Thermal Batteries

OPPORTUNITIES TO ACCELERATE DECARBONIZATION OF INDUSTRIAL HEAT

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RENEWABLE THERMAL COLLABORATIVE

NOTICE

This report was prepared for The Center for Climate and Energy Solutions (C2ES) and the Renewable Thermal Collaborative (RTC). C2ES is a U.S.-based environmental non-profit that forges practical and innovative solutions to address climate change, and engages with leading businesses to accelerate climate progress. The organization engages in policy innovation and leadership, business engagement, and trusted convening. The RTC serves as the leading coalition for organizations that are committed to scaling up renewable heating and cooling at their facilities and dramatically cutting carbon emissions. RTC members are industrial and commercial thermal energy buyers with ambitious emissions reduction targets who recognize the urgent need to meet the growing demand for renewable heating and cooling in a manner that delivers sustainable, cost-competitive options at scale.

The report reflects the analyses and opinions of the authors and does not necessarily reflect those of The Brattle Group's clients or other consultants.

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Executive Summary

Thermal energy storage (TES) has been used in many contexts and applications, from building management and manufacturing, to generation of electricity. In this report, we focus on an emerging, commercially available application: electricity-powered thermal batteries that can convert renewable electricity into heat to be used for industrial processes.

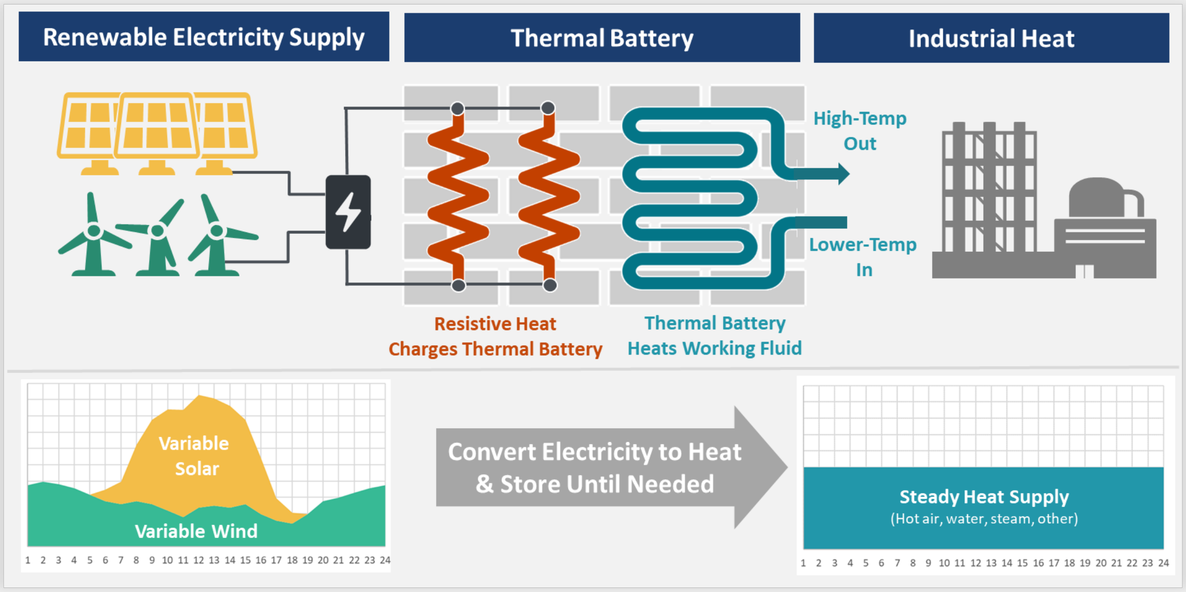
The primary findings of this study include that:

- Thermal batteries offer the potential to provide cost-competitive clean energy supply for industrial heating applications and deliver a large volume of flexible, controllable demand for balancing the power grid.
- Thermal batteries can be cost-competitive with natural gas in much of the US even today, though the strength of the business case depends on the configuration of electricity supply, location, access to wholesale power prices, any greenhouse gas (GHG) price that may be applied, and eligibility for policy support (particularly until the technology achieves sufficient deployment scale).
- The most critical barriers to large-scale deployment of thermal batteries are lack of access to wholesale power prices and modern electricity rate structures reflective of the underlying costs of delivering power to the thermal battery (i.e., "cost causation"), which can be substantially lower for flexible, controllable sources of demand like thermal batteries. Customers outfitted with thermal batteries can optimally schedule these systems in ways that reduce the net costs of electrification and help balance the grid.

WHAT ARE THERMAL BATTERIES?

Figure 1 illustrates a typical renewable-powered thermal battery configuration. Solar or wind resources produce electricity that runs through resistive heaters, heating the storage medium (consider a toaster containing hot bricks). The sensible heat generated can be stored in the thermal battery for 1 to 2 days (or even much longer if needed for a particular use case) with minimal energy losses, before being used for industrial processes. Using a thermal battery, variable renewable electricity can be converted into a stable stream of heat at the required temperature, replacing the role of a natural gas-powered boiler, kiln, dryer, or similar heat process. A working fluid, such as steam, air, or water, will pass through the storage medium and increase to the temperatures needed for the industrial processes in question. Commercially available and deployed thermal battery technologies can support temperatures as high as 750 °C (1,380 °F), or high enough to serve nearly 75% of all industrial heat demand. Thermal battery technology that can support very high-temperature processes up to 1,800 °C (3,300 °F) is expected to become commercially available by 2025 – 2030.[1]

FIGURE 1: TYPICAL RENEWABLE-POWERED THERMAL BATTERY CONFIGURATION
Converting Variable Renewable Power to Stabilized Steam Energy



WHAT ROLE CAN THERMAL BATTERIES PLAY IN THE CLEAN ENERGY TRANSITION?

Today, industrial process heat is supplied primarily by natural gas and, to a lesser extent, other fossil fuels such as coal and petroleum. These industrial emissions have historically been technologically challenging and expensive to decarbonize, given the lack of inexpensive and clean fuel alternatives, as well as competitive pressures that limit companies' ability to recover costs. Historically, there has not been an obvious way to substitute natural gas for non-emitting energy and achieve the high temperatures needed.

Thermal batteries promise to fill this gap and supply cost-competitive, greenhouse gas (GHG) free industrial heat. If widely deployed to their maximum potential, renewable-powered thermal batteries could displace the entirety of the emissions associated with industrial heating demand, amounting to 779 million metric tonnes (MMT, also equivalent to 1 Megatonne) of carbon

[1] Thermal storage solutions commonly have customizable operating conditions, including the temperature of the produced steam or other form of heat output. Most of the current manufacturers report their maximum achievable temperature to assuage concerns that the technology cannot meet customer needs. Currently, commercially available technologies can deliver steam at temperatures as high as 750 °C (e.g., Brenmiller Energy, Rondo Energy). In the near future, other providers will be able to deliver heat at temperatures above 1,500 °C (e.g., Antora Energy, Rondo Energy), and potentially above 1,800 °C (e.g., Electrified Thermal Solutions). Worldwide, there are approximately 10-20 companies investigating and pursuing thermal energy storage for industrial applications. Brenmiller Energy, "Technology"; Rondo Energy, "How It Works"; Antora Energy, "Technology"; Electrified Thermal Solutions, "Technology"; Renewable Thermal Collaborative, *Vision Report*, 2022; Long Duration Energy Storage Council, *Net Zero Heat*, 2022.

dioxide equivalent (CO_2e) emissions per year in the United States, or approximately 12% of total economy-wide GHG emissions.[2] Globally, renewable-powered thermal batteries could displace approximately 6,000 MMT of CO_2e per year, or approximately 14.5% of all energy-related emissions.[3]

Beyond its direct role to enable industrial electrification and decarbonization, thermal battery resources are ideally suited to provide power grid balancing services that will be urgently needed to enable comprehensive decarbonization of the power grid. Thermal batteries provide highly controllable electricity demand that can be scheduled by the industrial customer to match the output profile of their dedicated renewable supply projects. Alternatively, they can be scheduled by utilities, regional transmission organizations (RTOs), and independent system operators (ISOs) in ways that manage the net load variability of the broader power grid.[4] For example, controllable thermal batteries could be scheduled in advance to flatten the net load profile of the power grid, absorb excess renewable power that would otherwise be curtailed, or react on short timeframes (on the order of a few seconds to 3-minute response times) to increase or decrease charging rates.[5] Thermal batteries that are coupled with renewable resources can time both net grid injections and net grid withdrawals to offer even greater system benefits. With these short response times, thermal batteries can provide reliability services and ancillary services to the grid to help manage surprise outage events, system ramping needs, and prevent system outages.[6] Thermal battery systems can help balance renewable supply variability and provide essential reliability services that have historically been provided by fossil generation resources.

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[2] This GHG emissions displacement potential aligns with 100% GHG displacement for all industrial heating demand, at all temperatures (noting that the highest-temperature applications above 750 °C (1,380 °F) are not anticipated to be commercially deployed until approximately 2025 – 2030 timeframe). While renewable-power thermal batteries can displace GHGs associated with heating demand (e.g. carbon dioxide released from burning natural gas [$CH_4 \rightarrow CO_2 + H_2O$ + heat] to create steam), it will not displace the other 376 MMT of GHGs from industrial process emissions (e.g., carbon dioxide released when limestone is converted to lime [$CaCO_3$ + heat $\rightarrow CaO + CO_2$] for the production of cement). See U.S. EPA, *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, 2023. IPCC, *CO_2 Emissions from Cement Production*, 2000.

[3] This estimate assumes that the global breakdown between combustion and process emissions resembles that of the United States (33% and 67%, respectively). In 2022, there were 41.3 gigatonnes of CO_2 emissions globally. IEA, *CO2 Emissions in 2022*. March 2023.

[4] "Net load variability" refers to the variability in system-wide customer demand minus variable renewable energy resource output. Demand (or load) variability has always been managed by grid operators. However, systems with large and growing quantities of renewable resources must increasingly manage a much larger quantity of variability and uncertainty in the power grid "net demand".

[5] Response times provided by thermal battery system providers. Renewable Thermal Collaborative. Comments of the Renewable Thermal Collaborative, "FERC Docket No. AD21-10-000". 2023.

[6] Examples of the types of ancillary services that thermal battery systems can provide include offline (i.e. 30-minute) reserves, online (i.e. 10-minute) reserves, 5-30 minute ramp-up/ramp-down services, and multi-hour standby reserves. In general, the shortest-response reserves are the most valuable and scarce to the grid operator.

WHAT IS THE BUSINESS CASE FOR USING THERMAL BATTERIES TO DECARBONIZE INDUSTRIAL HEATING DEMAND?

Companies may consider deploying renewable thermal technology at existing or new industrial facilities for a variety of reasons, most centrally the opportunity to cost-effectively decarbonize heat supply. For companies considering only the economic business case for renewable-powered thermal batteries, the all-in cost of heat (measured on a $/MMBtu$_{th}$ or $/MWh$_{th}$) basis) will need to be below the cost of current fuel sources (typically natural gas). Figure 2 below compares the costs of producing steam from natural gas (on the left) to the cost of producing steam from renewable-powered thermal batteries under alternative configurations and rate structures. For the purpose of our analysis, we adopt thermal battery costs consistent with manufacturers' targeted all-in installed costs by the year 2030 (without applying any cost deductions that may be available under federal or state policy incentives).[7]

We find that the energy cost of renewable-thermal supply is cost-competitive with natural gas as a source for industrial heat in the most renewables-rich regions of the country, depending on the assumed cost of natural gas (we assume $6/MMBtu delivered cost of natural gas in our analysis). If a company or state applies a $50/tonne GHG value, industrial consumers in many more regions may find it cost-effective to deploy renewable thermal systems as an alternative to natural gas. Companies that deploy thermal batteries may also benefit from the ability to fuel-switch between power and natural gas supply to support reliable operations or hedge against fuel and emissions costs.

