Industrial Thermal Batteries

Decarbonizing U.S. Industry While Supporting a High-Renewables Grid

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EXECUTIVE SUMMARY[i,ii]

The power and transportation sectors tend to dominate headlines when it comes to cutting greenhouse gas (GHG) pollution, but we need to tackle a large and growing emissions source to hit our climate goals: industry. Industrial processes—such as steel, cement, and chemical production—are projected to be the United States' largest source of emissions by 2030.

While fossil fuels are currently used to generate almost all the heat needed in these processes, technological solutions like industrial thermal batteries and heat pumps can provide this heat while powered by clean energy. With the right policy support, we can economically scale up these technologies while cutting climate pollution at the speed and scale necessary to reach our emission reduction targets.

Thermal batteries, also called heat batteries, convert electricity into heat, store the heat for hours or days, and release it when the energy is needed. The battery consists of a large quantity of thermal storage material, such as graphite, enclosed in an insulating shell that minimizes heat loss. Wires connect to electrical resistance heaters inside the battery, which convert the electricity to heat. When the heat is needed, it can be extracted by pumping a gas through the storage material and into the industrial facility or by opening shutters in the battery's outer casing, emitting visible and infrared light. The battery can deliver heat at 1,500 to 1,700°C, hot enough to meet at least 93 percent of the industrial heat demand that is currently supplied by combustible fuels.

Thermal batteries can provide reliable heat at $35 to $62 per megawatt-hour (MWh) of thermal output, bringing the costs of producing heat from electricity down to a level that is competitive with continuing to operate existing natural gas equipment. The technology can theoretically displace an extremely large share of fossil fuels, likely on the order of 11,600 petajoules (PJ) per year in the U.S., or 75 percent of industrial non-feedstock energy demand.

Thermal batteries can be used in off-grid or grid-connected applications. An off-grid thermal battery enables an industrial facility to turn inexpensive wind and solar power into reliable, 24/7 heat. A grid-connected battery charges in hours when electricity prices are low, enabling the industrial facility to avoid buying electricity in hours when prices are high. An additional benefit of grid-connected batteries comes from their flexibility, which helps utilities balance the electric grid, integrate renewables, and avoid costly electric grid upgrades.

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[ii] Cover image: Detail of carbon blocks in Antora Energy's thermal batteries. Photo credit: Jason Augustine. Used with permission.

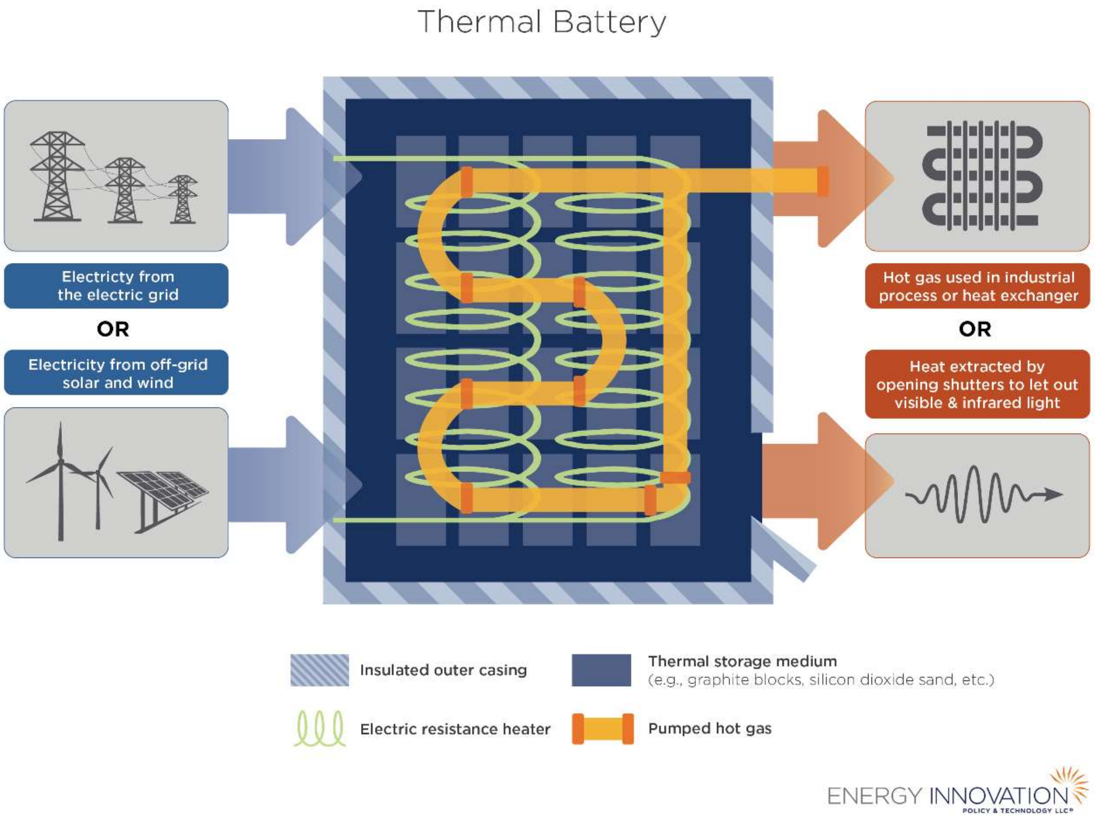

Figure ES1. Diagram of an industrial thermal battery.

Accelerating adoption of thermal batteries requires smart policy. State and local governments can offer incentives to industries that build or retrofit facilities with thermal batteries in their communities, and the federal government should allocate funding through the U.S. Department of Energy's (DOE) Industrial Efficiency and Decarbonization Office, Office of Clean Energy Demonstrations, Advanced Energy Project Credit, and Advanced Industrial Facilities Deployment Program. Additionally, the IRS should confirm thermal batteries' eligibility for the Advanced Manufacturing Production Credit (45X). Finally, policymakers can improve industrial firms' access to low-cost financing for thermal batteries through direct loans, co-lending, loan loss reserves, and loan guarantees through DOE's Loan Programs Office, as well as through state and regional green banks.

Policymakers should also help utilities and electric grid operators facilitate thermal battery deployment by establishing an electric rate class for highly flexible loads, ensuring grid access charges fairly reflect the value thermal batteries provide to the grid, and removing structural barriers to their deployment.

For the country to meet its emission reduction goals, federal and state policymakers must act to usher in a new clean energy era. With the right policy environment, thermal batteries can promote clean and competitive U.S. industry and enhance domestic technological leadership while reducing conventional and GHG pollution from industrial fossil fuel combustion. Policymakers should seize this opportunity to invest in U.S. manufacturing in a way that promotes public health and contributes to the country's climate goals.

