7,020,000	1.16	0.24	**1.40**
CBI	2,000,000	3,900,000	425,000	4,325,000	1.95	0.21	2.16
	3,500,000	5,350,000	550,000	5,900,000	1.53	0.16	1.69
	5,000,000	6,600,000	675,000	7,275,000	1.32	0.14	**1.46**
DN	2,000,000	3,000,000	1,300,000	4,300,000	1.50	0.65	2.15
	3,500,000	3,900,000	1,950,000	5,850,000	1.11	0.56	1.67
	5,000,000	4,700,000	2,400,000	7,100,000	0.94	0.48	**1.42**
MMI	2,000,000	1,973,630	394,726	2,368,356	0.99	0.20	1.18
	3,500,000	2,608,580	521,716	3,130,296	0.75	0.15	0.89
	5,000,000	3,229,945	645,989	3,875,934	**0.65**	0.13	**0.78**
UC Davis Consult	2,000,000	3,787,000	1,274,000	5,061,000	1.89	0.64	2.53
	5,000,000	6,435,600	1,911,000	8,346,600	1.29	0.38	**1.67**

8.2 Appendix B – UCD Thermal system (post Big-Shift)