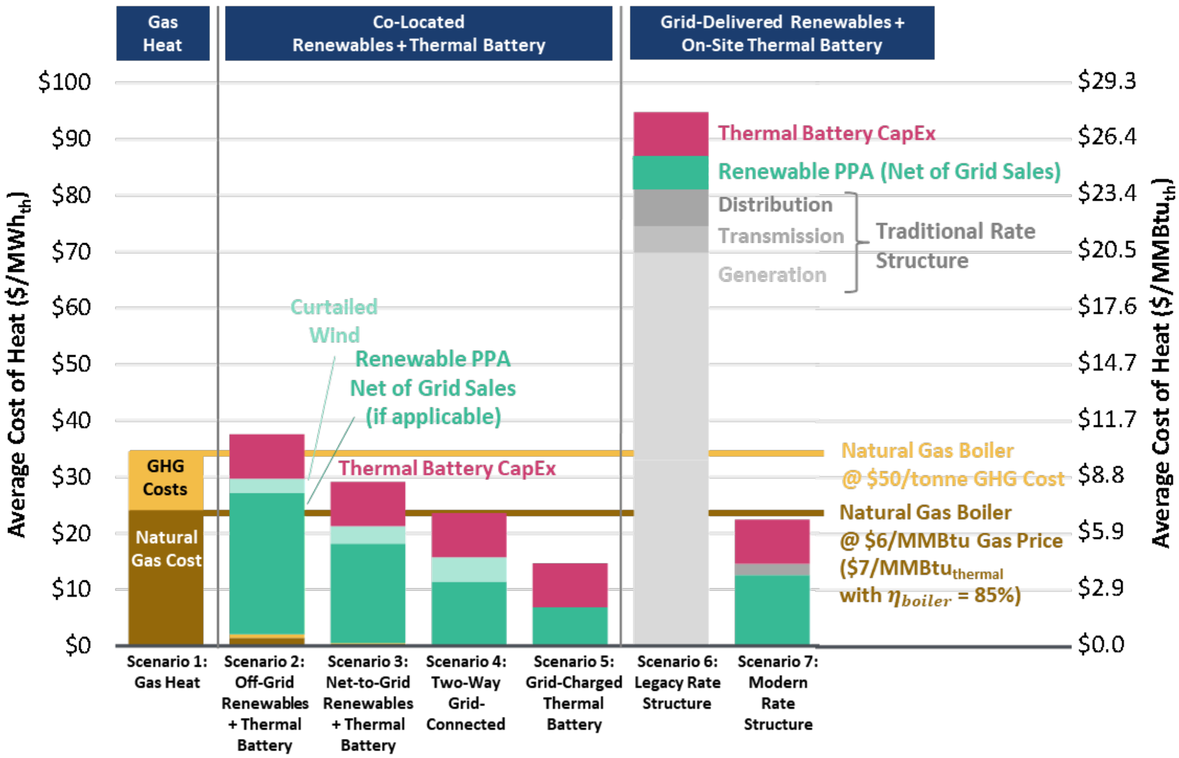
The underlying economics that make renewable thermal storage cost-competitive for some industrial facilities are: (1) the low cost of renewables, which for the first time can compete with natural gas on a primary energy cost basis (accounting for efficiency rates of converting each energy source to heat); and (2) the application of thermal storage to smooth renewable electricity into a stable stream of heat (noting that the capital costs of the thermal battery make up approximately 20% to 40% total system costs). The overall cost of delivering renewable thermal supply to industrial consumers also depends on carefully sizing the renewable and thermal battery system; whether the system relies on co-located renewables or grid-delivered renewables; what utility rate structures may apply; and whether the thermal battery resource can access wholesale power market prices for any net purchases or sales to the power grid.

Critically, we find that thermal battery systems can only be cost-competitive relative to natural gas in jurisdictions where industrial customers can either: (a) self-supply or directly contract with a renewable power supplier in an off-grid or partially grid-connected status; or (b) operate under modern, cost-reflective electricity rate structures that allow direct access to wholesale power prices and retail rate components that are closely tied to cost causation. The cost of a utility or power market to serve an industrial customer outfitted with a thermal battery can be far lower than the cost to serve other industrial customers. A renewable thermal battery system empowers

[7] Current thermal battery prices (excluding policy incentives) are higher than the 2030 prices used in our analysis, given that most of the companies are in early stages of commercialization. Companies we interviewed for this study report that achieving these target pricing levels will require sufficient early adoption to bring down costs via deployment experience and economies of scale.

the industrial customer to draw power only when prices are low and the grid is underutilized, and to prioritize renewable power injections to the grid (instead of charging the thermal battery) when supply is most needed by other customers during system peak times.

FIGURE 2: COMPARISON OF INDUSTRIAL HEATING COSTS NATURAL GAS VS. THERMAL BATTERY CONFIGURATIONS



Notes: Reported in 2023$, pricing as anticipated by 2030. No policy incentives for thermal batteries are applied. See Section III and Appendix for modeling assumptions.

WHAT BARRIERS TO ENTRY SHOULD BE ADDRESSED TO ACCELERATE THERMAL BATTERY DEPLOYMENT?

To understand current barriers to expanded deployment of thermal batteries, we conducted a series of interviews of thermal battery providers and industrial customers considering the technology. Interviewees cited a number of potential barriers, including lack of familiarity with the technology; thermal batteries are not yet routinely considered by industrial users or in policy contexts where they may be the most technically feasible and economically attractive option. Both producers and consumers expressed optimism that the technology readiness and underlying economics will be increasingly attractive for deploying thermal batteries at scale, particularly if relevant policies enable these systems on an equal basis to other technology alternatives.

The most critical barrier to thermal battery deployment highlighted by both producers and customers is that posed by traditional electricity rate structures and arrangements (a concern that is also demonstrated by our economic analysis). Though the specifics of the barriers cited differed in each conversation, the general problem is that traditional rate structures can inhibit market uptake of thermal battery systems if: (a) current regulations do not enable a willing buyer and seller to arrange for privately negotiated self-supply in both off-grid and grid-delivered renewable arrangements; (b) for grid-connected or partially grid-connected projects, applicable retail rates were developed in a way that does not consider the specific thermal battery capabilities to avoid consumption at times that would impose costs on utilities and the grid, and so the rates will tend to apply excess costs to customers electrifying with thermal batteries; and/or (c) thermal batteries are unable to engage directly with wholesale power markets and prices, which can enable them to offer greater value to the grid and reduce the net delivered cost of heat to customers.

To address these barriers, we recommend that industrial heating consumers examine the benefits of thermal batteries as a commercially available technology to be evaluated alongside other sources of industrial heat. For companies and policymakers seeking to achieve climate goals, we recommend comparing thermal battery systems to other decarbonization solutions on the same GHGs-avoided basis, and ensure that thermal batteries are considered an eligible technology under all state programs, planning processes, and climate polices.

To address barriers associated with traditional rate structures and arrangements, we recommend that state public utility commissions work with utilities to adopt modern rate structures that are closely tied to cost causation. These rate structures can benefit a wide array of different customer classes that can optimize their consumption relative to the cost of serving them. Customers outfitted with thermal batteries can be incentivized to optimize their net production and consumption in ways that drive the cost of service near to zero. Modern rate structures can encourage thermal batteries to eliminate any net consumption during system peak hours (and even prioritize net grid injections from renewables in these hours rather than charging the thermal storage), while the thermal battery would be charged either by self-supply or by net grid withdrawals only at low prices and in low-demand conditions that do not drive the need for capacity or transmission and distribution (T&D) investments.[8] Similarly, wholesale power market rules and transmission rate structures should ensure that thermal batteries could fully participate in bulk electricity markets under competitive structures, similar to those available for electricity-to-electricity batteries.

Thermal batteries are an emerging technology presently at early stages of commercial deployment but have the potential for substantially accelerated deployment if barriers to entry are addressed. Doing so would enable renewable thermal systems to deliver economic benefits to industry, contribute to decarbonization of industrial heating demand, and help balance the power grid.

[8] Retail rates are made up of several components, including: (a) ***generation component (investment)***, which includes the cost to build generation supply (sometimes reflected by "capacity" or "demand" charges that are driven by consumption during system peak demand times over the year or season); (b) ***generation component (fuel/variable),*** which reflects the variable cost of producing energy to serve a customer, and varies over time with fuel prices or with wholesale market prices; (c) ***transmission component***, which represents the cost of building bulk transmission infrastructure; and (d) ***distribution component,*** which represents the cost of building local distribution infrastructure.

I. What are Thermal Batteries?

Thermal Energy Storage (TES) refers to a relatively large class of technologies that can save energy in the form of heat, to be used immediately or stored for future use. Thermal storage has historically been widely used in building architecture, for example, as a means of maintaining indoor temperatures in a comfortable range: absorbing excess heat in the day to keep spaces cool, then releasing the heat in the evening to keep spaces warm.[9] Thermal storage has also been used in the power sector, as in concentrating solar thermal power plant research and development (R&D) and pilot projects: energy from the sun is reflected by a large array of mirrors toward a central receiving point, melting a heat storage medium such as molten salt, which can be stored and used later to generate steam and power.[10] Thermal energy storage has applications for a diverse array of circumstances, ranging from widely deployed technologies such as air conditioning and refrigeration, to early-stage academic research focused on advanced materials and chemical storage.[11]

This report focuses on an emerging, commercially available technology: electricity-powered thermal batteries. Though the specific technology application of thermal batteries to decarbonize industrial heating is new, the technology relies on components that are relatively well understood. The process to convert energy in the form of renewable power to heat for industrial use is illustrated in Figure 3 below:

1. Produce electricity from renewable resources, which can either be co-located with the industrial consumer, or delivered through the bulk transmission grid;
2. Convert electricity into heat with resistive heaters;
3. Store the heat in a suitable medium with a high heat capacity, such as bricks, blocks, rock, or another bulk storage material. The temperature of the storage medium is always managed to ensure that a portion of the material remains at or above the temperatures needed for the industrial processes in question, so that heat can be delivered at the required temperatures across all stages of charge, down to the fully discharged state; and

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9 Solar Energy Research Institute. *Low Temperature Thermal Energy Storage: A State-of-the-Art Survey*. 1979.

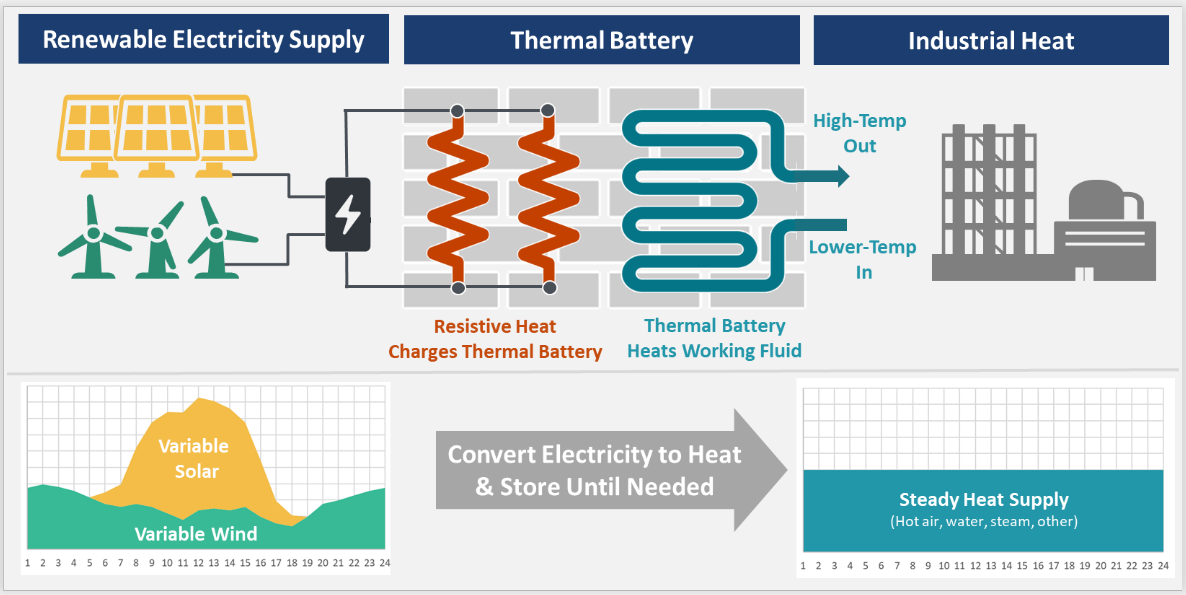
10 World Bank. *Concentrating Solar Power: Clean Power on Demand 24/7*. 2021.