Contents

THE CHALLENGE OF INDUSTRIAL ELECTRIFICATION

Industrial facilities produce the materials and products we rely on every day, such as metals, plastics, vehicles, and consumer goods. Many of these production processes are energy intensive. As a result, industry is a major source of GHGs. In 2020, fossil fuel combustion in U.S. industrial facilities emitted 727 million metric tons of carbon dioxide (CO_2), roughly a fifth of total U.S. CO_2 emissions.[1] The vast majority of these fuels (84 percent) are burned to provide heat for industrial processes, such as heating materials, melting metals, and driving chemical reactions.[2] Therefore, the central challenge in transitioning to clean and sustainable industry is to provide zero-emission industrial process heat.

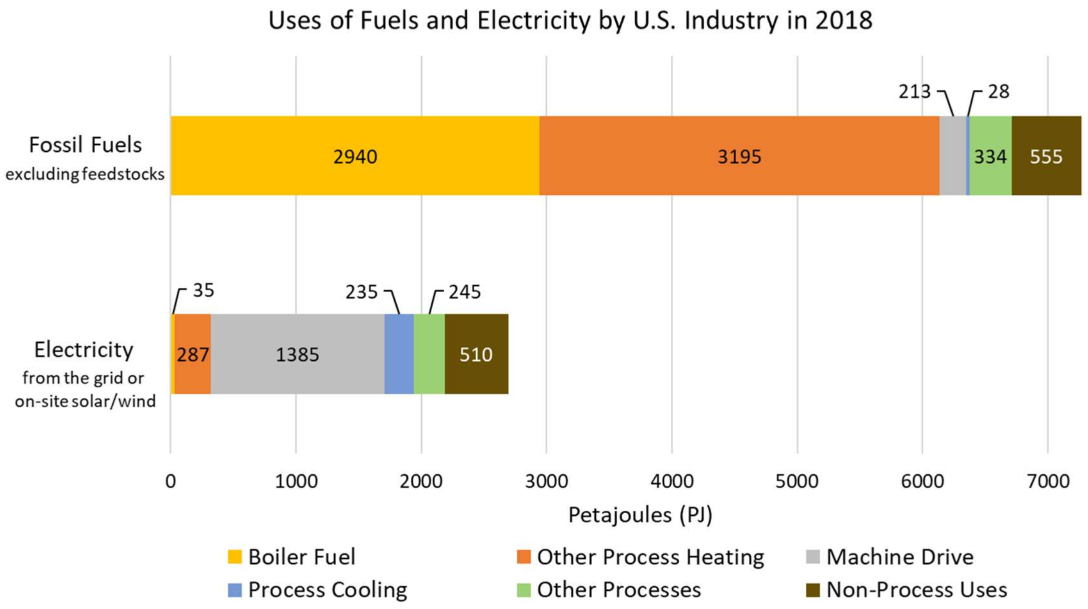

Figure 1. Uses of fuels and electricity by U.S. industry in 2018 (in PJ), excluding feedstocks and energy for which the fuel type and end use were not reported.[2]

Electricity has the potential to provide industrial heat that is clean and efficient. Compared to burning combustible fuels, direct use of electricity reduces heat losses when transferring heat to the product or material being processed, primarily because avoiding combustion means no hot exhaust gases or water vapor are formed. Additionally, at temperatures up to about 165°C,[iii] electrical heat pumps unparalleled efficiency, as they are capable of delivering several times more thermal energy than they consume as electrical energy.[3] Despite these efficiency benefits, only

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[iii] Though heat pumps capable of 165°C output have been commercialized, 80 to 100°C is a more common upper threshold for commercial and industrial heat pumps on the market today.

about a quarter of U.S. non-feedstock[iv] industrial energy use consists of electricity, and electricity's share of process heating (including boiler fuel and other process heating) is only 5 percent (Figure 1).

There are two primary reasons why electricity is not more widely used to replace fossil fuels in existing industrial process heating: ease of replacement and electricity costs.[v]

Ease of Replacement

Many electrical technologies already exist commercially for process heating in specific applications or industries. These include heat pumps, electrical resistance heating, electromagnetic induction, electric arcs/plasma torches, dielectric heating (radio wave or microwave heating), infrared heating, lasers, and electron beams. These electrical technologies cover the full spectrum of industrial temperature requirements.[vi]

In some cases, electrified equipment can be a drop-in replacement for fossil fuel equipment, such as substituting an electric boiler for a fossil fuel boiler (though increased electricity demand may necessitate upgrades to distribution lines, transformers, and other electrical equipment serving an industrial facility).[4] In other cases, such as heating a cement kiln using electrical plasma torches,[5] engineering development is needed to adapt the electrified technology to a new industry. Achieving the greatest possible efficiency may sometimes require reconfiguration of industrial production lines. For instance, instead of swapping a fossil fueled boiler for an electrified boiler, greater efficiency might be achieved by replacing the entire steam distribution system with an electrical technology that applies heat directly during specific processing steps.

Heat pumps, a promising option due to their exceptional efficiency, can only provide heat today at temperatures up to about 165°C, encompassing 27 percent (Figure 3) to 35 percent[3] of U.S. industrial process heat demand. Due to this web of considerations, switching to electrified industrial equipment is not always straightforward. To commit to electrification, industrial firms may demand energy cost savings. For higher-temperature applications where heat pumps are not practical, unlocking demand for electrified industrial heating equipment will require extra effort in addressing the issue of electricity costs.

[iv] Feedstocks are fuels that are chemically transformed to make up part the output product, such as petroleum used in the making of plastics, in contrast to fossil fuels that are burned for energy.

[v] Other reasons also exist, such as businesses' reluctance to change familiar processes or to pause their production lines for upgrades, but these hurdles could be overcome more readily if the energy cost and equipment availability challenges were addressed.

[vi] In fact, most of these electrical technologies (induction, electric arcs/plasma, dielectric heating, lasers, and electron beams) can achieve temperatures higher than fossil fuel or hydrogen combustion.

Electricity Costs

Today, electricity purchased from the grid costs more per unit energy than purchased natural gas or coal. In 2022, U.S. industrial buyers paid on average $25.77/gigajoule (GJ) for grid electricity, a little more than three times the price they paid for natural gas ($7.73/GJ).[6] (Coal prices for industry—$2.95/GJ to $5.73/GJ—are not directly comparable to electricity or natural gas prices because coal-burning equipment has higher capital costs and emits more particulates, which must be captured to meet air quality standards, adding capital and operating costs for exhaust treatment. Therefore, the fairest way to assess the cost-effectiveness of electrification is to compare electricity prices to natural gas prices, not to coal prices. This also reflects the reality that in the U.S., roughly 15 times more natural gas than coal is used for industrial process heating.[2])

There are several reasons why the cost gap is smaller than these prices suggest. First, fossil fuel prices are volatile: the natural gas prices noted above are three times higher than in July 2020 but only around half of what they were in July 2008.[7] This volatility makes it difficult for industrial firms to be confident in future costs when investing in equipment intended to operate for decades. (Large industrial firms sometimes secure long-term contracts, called *power purchase agreements*, to buy a quantity of electricity at a prearranged price for 10 to 25 years. In contrast, natural gas supply contracts typically last less than three years, and they tend not to be fixed-price contracts but rather use a price formula that balances risk between the gas supplier and the gas purchaser.[8])

Second, combustion processes can have substantial heat losses. For example, in a high-temperature industrial furnace, more than half of the energy in the combustible fuel can be lost in hot exhaust gases and formed water vapor.[9] Since electricity does not have exhaust gases and does not form water vapor, there is less heat loss. Therefore, less electricity is needed for an industrial process, reducing fossil fuels' price advantage.