11 For example, the *Future of Storage* study by the Massachusetts Institute of Technology reviews the R&D and commercialization status of a large number of thermal storage technologies. This study includes a comprehensive discussion of cost and commercialization status of different thermal battery storage mediums but focuses on the application of thermal batteries to enable conversion of electric energy to heat and then back to electricity. This is an inherently inefficient process, given that the conversion from heat to electricity via combustion turbines cannot achieve greater than approximately 47% round-trip efficiency (RTE) depending on the temperature of the storage medium). In this present study, we focus on a different use case of converting electricity to heat, to be stored and later used as heat (a process that can achieve approximately 90-98% efficiency, with maximum efficiency limited by the effectiveness of heat transfer processes and quality of insulation). MIT Energy Initiative. *The Future of Storage*. 2022.

4. Run a working fluid such as water, steam, or air through the storage medium to absorb the heat when it is need and deliver that heat to the industrial processes.

Overall, this technology can replace the role of a high-temperature unit process, such as a natural gas boiler, furnace, kiln, or dryer, in a typical manufacturing site. As an additional opportunity, some industrial sites may pursue a configuration relying on a thermal battery with the option to utilize excess stored heat to produce electric power. This thermal battery and cogeneration configuration would be most relevant for industrial customers that utilize both heat and electricity, with both requiring a stable and controllable consumption profile.

FIGURE 3: TYPICAL RENEWABLE THERMAL STORAGE CONFIGURATION
Converting Variable Renewable Power to Stabilized Steam Energy



Every step of this process involves technology components and engineering concepts that are already widely used in manufacturing processes, except for the thermal battery itself. In most cases, the thermal battery is designed to replace or augment a heating process at an existing manufacturing facility and thereby reduce its fossil fuel consumption, with the thermal battery size, flow, temperature, and energy requirements specified by the industrial customer. In some cases, the thermal batteries are designed and built as modular units that can be installed at an existing manufacturing site; in other cases, the thermal batteries are constructed at the facility. Both configurations connect directly to existing delivery infrastructure for the steam or other working fluid. The thermal batteries realize efficiencies in the range of 90 – 98% between the electric power and final industrial heating demand.[12]

Thermal batteries' size, heating capacity, core material for storage, and target temperature ranges are the subject of ongoing refinement as the companies deploy pilot systems and update commercialization plans. Table 1 below summarizes the storage medium, available

[12] MIT. *The Future of Energy Storage: Chapter 4 Thermal Energy Storage*. 2023.

temperatures, and commercialization status of thermal storage units offered by the companies interviewed for this study (we note that this table is not a comprehensive survey of all companies offering thermal storage systems).

TABLE 1: TECHNICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE THERMAL STORAGE UNITS

Company	Thermal Battery Model (if relevant)	Temperature Range	Storage Medium	Commercialization Status	Source
Antora Energy	-	Up to 1,500 °C (2,730 °F)	Carbon Blocks	Early Commercialization	[1]
Caldera	Storage Boiler	Primarily 90 °C – 300 °C (194°F – 572°F)	Recycled Aluminum and Crushed Rock	Pilot	[2]
Brenmiller Energy	bGen ZERO	130 °C – 750 °C (270 °F - 1,380 °F)	Crushed Rocks	Early Commercialization	[3]
Electric Thermal Solutions	Joule Hive Thermal Battery	Up to 1,800 °C (3,300 °F)	Firebrick	Pilot	[4]
Rondo Energy	RHB300	80 °C – 1,500 °C (180 °F – 2,730 °F)	Brick	Early Commercialization	[5]

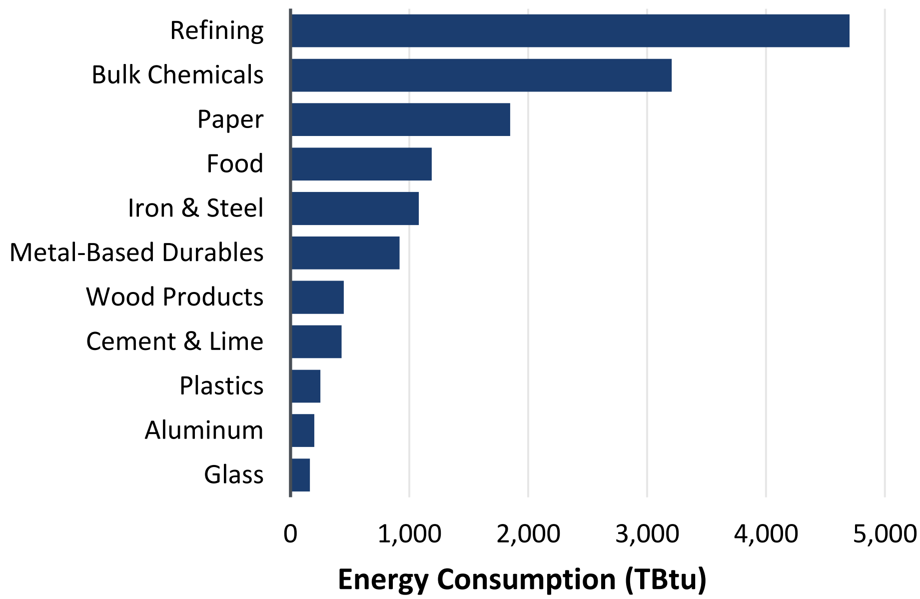
Sources and Notes:

[1] Canary Media, This startup’s energy storage tech is ‘essentially a giant toaster’, April 2022.
[2] Caldera, Personal Communication, September 13, 2023.
[3] Brenmiller Energy, Brenmiller - thermal energy storage (bren-energy.com).
[4] Electrified Thermal Solutions, Electrified Thermal Solutions – Electrifying industrial heat.
[5] Rondo Energy, Products — Rondo Energy.

Commercially available and deployed thermal batteries can support temperatures as high as 750 °C (1,380 °F), or high enough to serve nearly 75% of all US industrial heat demand. Thermal batteries that can support very high-temperature processes up to 1,800 °C (3,300 °F) are expected to be available by 2025 – 2030.[13] The primary sectors of industry that may benefit from renewable thermal storage are summarized in Figure 4, which reports the total heat consumption for each segment (the breakdown by temperature and economic sector differs in other global economies).

[13] Thermal storage solutions commonly have customizable operating conditions, including the temperature of the produced steam or other form of heat output. Most of the current manufacturers report their maximum achievable temperature to assuage concerns that the technology cannot meet customer needs. Currently, commercially available technologies can deliver heat at temperatures as high as 750°C (e.g., Brenmiller Energy, Rondo Energy). In the near future, other providers may be able to deliver heat at temperatures above 1,500 °C (e.g., Antora Energy, Rondo Energy), and potentially above 1,800 °C (e.g., Electrified Thermal Solutions). Worldwide, there appear to be between 10 and 20 companies investigating and pursuing thermal energy storage for industrial applications. Brenmiller Energy, “Technology”; Rondo Energy, “How It Works”; Antora Energy, “Technology”; Electrified Thermal Solutions, “Technology”; Renewable Thermal Collaborative, *Vision Report*, 2022; Long Duration Energy Storage Council, *Net Zero Heat*, 2022.

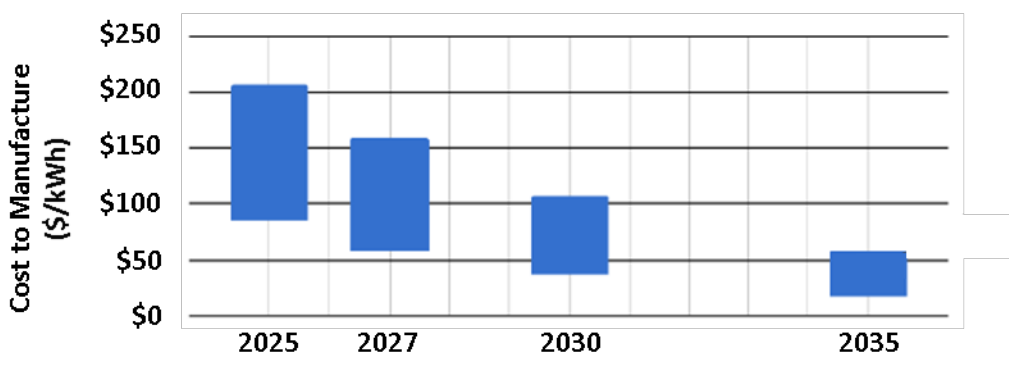
FIGURE 4: US INDUSTRIAL HEAT CONSUMPTION IN 2022



Source: U.S. EIA, Annual Energy Outlook 2023.

The outlook for near-term cost reductions is also positive. Currently, thermal battery companies are in early commercialization stages ranging from prototyping, first-of-a-kind deployments, or gaining experience from a small number of deployments. As such, several of these early-stage deployments may require policy incentives or other funding arrangements to proceed. However, as thermal battery companies gain deployment experience, they anticipate gaining economies of scale and reducing installation costs. Figure 5 reports near-term cost ranges and long-term forecasts projected by multiple thermal battery companies. The cost of a thermal battery (including manufacturing but not installation costs) ranges from about $85 to $210 per kWh for installation by 2025 but is expected to decline to $40 to $110 per kWh by 2030 and to $20 to $55 per kWh by 2035. In our economic analysis presented in Section III below, we assume thermal battery pricing in the range anticipated to be available by 2030.

FIGURE 5: THERMAL BATTERY COMPANIES' PROJECTED TOTAL MANUFACTURING COSTS



Source: Aggregated costs from multiple thermal battery providers, both within and outside the RTC.

II. What Role Can Thermal Batteries Play in the Clean Energy Transition?

If pursued to their maximum economic potential, thermal batteries can play two critical roles in the economy-wide clean energy transition, by:

- Enabling cost-effective decarbonization of industrial heating demand at large scale; and
- Offering flexible and controllable demand that can balance the power grid in regions with high penetrations of variable renewable resources.

In other words, thermal batteries are a promising technology that addresses two of the most critical barriers to economy-wide decarbonization. Further, thermal batteries do not suffer from the same challenges that might hinder large-scale deployment of other industrial decarbonization solutions. Thermal battery systems are in early commercialization stages, rely on well-understood processes, and utilize abundant, low-cost materials.

A. Enabling Large-Scale Decarbonization of Industrial Sector Heating Demand

Industrial heating demand contributes approximately 12% of total US greenhouse gas (GHG) emissions, as summarized in Figure 6. (The industrial sector also has other sources of emissions, including chemical process emissions and "indirect emissions" associated with power consumption that are outside the scope of this paper to address.)

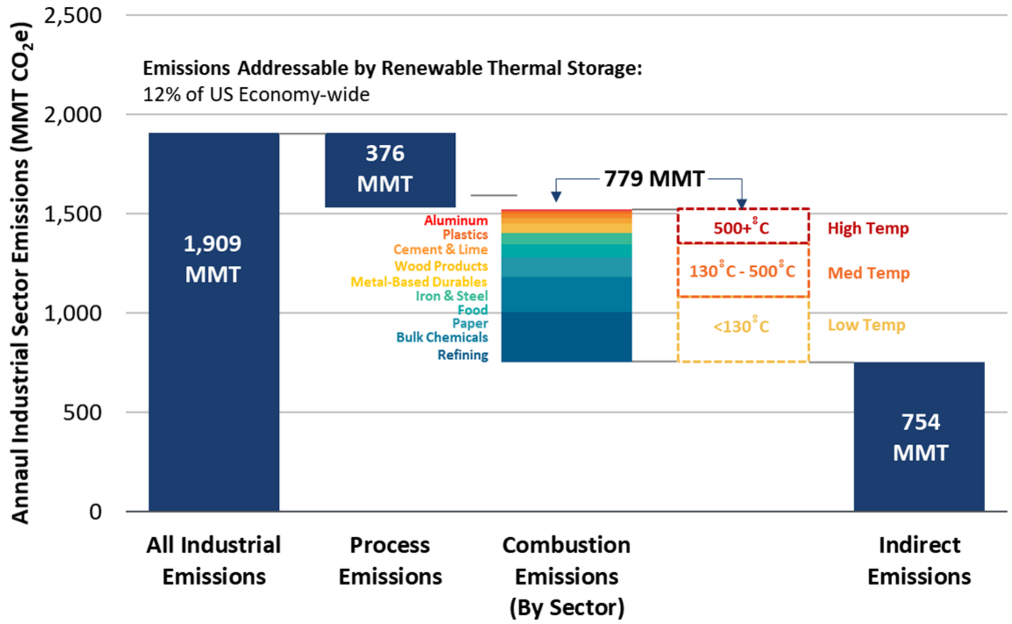
Renewable-powered thermal batteries can be deployed to cost-effectively electrify and decarbonize industrial heating demand at large scale. Historically, it has been either high cost or infeasible to decarbonize these segments of the economy. Further, the industrial sector has limited ability to make significant expenditures to address and reduce GHG emissions. Some consumer-facing industrial sectors, such as beverages and consumer products, may be able to pass along a modest cost premium associated with eliminating GHGs; but many manufacturers of commodity products face global trade pressures that make it infeasible to recover material green premiums. For these reasons, most policymakers seek to limit GHG policy impacts on trade-exposed industries that might make key economic and employment centers uncompetitive, or in the worst case create incentives to shift operations, jobs, and emissions overseas.[14] Adopting GHG policies that could impose high costs on such manufacturers are counterproductive if they incentivize employers to shift economic activity (along with emissions) to another jurisdiction without carbon policy (i.e. leakage).

[14] *See* The World Bank, *Report of the High-Level Commission on Carbon Pricing and Competitiveness*, 2019.

Renewable thermal storage has the potential to address these emissions and provide GHG-free heat to industrial customers at a levelized cost that is cost-competitive with natural gas. If deployed at the greatest possible scale for all industrial heating demand across the US, renewable-powered thermal batteries could displace 779 MMT of emissions annually.

FIGURE 6: US INDUSTRIAL HEATING EMISSIONS ADDRESSABLE BY THERMAL BATTERIES

Maximum Technical Potential, Consistent with US Emissions in Year 2021



Sources: Derived from EPA. *Inventory of US Greenhouse Gas Emissions and Sinks*. 2023; EIA. "Annual Energy Outlook 2023". 2023.

B. Grid Balancing via Flexible, Controllable Demand

Power grid regions absorbing more than approximately 20% renewable electricity begin to face challenges associated with managing substantial increases in net load variability (i.e., demand minus net renewable prediction) and uncertainty on the timescale of minutes and hours.[15] For states, customers, and cities aiming to achieve 50-100% clean energy, the challenges become greater: intraday balancing challenges are even more significant, while daily and multi-day imbalances emerge as well.

Managing these grid-balancing challenges without continued reliance on fossil resources will require technology breakthroughs to identify flexible, clean technologies that are able to serve grid reliability needs. By now, nearly all North American Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs), several US states, and many grid operators

15 "Net load variability" refers to the variability in system-wide customer demand minus variable renewable energy resource output. Demand (or load) variability has always been managed by grid operators. However, systems with large and growing quantities of renewable resources must increasingly manage a much larger quantity of variability and uncertainty in the power grid "net demand".

globally have conducted detailed studies examining the challenges of achieving 100% clean power grids.[16] The specifics of the challenges differ in each region, but a common theme emerges from these studies: the grid will urgently need flexible, clean resources and controllable demand resources to manage net load variability if the grid is to achieve climate goals reliably and affordably.

Thermal batteries are a technology that can help meet these grid-balancing needs. Thermal battery systems can be scheduled to charge during times of surplus (whether from co-located renewables or to absorb excess power from the grid), and to allow renewables to bypass the thermal battery to inject directly to the grid when the system is tight (waiting to charge the thermal battery until tight system conditions have passed). The overall result is that industrial customers enabled with thermal batteries can electrify heating demand in ways that absorb large volumes of renewable power that would otherwise be curtailed, and (depending on the configuration) provide net injections to the grid only when doing so offers reliability and economic benefits. Thermal batteries can also be responsive to ISO/RTO control signals on a short notice ranging from a few seconds to 3-minutes to precisely manage the level of net grid injections or withdrawals, in response to system ramping or contingency events. As long as the thermal battery can be charged sufficiently over a 24-48 hour timeframe from renewable self-supply or from grid power, these grid services will not affect the ability to deliver a stable stream of heat to the industrial heating processes. Typical thermal battery configurations need to charge only approximately 4-8 hours (contiguous or non-contiguous hours) across any given day to maintain a sufficiently charged state to support the heating demand.

To maximize value, thermal batteries would need to be able to offer these grid services on a competitive basis and be remunerated at the same wholesale market prices available to traditional power plants and electricity-to-electricity batteries. However, market structures and retail rate structures do not yet offer thermal battery systems access to these wholesale prices, as discussed further below.

[16] Examples of key studies include: ISO New England. *2022-2025 Roadmap to the Future Grid*. June 21-23, 2022; ISO New England, New York ISO, and PJM. *2021 Northeastern Coordinate System Plan.* July 22, 2022; MISO. *Markets of the Future.* November 2021; New York ISO. *A Balanced Approach to a Clean and Reliable Grid.* August 14, 2023; PJM. *Energy Transition in PJM: Frameworks for Analysis.* December 15, 2021.

III. What is the Business Case for Using Thermal Batteries to Decarbonize Heating Demand?

A. Potential Commercial Advantages of Thermal Batteries

In interviewing providers and customers of electricity-powered thermal batteries, the primary rationale cited for considering the technology was to pursue decarbonization of industrial heating demand at an affordable cost. However, our interviews revealed several nuances and secondary advantages of thermal batteries that may incrementally support the business case for some companies.

Potential commercial advantages of renewable thermal systems include:

- **Reducing GHG emissions.** Companies wish to reduce GHG emissions for many reasons, including to meet corporate sustainability commitments, meet state policy requirements, manage against risk of future GHG emissions policies, serve increasing consumer demand for green products (though this is only relevant for some industries), or to improve performance on environmental, social, and governance (ESG) metrics increasingly required by investors and lenders. We suspect that the companies we interviewed for this study may be more focused on GHG emissions reductions than the "typical" industrial customer, but the sentiments still reflect broad trends toward focus on ESG in all economic sectors. For example, CDP (formerly the Carbon Disclosure Project) reported that a record 18,700 companies disclosed performance on climate change issues in 2022.[17] As of 2021, nearly half of the world's largest 500 companies reported using an internal carbon price, and at least one third of manufacturing companies that choose to disclose via CDP report relying on one during decision-making.[18] Despite these trends, all interviewees emphasized that they must find ways to meet GHG commitments at low or no cost if they are to remain competitive.

- **Affordable energy supply.** Interviewees explained that few options exist for displacing fossil fuel supply at an affordable price. In particular, the cost of electrifying most industrial heating demand (without thermal batteries) at the "sticker price" of retail industrial rates is not cost-competitive relative to natural gas. Electrifying with renewable supply can be competitive with natural gas on a levelized cost basis in some regions, but the variability of renewables must be addressed for industrial customers that rely on consistent supplies of heat. By adding thermal batteries to a renewable resource, the overall levelized cost of a stable stream of heat supply can be cost-competitive with gas.

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[17] CDP. "Companies Scores", 2023.

[18] CDP. "Putting a Price on Carbon: The state of internal carbon pricing by corporates globally", 2021.

Interviewees stated that the long-term capital costs of the thermal batteries system (and savings associated with gas boiler retrofits or similar) are not the primary drivers of the economic decision. Instead, they point to the levelized cost of renewables versus the energy cost of natural gas as the key determinant in whether a thermal battery system is affordable.

- **Physical hedge on fuel price risks.** US natural gas prices had been quite low at $2–$3.90/MMBtu from 2019 to 2021 but rapidly increased to $6.50–$8.80/MMBtu over the timeframe from April 2022 to September 2022, after Russia's invasion of Ukraine.[19] In the past eight months, prices have again moderated to between $2–$3/MMBtu. Many prior examples exist of extreme gas prices, such as $10/MMBtu in the months after 2005's Hurricane Katrina and $10/MMBtu in the first half of 2008 associated with tight economic conditions. Companies relying on natural gas as a primary source of energy supply must actively manage and hedge against such risks. Renewable power supply is not subject to similar price volatility risks (its variable costs are zero). Shifting from natural gas to renewables as the primary energy source effectively creates a physical hedge protecting against fossil fuel price volatility.

- **Reliability**. Interviewees expressed that thermal batteries can offer improved reliability compared to natural gas alone. Though not cited as a common occurrence, natural gas deliveries can sometimes be interrupted in situations of peak demand or gas system freezes (when distribution companies must prioritize limited supply for residential customers). For example, during Winter Storm Uri in February 2021, industrial natural gas deliveries declined by the largest month-over-month volume on record (23% below prior-year levels in the same month).[20]

- **Electricity vs. gas fuel switching**. For companies electrifying via renewable thermal storage, one commonly anticipated option is to maintain existing gas infrastructure as a backup fuel source. If both renewable thermal storage and natural gas are available, the facility is able to fuel-switch between electricity and natural gas in response to prices in both markets or in response to reliability events. This would both improve reliability and reduce the net cost of supply that could be expected from either renewable thermal or natural gas as a single energy source.

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19 Prices quoted in nominal terms of monthly average spot prices at the US Henry Hub. S&P Global, Market Intelligence, as-of August 29, 2023.

20 Reductions in industrial consumption and high gas prices were driven by reduced gas supply due to well freeze offs that coincided with high demand from the heating and electricity sectors. U.S. Energy Information Administration, "Today in Energy: February 2021 weather triggers largest monthly decline in U.S. natural gas production", May 10, 2021.

B. Regional Differences in the Cost Advantage of Electrifying with Thermal Batteries

The primary determinant of whether electrification via renewable thermal storage can be cost effective depends on which is the lower cost of the primary energy supply: (a) natural gas, or (b) new renewables.

There is also an energy efficiency loss associated with combusting natural gas to produce heat, and a smaller efficiency loss as thermal batteries charge and store heat. Thermal batteries further contribute approximately 20% to 40% in up-front capital cost associated with the thermal battery. We account for these factors in our economic analysis, and how they affect the equation of whether gas, solar, or wind has the primary cost advantage.[21]

Whether it is cost-effective to electrify via thermal battery systems will have a different answer over time (as gas prices change) and by location, given that the cost of building new renewables differs greatly based on regional resource potential. Figure 7 below illustrates the regional variability in the attractiveness of electrifying via thermal batteries. The figure displays locational marginal prices (LMPs) across the US as averaged over 2022.[22] The top map displays 24-hour around-the-clock prices that would be applicable for a bulk system customer with a flat (i.e., relatively constant) electricity demand profile. The subsequent maps report the average price that would be paid by a thermal battery system charging in the lowest-price hours of the day (lowest 8 hours, 4 hours, or 1 hour).

The maps illustrate that the price of electricity varies greatly across the country, with relatively high prices in regions where natural gas and coal are the price-setting resources most of the time. However, across large parts of the Midwest and West, and in pockets of regions elsewhere, average wholesale market prices can be lower or much lower than the variable cost of fossil plants. In those regions, renewable power is abundant, low-cost, and being developed at a fast pace. In many places, the volume of renewables is high enough that the grid has become saturated and resources must often be curtailed on a relatively frequent basis. Power prices are usually zero or negative when renewables must be curtailed, resulting in a daily pattern of low/negative prices in some places. For a typical thermal battery configuration that might charge