Third, industrial heat pumps' exceptional efficiency can eliminate the price gap for low-temperature heat demand.[3]

Nevertheless, to deliver heat at temperatures greater than a heat pump can provide, electricity remains more expensive than natural gas in the U.S., absent a policy intervention such as carbon pricing or a way to avoid paying normal industrial electric rates. Fortunately, thermal batteries can make electricity and natural gas costs comparable for industrial heating, fundamentally changing businesses' decision-making around electrifying process heat equipment.

THERMAL BATTERIES

Thermal batteries, also called *heat batteries*, can decrease businesses' electricity costs by more closely aligning industrial electricity demand with output from low-cost variable renewable sources such as solar and wind—either by connecting to the renewables directly or by drawing electricity from the grid during periods when abundance of these sources suppresses wholesale prices. The first option allows for rapidly scaling industrial electrification while avoiding bottlenecks in connecting renewables to the grid, while the second helps the electric grid achieve a higher share of power from renewables by usefully modulating electricity demand at scale.

A thermal battery is a device that converts electricity into heat, stores the heat for hours or days, and releases it when the energy is needed. A thermal battery consists of a large quantity of a material with high specific heat capacity (the amount of energy required to raise the material's temperature) that will not chemically break down when heated, such as silicon dioxide[10] or graphite. This material is enclosed in an insulating outer shell that keeps heat losses to a minimum—less than 1 percent per day for some systems.[11] Wires pass through the outer shell and connect to electrical resistance heaters inside the battery, which convert the electricity to heat, warming the material inside. Today's thermal batteries can store heat at up to 1,800°C[12] and deliver output energy at temperatures up to 1,500-1,700°C.[11,13] When the heat is needed, two approaches can be used to extract the heat from the battery:

- A fluid, such as air or steam, can be pumped through the heat storage medium, where it absorbs heat. The fluid is then sent into the industrial facility, where it is used in an industrial process or heat exchanger.
- Shutters can be opened in the battery's outer casing, allowing energy to be transferred in the form of visible and infrared light emitted by the hot storage material.[14]

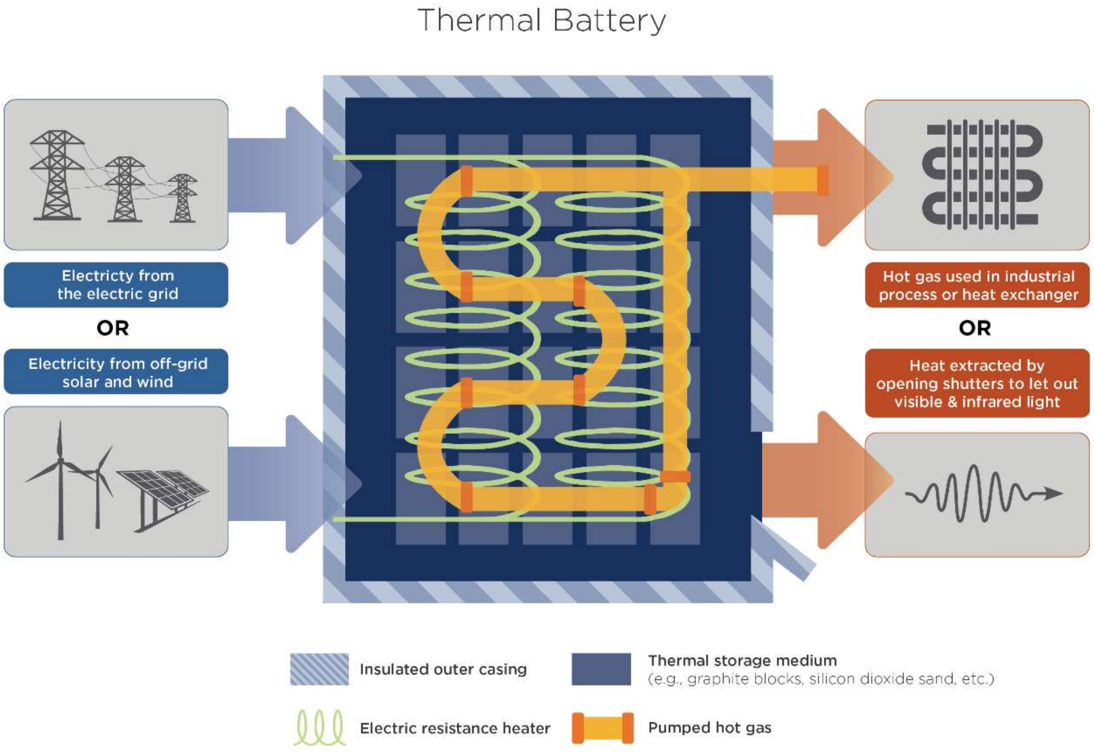

Figure 2. Diagram of an industrial thermal battery.

Heat transfer is not perfectly efficient, so the temperature inside the thermal battery must be higher than the temperature required by the industrial process. Round-trip efficiency (conversion of electricity to heat, then extraction of thermal energy from the battery) is around 95 percent.[11]

Thermal Battery Potential to Meet Temperature and Timing Requirements

Thermal batteries have the technical capability to satisfy a large share of U.S. industrial heat demand. Three quarters of industrial non-feedstock energy consumption consists of fossil fuels burned to produce heat at temperatures less than 1,000°C, primarily bulk heat delivery for applications such as boiling water to produce steam or heating equipment such as furnaces or kilns (Figure 3). Thermal batteries are well-suited to bulk heat delivery and could in theory replace almost all combustion-based sources under 1,500 to 1,700°C. A few combustion-based industrial processes do pose challenges for thermal batteries (such as primary steelmaking) or require extreme precision (e.g., oxy-acetylene welding), but these make up no more than 6 percent of U.S. industrial energy use. Therefore, the theoretical potential for thermal batteries to displace fossil fuels is extremely large, likely on the order of 11,600 PJ/year in the U.S., or 75 percent of industrial non-feedstock energy demand (Figure 3).

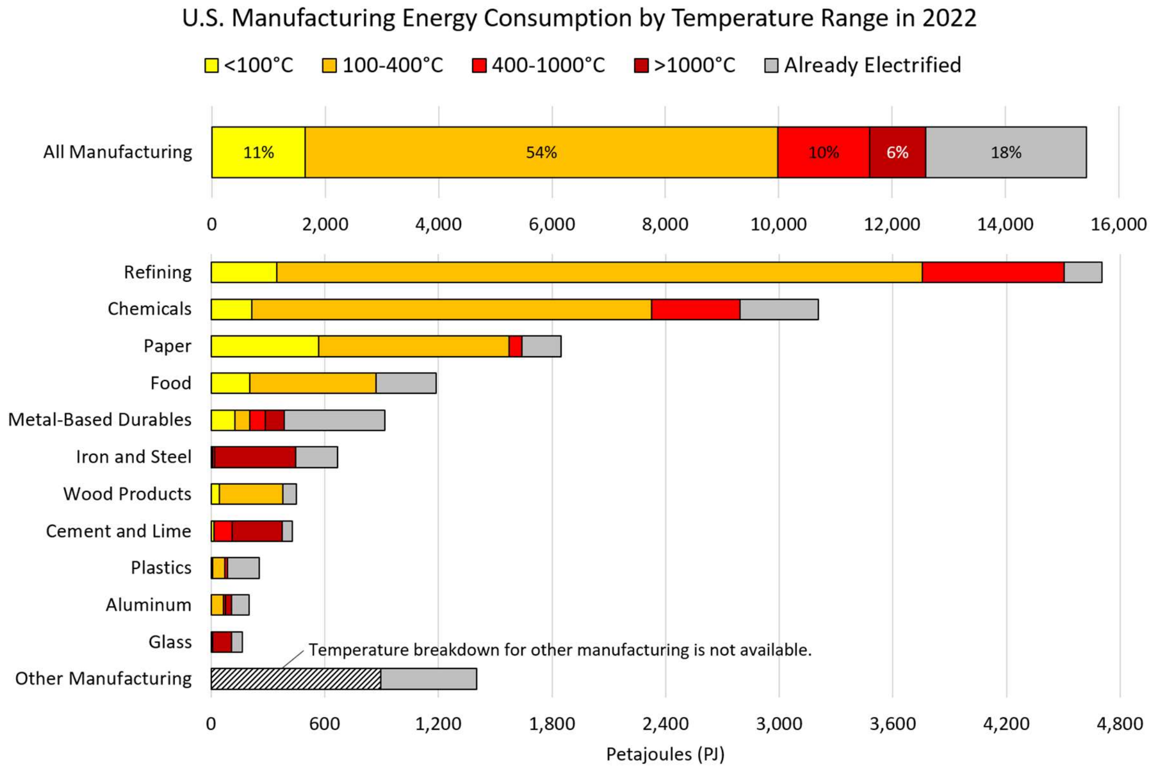

Figure 3. U.S. manufacturing energy consumption in 2022. Temperature ranges are shown for non-electrified energy use (i.e., fuel combustion), while electricity use is not broken out by temperature range (and is often used for non-thermal purposes). Feedstocks are not shown.[6,15]

Since thermal batteries are not just energy storage but also energy conversion devices, they can consume power at an input rate mostly independent of their output rate. The important variables in analyzing the potential performance of a thermal battery are:

- Price per unit of energy storage (e.g., dollars per kWh or mmBTU)
- Overall conversion efficiency from electricity to heat, which encompasses:
    - Efficiency of converting electricity to heat stored in the battery (as opposed to heat generated in electricity input equipment such as transformers)
    - Self-discharge rate, i.e., how fast heat leaks out of the battery (heat loss rate correlates with the temperature of the storage medium: losses are faster when the battery is closer to being fully charged)
    - Electricity consumption of auxiliary systems not for generating heat, such as operating blowers to move hot gases
- Thermal output power (typical steady state heat demand for an industrial facility)
- Total energy storage capacity (hours/days at which steady state demand can be served)
- Maximum input electric power as a proportion of steady state demand (i.e., how much faster does the battery charge than it discharges?)
- Cycle life (how many times can the battery discharge and recharge without too much degradation—thermal batteries typically perform well on this metric)

Different uses may optimize these parameters in different ways. Thermal batteries are typically very flexible on the input side (they can quickly adjust the power they draw to adapt to variable supply or prices on the scale of minutes). Meanwhile, the priority on the output side is heat at a rate determined by industrial needs.

Some industries, such as primary steelmakers, prefer to operate 24 hours per day because they don’t want their equipment to cool down, which would require them to reheat it every morning. Other industries operate only during daytime hours, reducing labor costs, or operate only seasonally, such as the processing of agricultural products following harvest.

Generally, industrial power demand only drops by 17 percent at night during the workweek, but it drops by 50 percent on weekends, when the longer break makes it worthwhile for more industries to power down their equipment (Figure 4). Broadly speaking, industrial electricity demand is relatively constant, especially during the workweek. Many industries (representing approximately half of industrial electricity demand) operate almost constantly, only shutting down their equipment for maintenance. Therefore, many industries need a constant supply of heat.[vii]

[vii] Data on industrial electricity consumption is available for all 8,760 hours of the year. Data on industrial fossil fuel consumption is not available with hourly time resolution. We assume the times at which industries are consuming more electricity are the hours in which they are operating, and hence, electricity demand and combustible fuel demand for process heat are correlated.