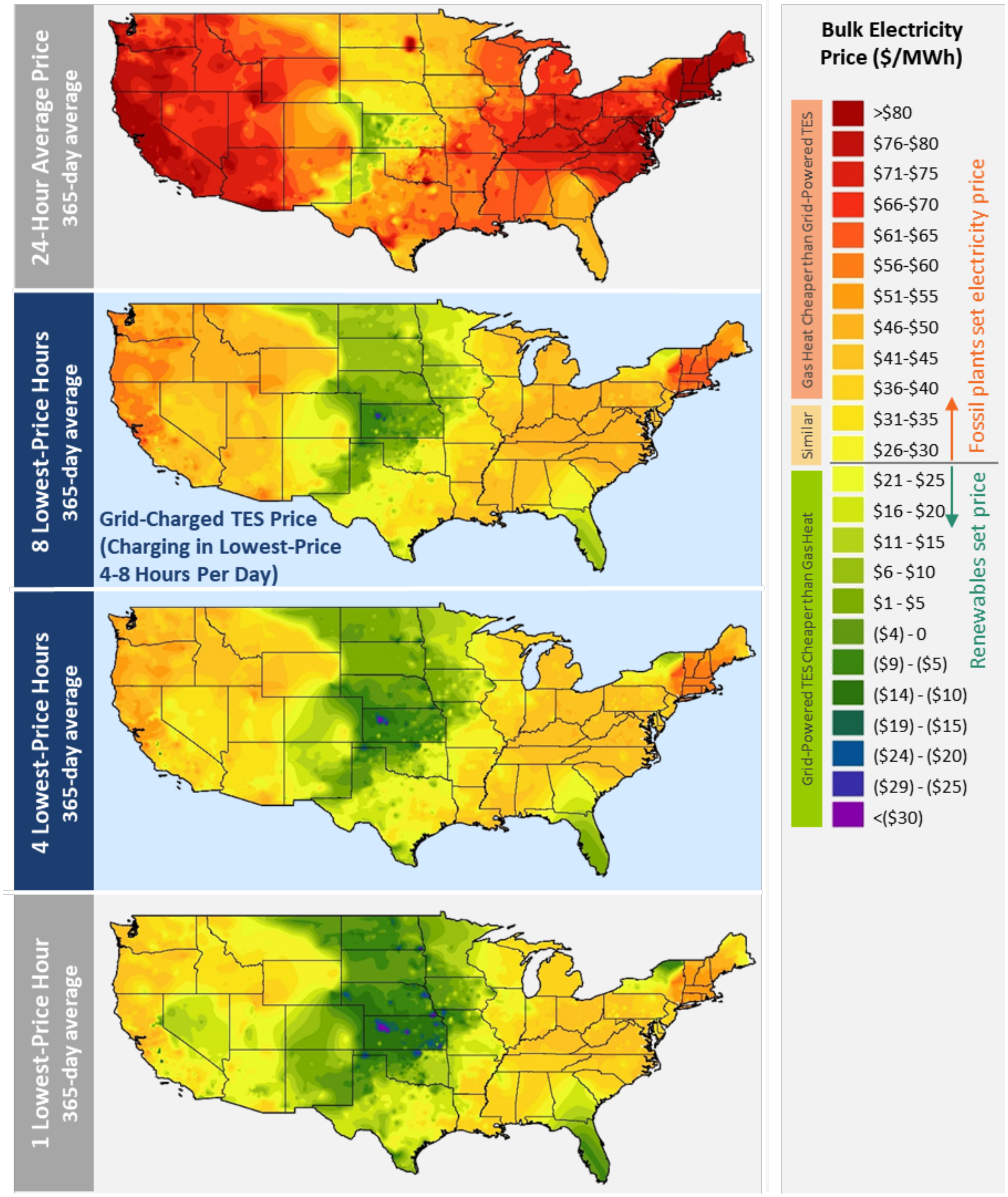
[21] Natural gas boilers or retrofit systems also contribute up-front costs and ongoing fixed costs, but we do not consider these in our economic analysis because we presume a brownfield site scenario where natural gas equipment is already in place and is not facing a major replacement or retrofit.

[22] "Locational Marginal Prices (LMPs)" are the pricing points relevant to the bulk power markets operated by ISOs and RTOs. The LMP is calculated every 5-minutes by the ISO/RTO at every distinct injection and withdrawal point in the grid, and reflects the marginal or incremental cost of supplying power at that point in the grid after accounting for all resource costs and transmission constraints. The LMP can vary greatly over time and by location even in relatively small sub-regions of the grid. Day-ahead and real-time LMPs are the price at which generators, utilities, distribution companies, and (some) large customers purchase and sell energy, while ensuring all grid reliability needs and constraints are respected. Approximately 38,000 distinct pricing points are shown. ISO/RTO real-time LMP data are used where available, and the nearest point data was used for some balancing areas where neither hub prices nor LMPs are available. Data compiled from Hitachi Energy, Velocity Suite, and S&P Global Market Intelligence.

from the grid only 2-8 hours over the day, this implies that in some places across the US it is already possible to charge from surplus renewable supply at average prices near or below zero on a consistent basis.

On the map legend, we further provide rough indicators of the LMP cutoff point where renewable thermal systems are approximately at parity with \$6/MMBtu natural gas for heat (with and without a \$50/tonne GHG price). Yellow-green coloring indicates that thermal battery systems may be cost effective in some cases, particularly if a carbon price is considered. Darker green coloring indicates that thermal batteries are very likely to be lower cost, while dark blue and purple coloring indicate that surplus renewable electricity is already available at a literal negative cost.

FIGURE 7: BULK ELECTRICITY SYSTEM PRICES AVAILABLE ON AVERAGE (24-HOUR) OR TO THERMAL BATTERIES CHARGING IN THE LOWEST-PRICE HOURS OF THE DAY (1, 4, OR 8 HOURS)



Source and Notes: Raw hourly price data is sourced from Hitachi Energy, Velocity Suite. Figures reflect nearest neighbor interpolation of the average LMP metric taken uniformly across all 365 days in 2022. The average LMP metric is calculated by determining the lowest 1-, 4-, 8-, and 24-hourly prices on each day and calculating the uniform average. In regions where there are no LMP nodes (e.g., Florida), the nearest neighboring node was used to fill the region.

The development of surplus renewable energy is rapidly increasing, such that the opportunity for industrial heating consumers to benefit from low-cost surplus renewable energy will expand to more regions and extend across more hours of a typical day. Thermal batteries, if adopted at scale in regions with abundant renewable resource potential, will further enable many more renewable resources to achieve interconnection without requiring large-scale transmission investments to enable power delivery to far-away electricity demand centers. Because most of the renewable-rich regions of the country (such as the Midwest and West) are far from key demand centers (Coastal regions and large cities), the transmission grid must be sized sufficiently to transport renewable power to these regions. The intermittency of renewables creates further cost tradeoffs with respect to transmission needs, with options to either: (a) incur costs to substantially over-size transmission lines relative to the average renewable power transferred, or (b) incur costs to develop excess renewable supply, much of which will be curtailed due to lack of transmission to deliver all the power produced in high-renewable-production hours. For these reasons, the lack of adequate transmission infrastructure and interconnection capability is commonly cited by the renewables industry as the single greatest development barriers.[23] The introduction of thermal batteries at a large scale and located nearby these renewable-rich areas could greatly enhance the ability to utilize renewable power that would otherwise be curtailed, and avoid the need for large transmission expansions.

This analysis indicates that in large parts of the US, thermal battery systems may already be lower-cost than natural gas as a primary energy resource and that the opportunity will expand to more regions over time. However, the ability of customers outfitted with thermal batteries to access these cost advantages will depend greatly on access to wholesale power prices as discussed further below in the context of a range of thermal battery configurations.

C. Economic Examples: On-Site Renewable Thermal Battery Configurations

To more fully assess the economic advantage of electrifying gas heating demand with electricity-powered thermal batteries, we evaluated the economics for an industrial heating consumer with an average steam demand profile of 1 MWh_{th} (3.412 $MMBtu_{th}$) every hour. We examine the costs of supplying heat from natural gas as compared to on-site renewables and thermal battery systems, with results summarized in Figure 8 below (and in more detail in the Appendix). In the next section, we compare natural gas to grid-delivered renewables with on-site thermal batteries. We conduct this examination in a region of the Southwest Power Pool (SPP) where wholesale power prices are relatively low (specifically at a node with $28/MWh around the clock average prices along with zero or negative prices approximately five hours per day).

Key features and findings across each scenario presented in the following figure are as follows:

- **Scenario 1: Gas Heat**. We assume a status quo configuration of natural gas at $6/MMBtu ($24/MWh_{th} after accounting for boiler efficiency losses), with and without a $50/tonne

[23] See, for example: American Clean Energy Grid. *Transmission Planning and Development Regional Report Card,* June 2023; and Lawrence Berkeley National Laboratory, Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection As of the End of 2022, 2023.

GHG price threshold. We assume the natural gas boiler is already in place and do not apply any fixed costs.

- **Scenario 2: Off-Grid Renewable Thermal Battery.** We assume that co-located wind is the renewable supply at a levelized contract price of $23/MWh, and that the renewable thermal system is developed in an entirely off-grid configuration. The thermal battery is sized at 24 MWh of energy charge capacity. The wind resource is slightly oversized by 4% on an annual energy needs basis, which is enough to provide energy supply under the large majority of conditions (but that requires the industrial customer to revert to natural gas backup energy occasionally when there are extended periods with below-average wind generation.) The islanded configuration further means that during extended periods of high wind output, there is excess wind supply that must be curtailed. The net cost of renewable thermal supply in this configuration nears parity with Scenario 1 (natural gas) if one considers a $50/tonne GHG cost, but is higher than the cost of natural gas if no GHG cost is considered. Companies considering an off-grid configuration will need to weigh the tradeoffs between over-sizing renewables (at the cost of increased curtailments) against the GHG costs associated with natural gas backup (which may be needed more frequently if renewables are right-sized on an annual energy basis, but that can still sometimes have multi-day periods with low output).

- **Scenario 3: Net-to-Grid Renewable and Thermal Battery System.** In Scenario 3, we assume a net-to-grid configuration, in which excess renewable supply can be injected to the power grid. Revenues from any net grid injections offset the overall net system cost, such that the renewable resource size can be increased sufficiently to reduce reliance on natural gas backup without increasing the average delivered cost of heat. Further, because the thermal battery system has flexibility on *when* to charge for self-supply versus allow net grid injections, excess daily renewable production is prioritized for net grid sales across the highest-price hours of any given day. This net-to-grid configuration substantially reduces the net cost of the renewable thermal system, given that renewable production that would have been curtailed in an islanded configuration can be sold to the grid and often earn a price premium by injecting during the most attractive hours. Overall, the renewable thermal system is closer to cost parity with natural gas, even without a GHG price.

- **Scenario 4: Two-Way On-Site Renewable Thermal Battery System.** In Scenario 4, we assume that the thermal battery system can freely choose whether to charge from self-supply, make net renewable injections to the grid, or draw power from the grid to charge the thermal battery. This scenario achieves cost savings by allowing the customer to optimize operations by prioritizing net renewable injections during high-price hours and scheduling net withdrawals in low- and negative-price hours. In most days, the system can both purchase and sell grid power, while ensuring that the thermal battery always remains sufficiently charged to meet heating demand. The economic efficiencies achieved under this scenario result in a renewable thermal battery system with a lower net cost than natural gas for delivering steam and lower cost than the other on-site configurations we examined.

- **Scenario 5: Grid-Charged Thermal Battery.** In Scenario 5, we examine the use case of an industrial customer outfitted with a thermal battery charging from grid power, with no dedicated renewable resource contract. We further assume that the customer can charge the thermal battery at prevailing wholesale power prices (without applying any utility charges, which we discuss in more detail in the next section). In this scenario, the industrial customer cannot claim the purchase or retirement of renewable energy certificates (RECs), but as a practical matter is nevertheless charging from renewable power that would otherwise be curtailed.[24] Such an industrial customer may be attracted to electrify via a thermal battery less by environmental goals than by the economic reality that the predominance of excess renewables at that location in the power grid produces near or below zero prices whenever renewables are curtailed (approximately 20% of the time at the location we examined). The customer seeks to charge the thermal battery in the lowest-price hours over the course of any given day (amounting to an approximately $8/MWh consumption-weighted average electricity charging price over the year, given that zero and negative prices occur in many but not all days).[25] At this location in the power grid, electrification via a thermal battery system would provide industrial heat at a levelized cost substantially below the cost of natural gas heat.