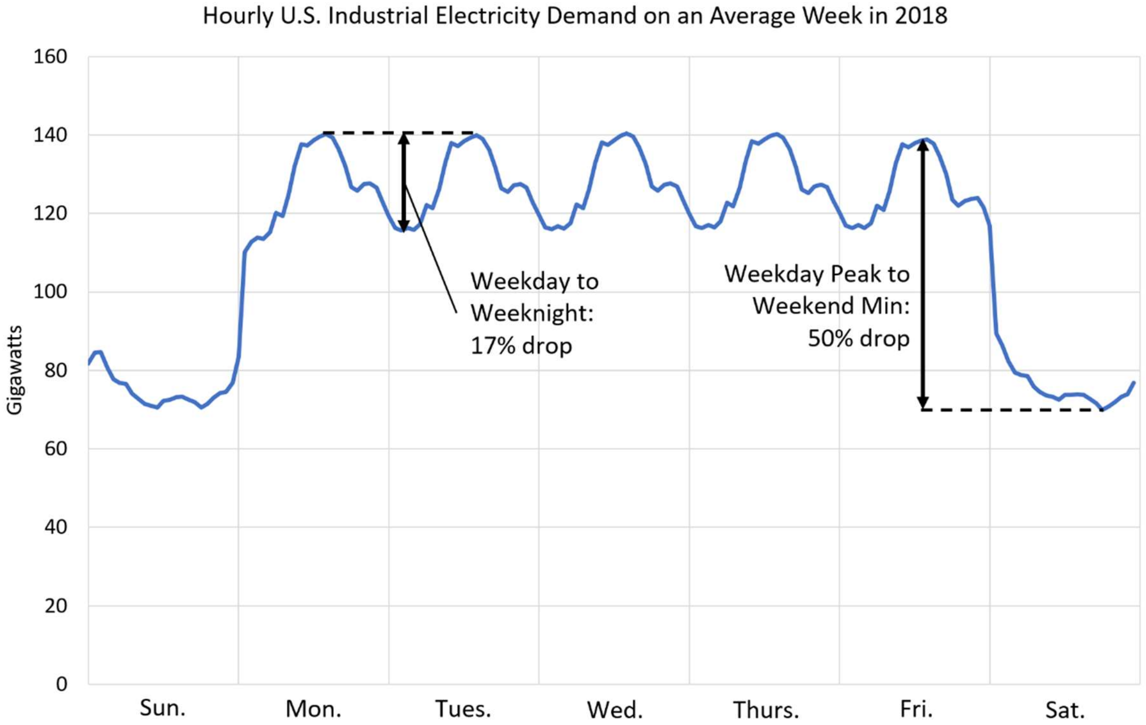

Figure 4. Total U.S. industrial electricity demand on an average week in 2018 (i.e., all weeks in 2018 averaged).[16]

Seasonally, industrial electricity needs are highest in summer, when the peak hourly demand is about 15 percent higher than in winter, the lowest-demand season. Weeknight and weekend demand follow a similar pattern, with seasonal variance of 23 percent for weeknights and 20 percent for weekends (Figure 5).

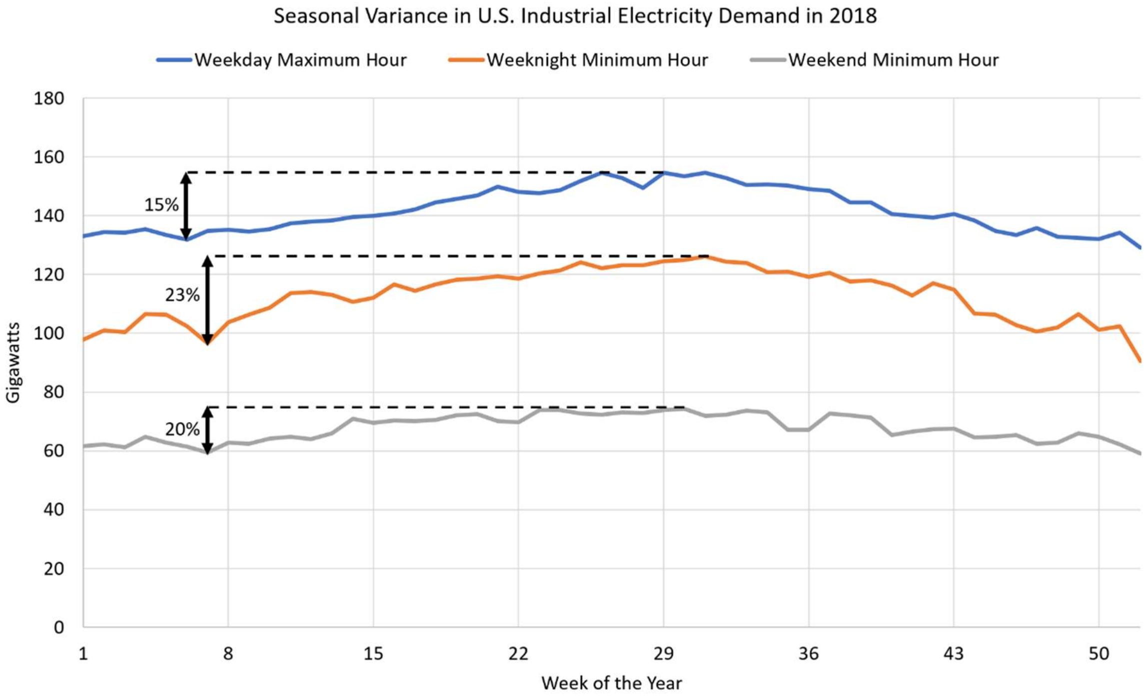

Figure 5. Seasonal variance in U.S. industrial electricity demand in 2018. For each week of the year, the maximum weekday hour, the minimum weeknight hour (Mon.-Thurs. nights), and the minimum weekend hour are depicted. Variance figures compare the highest week to the lowest week (excluding the week containing Christmas and New Years Eve, week #52).[16]

There are two principal "bookends" for how a thermal battery can provide convenient, reliable, and affordable steady state process heat for industry: "generation-following" batteries charging from captive renewable resources on one end of a spectrum of arrangements, and "price-hunting" batteries charging directly from the grid in a price-responsive way on the other end. We briefly describe each of these approaches, then provide some illustrative examples.

Generation-Following Thermal Batteries Can Take Advantage of Off-Grid Renewable Resources

Electric utilities sell electricity through the grid at retail rates, which include the cost of generation, transmission, and distribution, and may also be a means to cover the costs of public interest programs like efficiency or renewables mandates. For example, in 2021, 50 percent of large U.S. utilities' spending went toward electricity generation, while 21 percent went to paying for transmission, 17 percent for distribution, and 12 percent for other purposes (Figure 6). Wholesale electricity rates are the cost of generation only and are lower than the full retail rate.

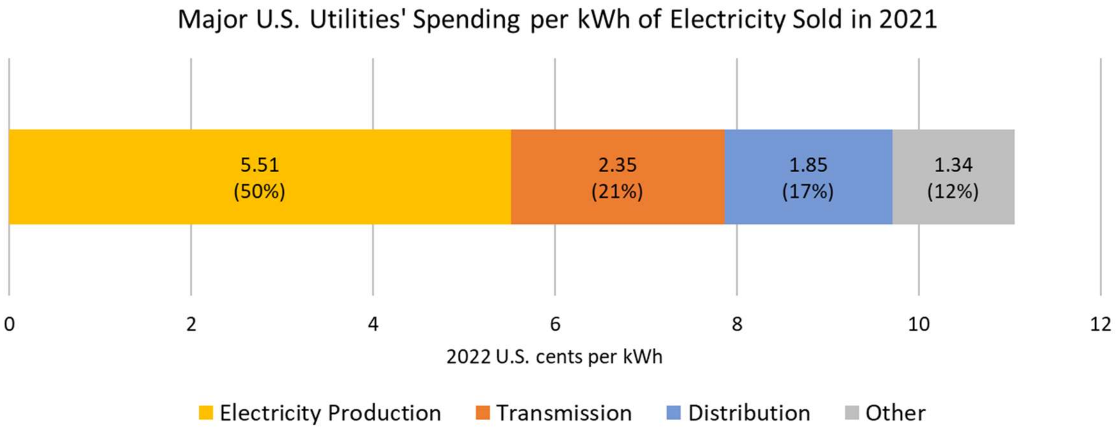

Figure 6. Major U.S. utilities' electricity-related spending, expressed per kWh of electricity sold in 2021. Electricity production expenses include the cost to build, operate, fuel, and maintain a utility's power plants, as well as to buy electricity from other generators or markets. Transmission and distribution expenses cover building, operating, and maintaining wires, poles, meters, and other electricity delivery equipment. Other expenses include general and administrative expenses, non-electrical infrastructure such as office space, and intangible goods such as licenses and franchise fees.[17]