Conducting this analysis for a hypothetical industrial heating customer reveals that the economics of a thermal battery system are dependent on the sizing of the renewable resource, the assumed cost of natural gas (with and without a GHG price), and the extent to which the system can be fully interconnected to the power grid. Even in an islanded configuration, renewable and thermal battery systems may be cost-competitive in some cases for companies or jurisdictions that apply a GHG emissions premium. However net-to-grid and two-way-grid-connected configurations offer substantially lower all-in costs. An even lower all-in cost of heat may be achievable for thermal battery systems that do not opt to contract with dedicated renewables, but that are located in places where it may be possible to take advantage of frequent

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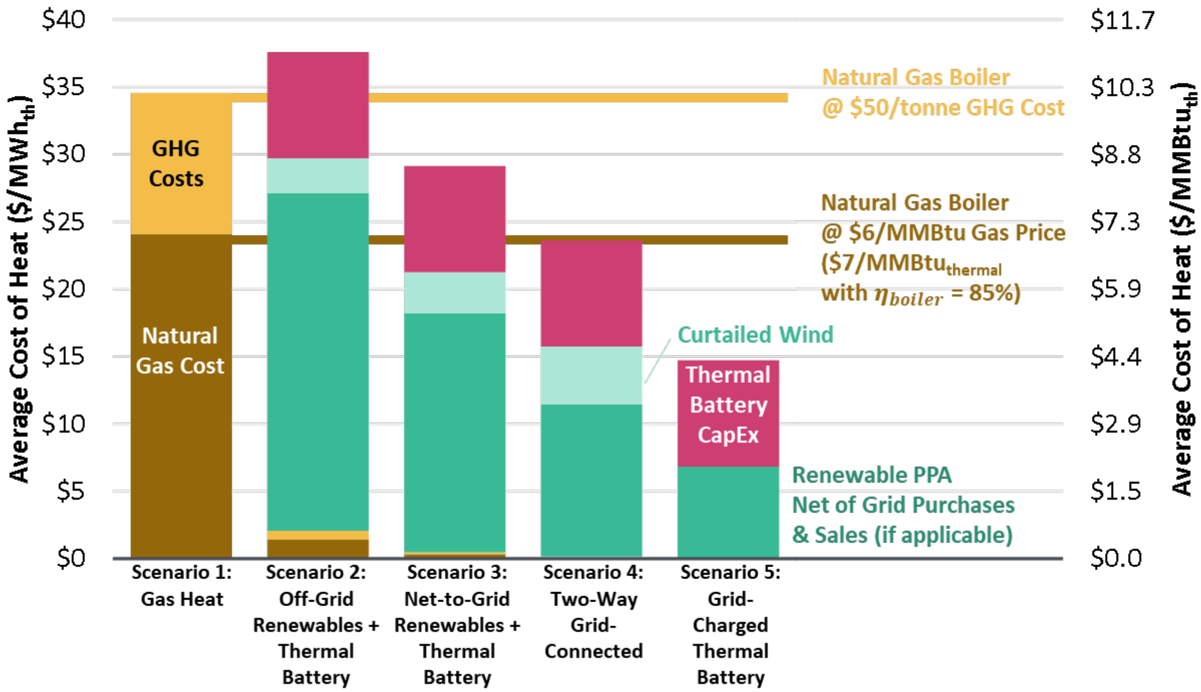
[24] LMPs are set at the marginal cost of producing power. When renewable resources are "on the margin" and setting prices at zero on negative levels, this indicates that more renewable resources are seeking to inject to the grid than can be absorbed – either because customer demand is less than renewable supply system-wide or because there is insufficient transmission infrastructure available to transport the renewable supply to customers. In these cases, the grid operator must curtail renewable resources, and LMPs are set at zero or negative prices. If a customer increases or schedules consumption during these negative-price hours as we envision in this thermal battery configuration, in effect the customer is enabling more renewable production that would otherwise be curtailed. For this reason and due to the thermal battery's charging schedule, more RECs can be produced by nearby renewable suppliers (though the RECs themselves are entirely unbundled and abstracted from these physical grid realities, and so may be sold to far-away customers).

[25] Note that this economic case for electrification via thermal batteries (and without dedicated renewables) is only attractive in locations with abundant and frequently-curtailed renewables (which manifests as near or below zero power prices). Regions without frequent renewable curtailments produce electricity prices consistent with the marginal cost of fossil-fuel power plants, including the cost of fuel plus approximately 50% efficiency losses in converting the fossil fuel to electricity. The total delivered cost of fossil fuel, converted to electricity and then converted to heat, will always substantially exceed the cost of directly converting the fossil fuel to heat. Therefore, in regions without frequent renewable curtailments, thermal batteries would need to be charged by low-cost, dedicated renewable resources (whether on-site or grid-delivered) if the thermal battery system is to be cost-competitive with natural gas as the source of heat supply.

low or negative prices. Under all configurations, the net cost can be further optimized by carefully sizing the renewable thermal systems to match the use case, and managing net injections, withdrawals, and state of charge relative to forecast grid prices.

Critically, the net-to-grid, two-way grid-connected, and grid-powered thermal battery configurations are not always fully enabled under current state electric regulatory processes and wholesale power market designs. As we discuss further in the following sections, thermal batteries will need to have full access to wholesale power markets at prevailing prices if these systems are to be economically attractive and offer benefits to the grid.

FIGURE 8: COMPARISON OF INDUSTRIAL HEATING COSTS, NATURAL GAS VS. CO-LOCATED RENEWABLES + THERMAL BATTERY CONFIGURATIONS



Notes: Reported in 2023$, pricing as anticipated by 2030. No policy incentives for thermal batteries are applied. See Appendix for modeling assumptions.

D. Economic Examples: Grid-Delivered Renewable Thermal with Alternative Electricity Rate Structures

We further extend our economic analysis of the costs of electricity-powered thermal batteries by examining configurations with renewable supply that is delivered to the customer via the power grid, before charging the on-site thermal storage system. This grid-delivered configuration may be more attractive and feasible for some industrial customers for a variety of reasons. Those include: if there is insufficient space to accommodate on-site renewables, if another site offers lower-cost renewable resources for development, or if the customer needs to procure only a portion of the output from a large renewable generator serving multiple customers.

In this analysis, we assume that the thermal battery system is similar to that as described in Scenario 4 in the previous section, but that the renewable resource is sourced from another point on the power grid and delivered to the industrial customer for charging. In a wholesale power market region, this would be supported by a multi-step arrangement in which: (1) the contracted renewable resource sells power into the grid under a contract-for-differences arrangement with the industrial customer (the net cost of renewable power after accounting for sales at the market price shown in green);[26] (2) the industrial customer's local utility purchases power from the power grid at prevailing market prices; and (3) the local utility sells power to the industrial customer under a rate level and structure approved by the state regulator.

Perhaps surprisingly, the economic viability of renewable thermal storage under a grid-delivered scenario has far less to do with the underlying renewables cost advantage (as discussed in the prior two sections), but rather is dominated by the nature of industrial power rate structures that may apply. As illustrated in Figure 9, thermal battery systems with the same underlying costs and technical parameters may be entirely uneconomic if subject to legacy rate structures, and cost-competitive if subject to modern rate structures.

The rate structure scenarios we examine include:

- **Scenario 6: Legacy Rate Structures.** In this scenario, we assume that the industrial customer is subject to the "sticker price" or average rate applicable to industrial consumers (rate levels are the approximate average rate applicable across states in the SPP region).[27] At this average rate, the industrial customer must pay for power at price levels far above the net cost of the renewable electricity and thermal battery. Further, the rate structure offers limited or no opportunity to offer net grid benefits by optimally scheduling the thermal battery relative to power grid needs. Under such a legacy rate structure, the key components of which are detailed below, renewables with thermal battery storage are not close to cost-competitive with natural gas as a primary energy source.

- **Scenario 7: Modern Rate Structures.** In this scenario, we assume that the industrial customer can purchase electricity either directly from the wholesale power grid at prevailing prices, or through a local utility that offers a modern rate structure reflective of system costs. Under this modern rate structure, renewables plus thermal battery storage are below the cost of natural gas for heating because the thermal battery can

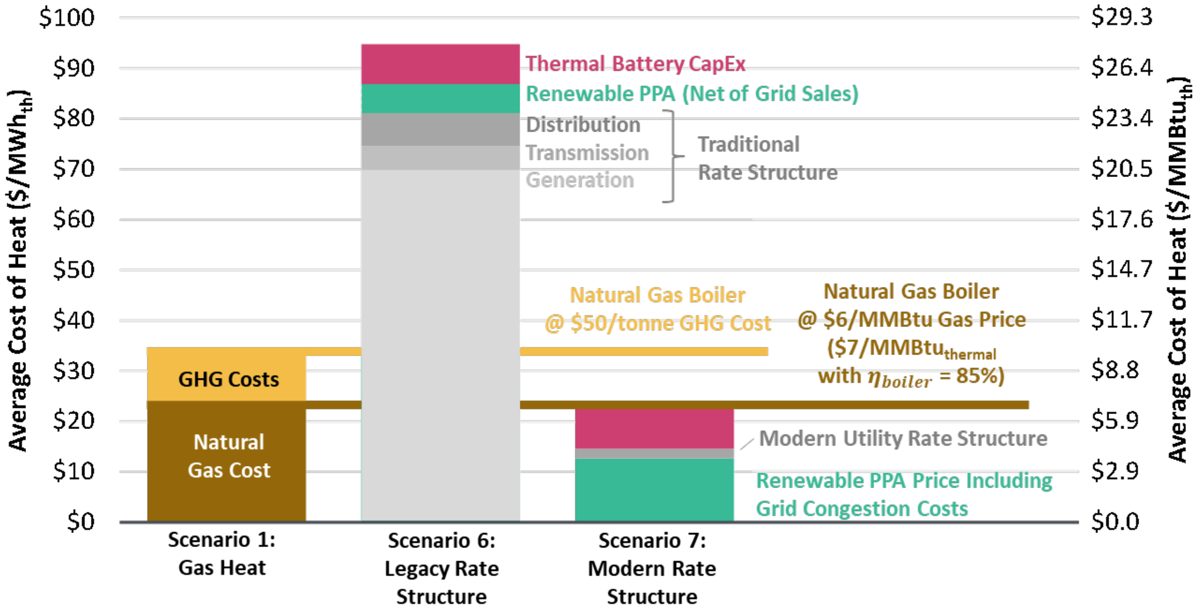
[26] A "contract for differences" is a typical bilateral power purchase agreement (PPA) structure in which the buyer and seller agree on a fixed price for energy in $/MWh. However, because both parties must also settle their power injections (or withdrawals) from the grid with the ISO/RTO relative to the LMP at their generator or load node, the bilateral contract for differences price is typically structured as a net payment from the customer to the generator based on the difference between the LMP and the contract-agreed price (i.e. at LMP minus contract price). Further, the contract must specify the relevant location for the LMP, since one of the two parties must bear the "congestion risk" or the risk that the LMP at the generator node is substantially different from the LMP at the customer node.

[27] The estimated legacy rate is based on Brattle analysis of data collected by Edison Electric Institute (EEI). EEI, *Typical Bills and Average Rates Report – Summer 2022*, 2022.

optimize its schedule relative to wholesale power prices (similar to the discussion under Scenarios 3 and 4 above), and would avoid any utility charges that are associated with time of use.

The large difference in the net cost of supply under these two scenarios highlights the most critical barrier to thermal battery deployment: the need to provide direct access to wholesale power prices and modern retail rate structures.

FIGURE 9: COMPARISON OF INDUSTRIAL HEATING COSTS, NATURAL GAS VS. GRID-DELIVERED RENEWABLES + ON-SITE THERMAL BATTERY CONFIGURATIONS



Notes: Reported in 2023$, pricing as anticipated by 2030. No policy incentives for thermal batteries are applied. See Appendix for modeling assumptions.

Below we further unpack the economic drivers of the "sticker price" or legacy utility rate structures that could limit the ability to deploy or optimally operate thermal battery systems, and describe how modern rate structures reflective of underlying system costs can be structured. Note that a modern rate structure would offer benefits to any type of customer that can adjust their consumption behavior in ways that reduce the cost of service, though the magnitude of demand shifting and shaping offered by thermal batteries far exceeds what has historically been possible to achieve by traditional demand shifting measures or related programs.

Typical industrial rate structures include:

- **Generation Cost Component.** The generation cost component of an industrial customer's bill is derived from the all-in capital cost, fuel cost, and net grid purchase costs (or sales revenues) that the utility incurs to deliver energy to the average customer. This cost is usually apportioned between industrial, commercial, residential, and other customer classes based on the typical energy consumption profile, with costs billed on an averaged $/MWh basis to individual customers. This ratemaking approach is sensible for many customers that cannot meaningfully respond to system conditions but is not an efficient approach for customers outfitted with thermal batteries because it eliminates any incentive to optimize the charging schedule or to offer the associated balancing value to the grid. A modern rate structure would seek to structure rates so as to closely align with cost causation, breaking the generation component into two pieces:

- *Fuel and Net Grid Purchases Cost:* One component of generation costs is associated with fuel cost and net grid purchases or sales that a utility incurs to deliver energy at any given time to a specific customer. Traditional rate structures aggregate and average this cost, but it can be signaled more accurately and more precisely by the wholesale market price at any given time. If industrial customers with thermal storage can pay this price directly based on real-time system conditions, they can optimize their schedules to greatly reduce this cost.