To purchase cheaper electricity, industrial projects may choose to source their electricity directly from dedicated projects siloed from the grid, similar to a residential customer that self-supplies with rooftop solar.[viii] The cost may be even lower than the "electricity production" expenses in Figure 6, since utilities procure electricity from a variety of sources, but an off-grid industrial facility could rely exclusively on the cheapest sources—typically wind, solar, and hydro. This also enables environmentally conscious firms to exclusively procure renewable electricity rather than accepting a mix of renewable and non-renewable electricity sources from the grid. For these projects, thermal batteries can buffer and convert low-cost, variable electricity supply into steady 24/7 heat.

When an industrial project chooses to supply some or all of its own electricity, location will be a key determinant of project success. A facility's location matters tremendously in terms of the quality and diversity of resources available nearby and what type of tax credits are available. (For example, the Inflation Reduction Act provides for extra tax incentives for renewable projects built near "energy communities."[ix]) Solar energy is the easiest form of renewable electricity to procure as good resources are widely available geographically, and solar generation provides modular

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[viii] In some cases, preexisting rules may complicate off-grid projects. For example, a regulated monopoly utility might have been granted the exclusive right to transmit electricity across public rights-of-way, which would prevent an industrial firm from connecting to an off-grid wind or solar farm if the electricity line would cross a public road. For more on how to ensure existing rules do not hamper thermal battery deployment, see the "Policy Recommendations" section below.

[ix] An "energy community" is an area where a coal-fired power plant or coal mine closed since 2010, an area that receives at least 17 percent of its employment or 25 percent of its tax revenue from fossil fuel extraction and processing, or a brownfield site affected by contaminants.[18]

capacity—for example, individual solar panels are less than 1 kilowatt each, while individual wind turbines come in megawatt increments. However, wind can generate power at times when solar cannot, providing valuable diversity benefits for facilities that can access it.

In addition to the day/night cycle, both wind and solar energy supply can be affected by multi-day lulls (e.g., rainy weather). Thermal batteries can provide reliable, 24/7 heat, helping industrial facilities ride out this variability in generation. The intensity of sunlight and hours of sunlight per day vary by season, as does wind output. In some locations, average hourly supply in the summer can be more than double the supply in the winter. This means that to provide reliable power in the winter, a larger number of solar panels would need to be installed, which would result in producing more electricity in the summer than is needed for the industrial facility. A thermal battery lessens the need for excess summer renewable generation capacity.

Finally, using a dedicated low-cost variable renewable energy supply to charge a generation-following thermal battery can provide two major, additional benefits. First, since there is no need to purchase fossil fuels (and the capital costs of wind and solar are known upfront), using dedicated wind and solar provides predictable energy costs. This protects industrial firms from high volatility in electricity and fossil fuel pricing, providing cost certainty that can facilitate cost-effective investments and long-term business decisions. Second, in a jurisdiction with mandatory emission reduction goals, or for companies with voluntary ambitions to procure clean energy, a dedicated supply comes with unimpeachable credentials for a clean emissions profile.

Price-Hunting Thermal Batteries Could Take Advantage of Electricity Price Variability

Not all facilities may choose to procure their own electricity supply, especially if their location is fixed and they have no attractive supply options nearby. Fortunately, such a facility can still take advantage of a thermal battery if it has access to industrial rates that include variable electricity pricing.

In most electricity markets, wholesale prices are not constant throughout the day. In some markets, they can vary several orders of magnitude from hour to hour and are sometimes even negative.[x] In general, the cost of electricity varies based on total electricity demand, available supply, and certain other factors, such as congestion in electricity transmission lines. The greater the share of variable generation (such as wind and solar) in the electricity grid, the greater effect of varying wind and sun conditions on electricity output and prices. At times of low demand, energy needs can be met using only inexpensive plants, such as renewables and some baseload plants. At times of high demand, utilities may need to utilize plants that can quickly ramp their power output up and down, known as "peaking" power plants. The electricity from peaking plants is costly because they are less efficient than other plants, they typically pay more for fuel, and utilities must

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[x] Negative prices refer to when electricity consumers are paid to consume electricity because this relieves electricity congestion and helps with grid management.

cover the capital and fixed operating and maintenance costs to keep the plants on standby even though they generate electricity for relatively few hours per year. These factors all contribute to hour-to-hour electricity price variance. (See the "Price-Hunting Thermal Battery Model Results" section below for an example.)

A thermal battery allows an industrial consumer to bargain hunt by purchasing large amounts of electricity in hours when electricity is cheapest, storing that electricity in the form of heat, and steadily dispensing the heat to industrial processes during more expensive hours. This can greatly lower annual electricity expenses while enabling the industrial facility to continue to operate 24 hours per day.

While a traditional lithium-ion battery could theoretically provide similar energy cost benefits, batteries that store electricity have vastly higher capital costs than thermal batteries. Lithium-ion batteries cost around $150/kWh of energy storage capacity in 2022.[19] A thermal battery, which relies on simpler components and does not require rare earth elements, costs less. The storage material may cost up to $10/kWh of storage capacity.[11] Costs for the battery's electrical input equipment and heat output equipment vary with electricity input rate and heat output rate rather than with storage capacity. However, when sized for an optimized battery (per the "Modeled Industrial Thermal Battery Examples" section below), they may add a further $17/kWh once thermal batteries are manufactured at large scale, pointing to a total battery cost around $27/kWh in the longer term (or slightly less if innovation brings down thermal storage medium costs). Therefore, thermal batteries could make financial sense for industries where chemical batteries do not.[xi]

In some regions, industries are not directly exposed to wholesale electricity prices. They may buy power at retail rates, which are higher than wholesale rates and may not vary by hour—they certainly vary less than the underlying supply and demand dynamics of the grid might warrant. Still, if the underlying tariff for power varies sufficiently over time, price-hunting thermal batteries could be cost-effective.

Since facilities with thermal batteries purchase more electricity at the times of lowest cost to the utility and less electricity when the utility faces its highest costs or needs to more closely manage its reserves, it would make sense for the utility to develop a new rate class for thermal batteries that reflects their lower cost to serve. For instance, the utility could provide lower time-varying retail rates, align flexible loads' demand charges with their contribution to coincident peaks, and/or directly pay facilities with thermal batteries for shifting their consumption.

[xi] Chemical batteries still have the advantage of returning energy directly as electricity with decent round-trip efficiency (~80 percent) and thus have other roles to play, such as supplying non-thermal energy to electric vehicles, and can also be used for grid regulation and balancing.

Key Differences Between Generation-Following and Price-Hunting Thermal Batteries

Price-hunting thermal batteries have several key differences from generation-following thermal batteries:

- Emissions Tracking: Because the price-hunting battery typically optimizes its consumption behavior around least cost, it can't easily lay claim to using only clean power. On the other hand, it helps the grid by buying power when it has the least value to other customers, and low and negative prices often occur when the cleanest resources are abundant and set the marginal price, so it likely would predominantly charge using cleaner-than-average resources. That said, a grid-connected thermal battery could be operated by targeting dual objectives of lowering cost and reducing emissions, assuming marginal emissions data are available.
- Role of Capacity/Duration: For generation-following thermal batteries, the number of days of storage is crucial for reducing the occasions on which the battery is full and excess renewable electricity goes to waste. Capacity is also crucial for providing reliable heat output. For grid-connected, price-hunting batteries, the expectation is that power is almost always available, so high capacity is not required for reliable heat output. However, a larger heat capacity improves the battery's ability to wait for low price events before charging up, reducing annual energy costs.
- Operator Choice Facing Uncertainty: For a generation-following thermal battery, once the operational parameters of the battery are commissioned, there is very little choice left for the operator: the captive renewable generation provides electricity as determined by the weather and the battery reacts accordingly. Operators may have a choice to throttle thermal output in anticipation of a lull in generation (e.g., based on an unfavorable weather forecast), but that depends on the industrial facility's needs. Meanwhile, a price-hunting battery must constantly predict what future prices will look like: should it charge now or wait for cheaper prices? If the battery doesn't charge now, will it be forced to buy power at a higher price if its state of charge gets too low? In our model, we presumed perfect knowledge of the future, so the battery could charge at optimal times. This means that our price estimates should be taken as lower bounds and that thermal batteries may need to be a bit more conservative (i.e., being willing to charge at slightly higher prices when their state of charge gets low) to ensure reliable heat output.

MODELED INDUSTRIAL THERMAL BATTERY EXAMPLES

To better illustrate the bookend scenarios described above, we have modeled the operation of a thermal battery in both generation-following and price-hunting modes. In both cases, the battery has three main sources of capital costs: electricity input equipment (wires, switches, transformers, etc.), equipment for delivering heat (e.g., a heat exchanger), and the thermal storage medium. The first two costs scale with electrical input power ($/kW-in) and thermal output power ($/kW-out), while the storage medium cost scales with energy capacity ($/kWh). We model the cost of input equipment at $100/kW-in, based on the cost of similar equipment for lithium-ion batteries. We model heat delivery equipment costs at $300/kW-out, based on the costs of heat exchangers connected to today's boilers. We model average thermal battery storage medium costs at $5/kWh. Since this is the most novel and uncertain part of these batteries, we also consider a range of prices of $1.5 to $10/kWh, based on estimates from the National Renewable Energy Laboratory and thermal battery manufacturers.[10,11] We assume round-trip efficiency of charging and discharging the thermal battery is 95 percent.[11] For battery financing costs, we use an annual capital recovery factor of 14 percent (equivalent to a 7 percent weighted cost of capital over 10 years, or 11 percent over 15 years).

For the generation-following examples, to understand how location matters, we picked two representative locations with different renewable resources: western Texas, which has high-quality wind and solar, and an area in California's Central Valley dependent solely on high-quality solar.

In the price-hunting example, we used the Texas location because price-hunting is most likely to be economically advantageous there; Texas' market design makes it easier for on-grid industrial facilities to pay for their electricity at wholesale power costs while minimizing non-energy costs. For instance, Texas industrial facilities need not pay reliability-related capacity charges,[xii] and they can also avoid some transmission charges by reducing their power consumption during the peak 15-minute period in June, July, August, and September. (There exist services that help companies predict when these peak periods are likely to occur.)[21,22] To reflect changes in renewable electricity generation and natural gas pricing over time, we examined a low-price year (2020) and a high-price year (2022) using a battery charging strategy with perfect foresight to get a sense of how the economics of the price-hunting thermal battery might change from year to year.

Wind and solar prices were modeled using data from the 2022 National Renewable Energy Laboratory's Annual Technology Baseline,[23] and solar and wind power output was modeled for each location using the Renewables.ninja tool.[24]

Resource Availability by Location

The two modeled locations' breakdowns of wind and solar capacity and electricity generation are shown below in Table 1.

[xii] Texas is implementing a new Performance Credit Mechanism that might create extra costs for industrial consumers. New legislation includes a cost cap of $1 billion that might reduce exposure for these customers if they are flexible.[20]

Location	Wind/Solar Capacity Fraction	Wind/Solar Energy Fraction
California	0/100	0/100
Texas	57/43	69/31

Table 1. Wind and solar capacity and energy (electricity generation) shares in two locations where industrial thermal batteries were modeled.

Since each location featured different weather and a different mix of wind and solar resources, they had different levels of annual variability in renewable generation. The California location, relying only on solar, had electricity output just 51 percent of its annual average in December and as much as 130 percent of the annual average from June through August. By contrast, Texas ranged from 85 to 118 percent (Figure 7).

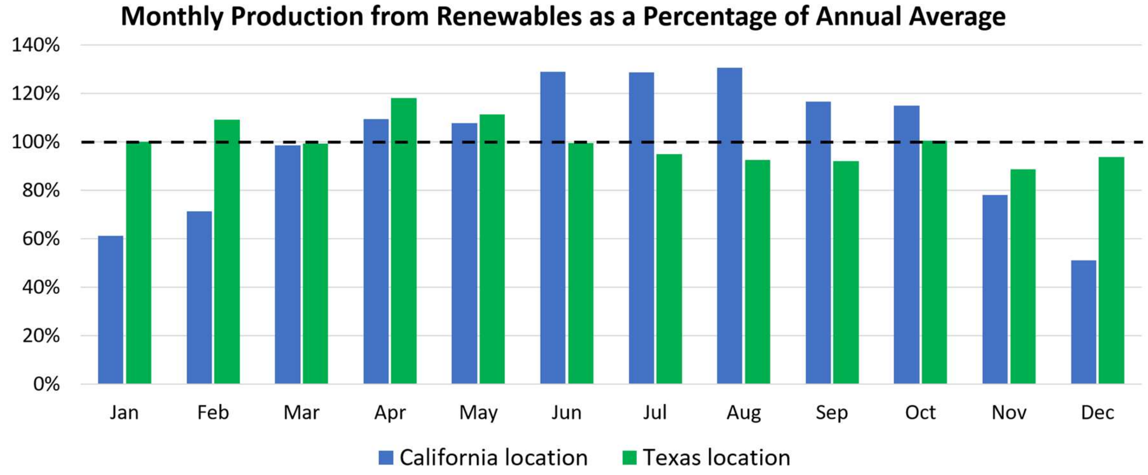

Figure 7. Monthly average renewable electricity production as a percentage of annual average (by location) in 2019.