- *Generation Capacity and Investment Cost:* The other primary component of generation costs is associated with generation investment costs, the need for which is driven by system coincident peak demand conditions.[28] To determine the total MW of generation that is needed to reliably serve customers, utilities project anticipated peak loads of all customers and build the needed quantity of generation plus a reserve margin. Given that the driver of these costs is associated with consumption during a handful of annual or seasonal peak hours, the most efficient way to allocate the associated costs is to apply them based on consumption during these critical hours. In regions with capacity markets, the applicable rate structure would apply the wholesale capacity price as applied over the relevant market-defined coincident peak hours.[29] Customers outfitted with thermal batteries can easily avoid consumption in these hours, would avoid incurring the need to build any associated generation, and would avoid paying any associated costs.

- **Transmission Component.** Transmission costs are applied to recover the cost of building transmission lines and can be applied in different ways, including a volumetric ($/MWh) charge, a demand ($/kW) charge based on an individual customer's monthly peak consumption, or a demand ($/kW) charge applied to consumption only during system coincident peak hours (monthly, annual, or seasonal). Of these, only the last method based on *system coincident* peak can incentivize customers and thermal battery systems to draw power at times when the grid has ample transmission capability. Any transmission costs driven by consumption during coincident peak demand hours (or by other

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28 Coincident peaks refer to the highest periods of demand in an ISO/RTO region or utility region. An individual customer's demand during these periods is often used to determine causation when costs are being allocated to customer classes. The number of peak hours across which peak demand is measured varies by region, for example 1 ("1CP"), 4 ("4CP"), or 12 ("12CP"). *See* NARUC, Methodology of Cost Allocation, 2013.

29 "Capacity markets" are operated by some RTOs/ISOs as a means for ensuring that sufficient capacity resources will be available and committed to meet annual or seasonal peak demand plus a reliability reserve margin. The capacity markets are structured as auctions to procure reliability commitments from qualified resources (whether generation, batteries, demand response, etc.), guaranteeing that they will be available when needed to serve reliability needs. Capacity procurement costs are allocated to customers in proportion to consumption during peak hours.

underlying system conditions) are best applied in these hours to ensure that customers will avoid consumption at these times. Thermal battery systems can readily avoid consumption during such times.

- **Distribution Component.** Distribution costs, similar to transmission costs, are driven in large part by consumption during coincident peak hours and can be allocated most efficiently during these hours. However, there are also some components of distribution system costs, such as direct customer hookup costs, that are primarily driven by the fact that the customer is interconnected. These costs cannot be avoided by any customer connecting via a distribution grid, and will apply to customers with thermal batteries, likely based on a fixed monthly customer charge.

- **Regulatory Transition Charges.** Another category of charges that applies in some states and utility regions is associated with major "regulatory transition" or other unique historical events. For example, many states in the transition from vertically integrated utility models to retail choice introduced a "transition charge" to customer bills to recover legacy costs incurred by the utility under the prior regime. The general concept of these charges is to allow utilities to recover the investment costs they incurred to build generating resources for the customers they expected to serve. However, these charges should not generally be applied to industrial heating customers that are newly electrifying, since these customers were not considered in the prior regime and are often electrifying with their own renewable supply resources.

- **Other Charges.** Many other categories of charges may apply in some states, for example, "social benefits" charges that are used to fund environmental programs or provide low-income rate assistance. Whether and how such charges would be applied to customers with thermal batteries would differ in each case, but as general rules, we would recommend aligning both the level and structure of these charges to cost causation where possible and considering a balance of policy priorities in other situations. In the case of renewable surcharges, these generally would not apply to thermal battery customers that are already fully self-supplied with renewable power. In the case of low-income assistance, the surcharge would have to consider the benefits of funding the assistance against the cost that the higher charge may discourage industrial customers from electrification.

By enabling industrial customers to directly access wholesale power prices and adopting modern rate structures tied to cost causation, state regulators can empower manufacturers in their states to examine the potential GHG and economic benefits of thermal batteries using purely economic fundamentals (without artificially limiting the size and configuration options of renewable electricity sources that could be available).

IV. What Barriers to Entry Should Be Addressed to Accelerate Thermal Battery Deployment?

To assess the barriers to accelerated thermal battery deployments, we have conducted a series of interviews with thermal battery providers and with industrial heat users. We classified the identified barriers by category, including technical, customer readiness, policy, economic, retail electricity rate structures, and wholesale electricity market structures. A full list of barriers we identified is located in Table 2 below. In the right-hand column of the table, we offer our own assessment of the extent to which these barriers will constitute a major roadblock to accelerated thermal battery deployments over the coming years.

As to be expected with emerging technologies or technologies with limited commercial deployment (often referred to as "first of a kind" technologies), interviewees relayed encounters with general lack of familiarity with the technology. Thermal battery systems are not yet routinely considered by industrial users or in policy contexts where they may be the most technically feasible and economically attractive option. Perhaps surprisingly, neither producers nor consumers expressed that major technical breakthroughs are needed to demonstrate viability, though deployment experience and economies of scale are needed to bring down costs.

Instead, producers and customers highlighted traditional electricity rate structures and arrangements as the most critical barrier to large-scale thermal battery deployment. Though the specifics of the barriers cited differ in each context, the generalized problem is that traditional rate structures can inhibit market uptake. For example, cost-effective thermal battery deployments can be prevented if:

- Current regulations prohibit a willing buyer and seller to arrange for privately-negotiated self-supply in both off-grid and grid-delivered renewable arrangements.

- For grid-connected or partly-grid-connected projects, applicable retail rates were developed in a way that does not consider the specific capabilities of a thermal batteries to avoid consumption at times that would impose costs on utilities and the grid (and so the rates will tend to apply unrelated costs to customers electrifying with thermal batteries).

- Thermal battery resources are unable to engage directly with wholesale power markets and prices, which can enable them to offer greater value to the grid and reduce the net delivered cost of heat to customers.

Interviewees also highlighted examples of innovative utility rate structures that provide strong examples of modern rate structures that are aligned with the cost causation principles described in Section III.D above and therefore can enable thermal battery systems to deliver benefits to customers and the broader power grid. One example is the Vermont Electric Cooperative, which has a specific rate structure available for "Specific Use Dynamic Pricing Rate" customers, which is tied to underlying system costs such as wholesale energy and capacity prices (consistent with time of use), local transmission and distribution costs (aligned with local system peak demand), and other ISO charges passed through in alignment with costs incurred.[30] Another example is a tariff offered by Victory Electric Coop in Kansas for industrial customers that is aligned with wholesale power prices, consumption during system coincident peak demand, and other (smaller) cost components, including local delivery charges.[31]

Consistent with our findings in the previous section, we anticipate that large-scale thermal battery deployment will be substantially diminished compared to its total cost-effective potential until these barriers are addressed and industrial heating customers are able to fully access renewable thermal supply at its direct cost and accounting for net costs after providing grid balancing services.

TABLE 2: BARRIERS TO ACCELERATED THERMAL BATTERY DEPLOYMENTS & ASSESSMENT OF OUTLOOK FOR RESOLVING BARRIERS

	Barriers to Thermal Batteries	Assessment of Outlook
Technical Barriers	• Commercially available technology not currently above 750 °C (covers 75% of industrial heating needs in the U.S.) • Each site has specific technical characteristics and heating requirements, requiring customization to site needs	Positive Outlook. • Temperatures up to 1,800°C by 2030 (high enough to serve all customer heating demands) • Many sites can readily "plug in" thermal batteries into existing steam or other working fluid systems to deliver heat • No interviewees cited concerns with space limits, safety, or infeasibility (all were asked)
Customer Awareness & Readiness	• Industrial consumers are not generally familiar with thermal batteries • Companies that have historically used gas as the primary fuel source may not have internal expertise with electricity markets/rates and power supply planning	Positive Outlook. • More industrial companies seek opportunities to decarbonize, with few clean energy supply options cost-competitive vs. natural gas • Industrial customers have sophisticated engineering teams that can readily assess and understand thermal battery technology • Phased and modular renewable thermal battery deployments can be used to gain familiarity
Policy Barriers	• Policymakers are not yet aware of renewable thermal batteries & potential benefits • Most economic planning studies and environmental policies have not considered thermal battery heating supply	Enabling Reforms Needed. • Policy structures would need to be updated to qualify thermal batteries on a level basis with other GHG abatement options, to enable uptake when thermal batteries are the most cost-effective option

[30] See "Schedule of Electric Rate and Rules and Regulations Governing Service," Vermont Electric Cooperative, Inc., Service Classification #5: Specific Use Dynamic Pricing Rate.

[31] See "Schedule of Tariffs", The Victory Electric Cooperative Association, Inc., Schedule 16-STR: Sub-Transmission & Transmission Level Electric Service 34.5 kV.

	Barriers to Thermal Batteries	Assessment of Outlook
Economic Barriers	• Renewable resource costs still exceed the cost of natural gas in many regions of the US • Thermal battery costs reflect early commercialization stage; have not yet achieved cost reductions from scale or deployment experience • Competitive pressure in commodity businesses limits ability to consider any expenditures for green premium	Positive Outlook. • Raw materials for thermal batteries are low cost and abundantly available. Costs are projected to decline with deployment experience • Declining renewable resource cost (and increasing fossil + emissions cost) will improve business case over time in more regions
Rate Structures and Retail Arrangements	Barriers differ substantially by state and utility region; one or several of the barriers apply across most of the US: • Bilateral contracts for renewable and thermal battery self-supply (between industrial site and renewable electricity producer) are not allowed (or are only allowed in on-site configurations or if additional fees are applied) • Customers with thermal batteries are not able to directly access wholesale power prices • One or more rate components calculated in a fashion not tied to cost causation, such as on volumetric (\$/MWh) basis, based on individual customer peak demand (\$/kW based on individual peak monthly hour), or based on a "typical" industrial consumption profile. All of these rate structures inflate costs to industrial customers with thermal batteries • Rate components applied that are not relevant for newly electrified customers (e.g. regulatory transition charges, or legacy generation investment costs)	Critical Barrier: Enabling Reforms Needed. • Industrial suppliers and consumers alike cited electricity rate structures as the most critical barrier preventing the uptake of thermal batteries • Thermal battery configurations with sound underlying economics (renewables + thermal battery cost below the cost of natural gas) will not be pursued if rate structures introduce excess costs
Wholesale Power Markets	• Lack of access to wholesale power prices for renewable + thermal batteries systems (particularly for any net purchases) • Lack of defined participation model for thermal batteries as an ISO/RTO controllable demand resource • Transmission and other demand charges not always aligned with cost causation (may impose excess costs for thermal battery customers, even if never drawing from the grid in cost-driving hours) • Renewable projects are delayed in grid interconnection queues (limiting options for grid-delivered configurations)	Critical Barrier: Enabling Reforms Needed. • Current wholesale market structures may accommodate cost-effective use of net-to-grid thermal battery systems, but will not accommodate the most beneficial two-way grid connected and grid-delivered configurations • Specific participation model for thermal batteries (similar to participation model for electric-to-electricity batteries) needed to activate thermal battery systems for maximum grid benefit

V. Detailed Recommendations

To address the barriers to entry described in Section IV above, we offer a series of recommendations for industrial heat consumers, state policymakers and utility commissions, and for updating wholesale power market structures.

A. Recommendations for Users of Industrial Heat

All companies that deploy heat for industrial processes are potential users of thermal battery systems, even though this technology has not historically been widely utilized. We recommend that these companies:

- **Invest time to understand thermal batteries** and how they could be used to electrify heating demand. In particular, we recommend that companies prioritize considering thermal batteries if:
  - Heating needs are in any range from low or up to 750 °C (1,380 °F) today, or up to 1,800°C (3,300 °F) available in the near future 2025 - 2030;
  - Corporate commitments, consumer sentiment, or public policies are anticipated to require partial or full decarbonization of current energy supply (or may impose substantial costs for continued emissions);
  - The industrial facility is in a region with abundant renewable resource potential or has low *2 to 8-hour-off-peak* wholesale power prices (see maps in Section III.B);
  - The industrial facility faces high costs from fossil fuels; and/or
  - The industrial facility is exposed to risks associated with current fossil fuel supply, such as pricing risk, fuel availability and delivery risk, or safety risks that could be eliminated by switching to renewables as the primary energy source.
- **Conduct head-to-head economic analysis** to determine if a thermal battery system is cost-competitive with current fuel supply on the basis of: (a) cost per unit of delivered heat; and/or (b) cost per tonne of GHG emissions avoided. We recommend conducting an analysis that is sufficiently robust to consider the unique economic advantages of thermal battery systems and how those may apply differently to the particular configurations of each industrial facility and region of the country. A robust economic analysis of renewable thermal storage should consider:
  - *The capital cost of the thermal battery* system. Similarly, the avoided capital and fixed costs of a traditional boiler system should be accounted for but will not typically drive the economics if the boiler system is already in place;

- *The levelized cost of primary energy supply from renewable resources* that can be secured by self-supply or power purchase agreement.
- *The cost differences for alternative configurations* including islanded, net-to-grid, two-way-grid connected, thermal battery only, and grid-delivered renewable thermal battery systems, to the extent that all of these arrangements are enabled in the applicable utility region.
- *Optimizing the size of the renewable electricity and thermal battery system* to balance the potential costs of overbuilding the renewable system relative to heating demand, versus the costs of making net grid purchases or using gas fuel as a backup if the renewable electricity system is under-built. If a partially-grid-connected, two-way grid-connected system, or through-grid renewable delivery configuration can be considered, the net costs of over- or under-building the renewables will be much smaller than in a fully islanded, off-grid system.
- *Optimizing the schedule of thermal storage charging, net grid sales, and net grid purchases* relative to wholesale power prices and applicable retail rate structures. We stress that the "sticker price" or average $/MWh retail industrial power rate should not be used in this analysis, particularly in any states or utility regions where modern rate structures have been adopted.

- **Work with local utilities and state policymakers to adopt modern rate structures** that reflect underlying power system economics (see more detail below). This may be particularly important for large industrial customers with compelling economic or emissions advantages from electrifying via thermal batteries, but where current rate structures limit the ability to access these benefits. We observe that industrial customers are often able to participate in utility pilots that implement experimental rates and recommend that companies pursue this to help establish evidence of success for both parties.

B. Recommendations for Policymakers and State Public Utility Commissions

All states should consider the potential benefits of renewable thermal battery systems and enable customers to access these benefits. Even if a state has not adopted any specific climate commitments, it may realize economic and employment benefits by ensuring that its industrial sector has the option to pursue cost-competitive electrification and decarbonization when there is a compelling business case. For states aiming to achieve strong climate commitments, enabling thermal batteries is even more important given the lack of other low-cost solutions for decarbonizing industrial sectors and balancing the grid with fewer fossil plants. We recommend that state policymakers and public utility commissions:

- **Gain familiarity with thermal batteries** and the technology's potential benefits, including:

  - Decarbonizing the industrial sector;
  - Offering cost-competitive energy supply to key economic and employment segments (with energy costs hedged against global fossil fuel prices and GHG emissions costs); and
  - Providing grid-balancing services in regions with high renewable penetration.

- **Consider renewable-powered thermal batteries as a qualified technology solution** that can be considered equally alongside other alternatives in all state and federal policies and processes including:
  - Planning studies examining economy-wide and grid decarbonization pathways; and
  - Financial support mechanisms for deploying thermal batteries, particularly those focused on GHG abatement and beneficial electrification at the state and federal level.

- **Adopt modern industrial electricity rate structures** that are closely tied to cost causation and that can allow industrial facilities and the power grid to access the benefits of thermal battery systems, considering the approaches adopted by other utilities that have already adopted similar rates.[32] Specifically:
  - Enable thermal battery resources to directly access wholesale power prices (locational marginal prices), to incentivize optimal scheduling of net renewable power injections and net withdrawals for thermal charging;
  - Ensure that industrial customers can engage in bilateral self-supply of renewable thermal battery systems, whether in off-grid, semi-grid-connected, or grid-delivered arrangements;
  - Update transmission and distribution system rates to align with cost causation, such as by applying demand charges based on consumption during annual or seasonal system coincident peak hours (not based on volumetric rates or based on the individual customer's monthly peak usage);
  - Do not apply legacy system or restructuring transition charges to industrial customers that are newly electrifying via thermal battery systems (considering that these legacy costs were not incurred on their behalf, and applying these charges may prevent go-forward electrification decisions); and
  - For other rate- line items not driven by cost causation (e.g., social benefits charges or low-income assistance), ensure that the intended policy benefit is relevant and is not outweighed by the potential for such charges to discourage go-forward thermal electrification decisions.

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[32] As two tariff structures that offer relevant examples, see: (1) "Schedule of Electric Rate and Rules and Regulations Governing Service," Vermont Electric Cooperative, Inc., Service Classification #5: Specific Use Dynamic Pricing Rate; and (2) "Schedule of Tariffs", The Victory Electric Cooperative Association, Inc., Schedule 16-STR: Sub-Transmission & Transmission Level Electric Service 34.5 kV.

C. Recommendations for Wholesale Power Markets

Wholesale power markets are increasingly facing the challenge of how to cost-effectively manage net supply variability and uncertainty in regions with high levels of renewable resource penetration. These challenges are more acute for power markets that are dealing with retirements of fossil power plants to align with state policy goals. Thermal batteries offer a clean resource that is perhaps uniquely well suited to assist in managing grid variability and uncertainty. We recommend that wholesale market operators and the Federal Energy Regulatory Commission (FERC):

- **Understand the technical potential of thermal batteries to provide grid-balancing services** and ensure that these resources can be activated by the bulk power system when cost effective. Compared to renewables as a stand-alone resource or other industrial consumers without thermal batteries, thermal battery systems can:
  - React to power control signals on a short timescale (on the order of a few seconds to 3 minutes);
  - Be a net consumer of electricity (when charging the thermal battery) or a net producer of electricity (by allowing renewable supply to be injected into the grid rather than to charge the thermal battery), with a high degree of flexibility and control on the precise level and timing of net injections/withdrawals;
  - Operate on a pre-scheduled basis or react to short-term signals to maximize grid value (these changes to net electricity charging/discharging schedules do not affect the ability to serve heat to industrial customers, as long as the thermal battery remains sufficiently charged on a daily basis); and
  - Provide most or all defined ancillary services to grid operators, as long as the services are defined in a technology neutral fashion that considers the unique characteristics of thermal batteries and co-located renewable+thermal battery systems.[33] For example, thermal batteries can provide ramp-up, regulation-up, 10-minute, and 30-minute services by stopping or cutting back on any net grid purchases in response to an ISO/RTO control signal, or by routing co-located renewables to provide net grid injections rather than charging the thermal battery. Ramp-down and regulation-down services can be provided in the opposite fashion (by beginning or increasing thermal battery charging in response to an ISO/RTO control signal).
- **Develop viable participation models in wholesale power markets** for thermal batteries under alternative configurations. Similar to the role and outcomes of FERC Order 841 and 2222 pertinent to electricity-to-electricity storage and distributed resources respectively,

[33] Examples of the types of ancillary services that thermal battery systems can provide include offline (i.e. 30-minute) reserves, online (i.e. 10-minute) reserves, 5-30 minute ramp-up/ramp-down services, and multi-hour standby reserves. In general, the shortest-response reserves are the most valuable and scarce to the grid operator.

we recommend that the FERC and RTO/ISOs undertake market rule updates to enable thermal battery resources to fully participate in wholesale power markets.[34] The enhancements would:

- Ensure that thermal batteries can fully participate in all energy, capacity, and ancillary service markets on a level basis, consistent with technical properties and demonstrated capability to provide each service;
- Contemplate distinct participation models for: (a) stand-alone thermal batteries as controllable demand; (b) co-located renewable electricity and thermal battery systems that can be scheduled to make net injections or withdrawals from the same interconnection point; and (c) grid-delivered renewable electricity and thermal battery systems;
- Enable all resources above a defined size, such as the 0.1 MW minimum size threshold applicable to electric batteries;[35]
- Enable thermal batteries to access wholesale energy prices, selling net injections to the grid (or purchasing net withdrawals) at the same locational marginal price available to generation resources and electric batteries; and
- For the purpose of net power withdrawals, treat thermal batteries and electric batteries in the same fashion by eliminating transmission charges whenever the resource has been dispatched by the ISO to provide a bulk system service.[36]

- **Update transmission and other charges to align with cost causation.** To the extent that transmission charges or other charges are applied to customers, ensure that these are applied in a fashion that aligns with cost causation. In particular, for transmission costs or other charges that are driven most directly by consumption during system peak hours, apply these charges based on consumption during system peak hours (not based on the customer's individual peak demand nor based on a flat volumetric rate). This rate structure will ensure that thermal battery resources have the incentive to avoid net withdrawals in these hours.

[34] FERC, 162 FERC ¶ 61,127, Order No. 841, 2020.
FERC, 172 FERC ¶ 61,247, Order No. 2222, 2020.

[35] FERC, 162 FERC ¶ 61,127, Order No. 841, 2020, p. ii.

[36] "Therefore, we find that electric storage resources should not be charged transmission charges when they are dispatched by an RTO/ISO to provide a service because (1) their physical impacts on the bulk power system are comparable to traditional generators providing the same service and (2) assessing transmission charges when they are dispatched to provide a service would create a disincentive for them to provide the service." FERC Order 841, p. 192.

List of Acronyms

BTU	British Thermal Unit
C2ES	The Center for Climate and Energy Solutions
CapEx	Capital Expenditures
CDP	CDP (formerly The Climate Disclosure Protocol)
CO_2e	Carbon Dioxide Equivalents
ESG	Environmental, Social, and Governance
FERC	Federal Energy Regulatory Commission
GHG	Greenhouse Gas
ISO	Independent System Operator
kW	Kilowatt
LMP	Locational Marginal Price
MMBtu	Million British Thermal Units
MMT	Million Metric Tonnes (Note: one tonne is equivalent to 1,000 kg)
MWh	Megawatt Hour
MWh_{th}	Megawatt Hour Thermal
PPA	Power Purchase Agreement
REC	Renewable Energy Certificate
RTC	Renewable Thermal Collaborative
RTE	Round-Trip Efficiency
RTO	Regional Transmission Organization
R&D	Research and Development
SPP	Southwest Power Pool
TES	Thermal Energy Storage
T&D	Transmission and Distribution
US	United States

Appendix: Detailed Assumptions and Results

The following tables provide a detailed summary of input assumptions and results of the economic examples presented in Sections III.C and III.D.

TABLE 3: GENERAL MODELING ASSUMPTIONS

Model Input	Value
Location	Region in western SPP with average LMP of \$27.60 that is negative 20% of the time.
Renewable Profile	SPP
Renewable Resource	Wind, 47% capacity factor
CapEx:	\$57.5/kWh_{th}
Resistive Heating Efficiency	95%
Thermal Storage Efficiency	98%
Thermal Conversion Efficiency	99%
Natural Gas Boiler Efficiency	85%

TABLE 4: SCENARIO-SPECIFIC MODELING ASSUMPTIONS AND RESULTS

	Unit	Scenario 1: Gas Heat	Scenario 2: Off-Grid Thermal Battery	Scenario 3: Net-to-Grid Thermal Battery	Scenario 4: Two-Way On-Site Thermal Battery	Scenario 5: Grid-Powered Thermal Battery	Scenario 6: Legacy Rate Structure	Scenario 7: Modern Rate Structure
Inputs: Thermal Battery Configuration								
Average Industrial Demand	MW_{th}	1	1	1	1	1	1	1
Thermal Capacity	MWh_{th}	-	24	24	24	24	24	24
Charge Rate	MW	-	2.50	3.50	3.50	6.00	6.00	6.00
Renewable Resource	-	None	Wind	Wind	Wind	Wind	Wind	Wind
Renewable Resource Size	MW	-	2.50	3.50	3.50	2.40	2.40	-
Inputs: Thermal Battery Costs								
CapEx	\$/kWh_{th}	-	\$57.5	\$57.5	\$57.5	\$57.5	\$57.5	\$57.5
Levelized Cost of Electricity	\$/MWh	-	\$23.19	\$23.19	\$23.19	-	-	-
Average Cost of Heat	\$/MWh_{th}	\$34.6	\$37.6	\$29.1	\$23.6	\$14.7	\$94.8	\$22.5

Note: Modeling assumptions reflect the outlook for 2030 operating conditions of thermal batteries, based on communication with technology providers.

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