Generation-Following Thermal Battery Model Results

Reliability and Cost Optimization

Some industrial facilities may demand extremely reliable heat output, while others may be able to tolerate occasional pauses during extended periods of low wind and solar generation. Optimizing a least-cost heat supply can involve many parameters, but for a given level of required reliability, the two main factors are the degree of renewable curtailment[xiii] and the amount of energy storage

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[xiii] The share of renewable electricity generation that can neither be stored in the battery nor used immediately by the industrial facility is its *curtailment rate*. Some curtailment is to be expected for almost any off-grid project, and projects

capacity. Both approaches increase capital costs: more curtailment implies more renewable generation capacity, while having more hours of storage necessitates a larger thermal battery. Figure 8 shows contour plots for various levels of heat battery output reliability (heat delivery during 95 percent, 98 percent, 99 percent, 99.9 percent, and 100 percent of possible hours) as a function of these two parameters.

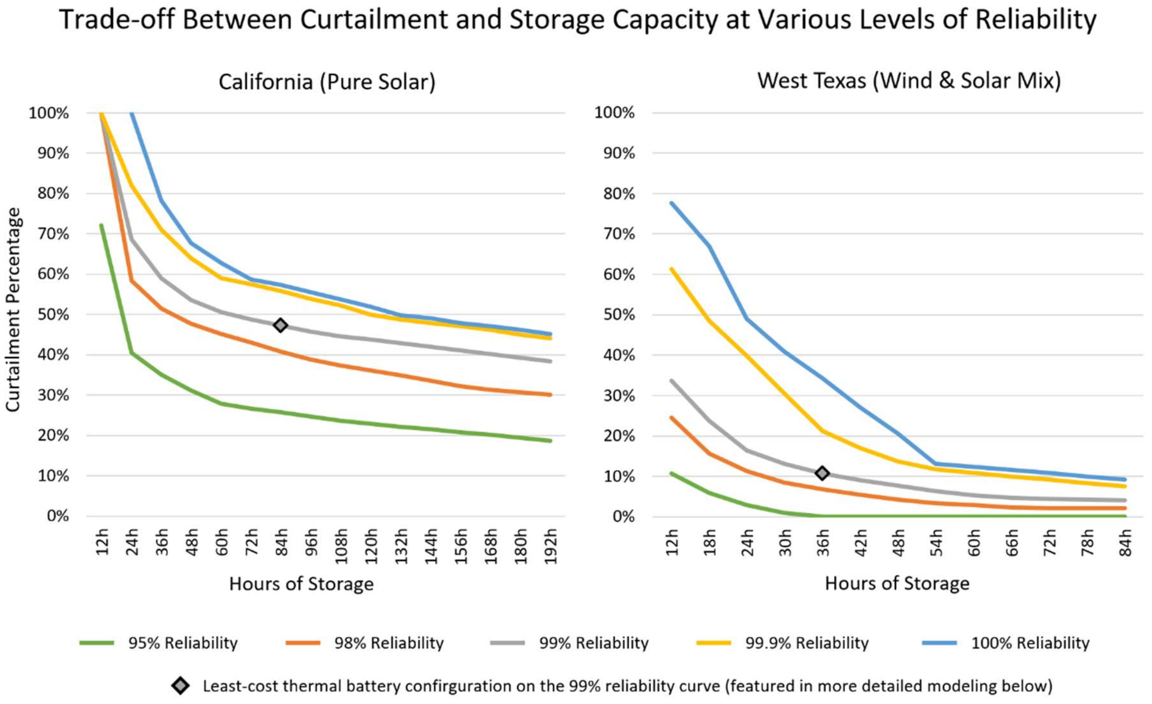

Figure 8. Contour plots illustrating the trade-off between hours of thermal battery storage capacity and curtailment rate at different levels of reliability of steady-state heat output. The least-cost point on the 99 percent reliability curve (featured in more detailed modeling below) is indicated.

All the contour lines have a concave shape, reflecting the fact that with a low number of hours of storage, extra generating capacity is needed to maintain a given level of thermal battery reliability. Increasing hours of storage capacity sees diminishing returns to reliability. The optimal price of heat supply along each curve is a function of the competing incremental cost of storage capacity (in dollars per hour of storage) and the incremental cost of curtailment (in dollars per percent curtailment). If "dollars per hour of storage" and "dollars per percent curtailment" are constants, the optimal cost solution for any given curve is the point on that curve whose tangent line has a slope equal to the ratio of these two figures (measured in percent curtailment per hour of storage).

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that curtail some electricity can nonetheless be cost-effective, depending on the cost of alternative energy supply options.

While “dollars per hour of storage” is likely to be near-constant (as amount spent and the quantity of storage medium purchased likely have a mostly linear relationship), “dollars per percent curtailment” is not constant. For example, a 10-percentage-point improvement in available capacity from 90 percent curtailment to 80 percent curtailment doubles useful electricity output per unit capacity, halving the required gross solar capacity requirement, whereas going from 10 percent curtailment to 0 percent curtailment only reduces the required gross capacity by 10 percent. To obtain a cost metric with a linear relationship, we convert the curtailment rate, C, to excess generation rate, where:

$$\text{Excess generation rate} = - C / (C - 1)$$

Excess generation rate represents the quantity of non-useful electricity produced as a share of the useful generation (i.e., electricity used to supply heat or charge the thermal battery). Since useful generation for an off-grid project is largely determined by industrial heat needs, it is relatively constant, so “dollars per percent excess generation” should be relatively constant and a reasonable metric to use for cost optimization.

An optimized cost point exists on each reliability curve. For more detailed modeling of cost-optimized battery configurations, we selected a reliability level of 99 percent. (Although industrial firms often can tolerate more than 1 percent annual downtime for maintenance, it may be undesirable for the maintenance schedule to be determined by periods of low wind and solar production, particularly if those periods are short and are clustered in winter months.) Assuming “dollars per hour of storage” and “dollars per percent excess generation” are constants, the least-cost configuration in the California location involves 89.8 percent excess generation (equivalent to 47.3 percent curtailment) and 84 hours of storage, while the least-cost values for the Texas location are 12.0 percent excess generation (10.7 percent curtailment) and 36 hours of storage (Figure 8). Curtailment and storage size values to achieve 99 percent reliability are significantly larger in the California location because its solar-only generation profile doesn’t match the desired, fixed 24/7 thermal output as well as the wind/solar mix in Texas.

Further Cost Optimization Approaches

For simplicity and clarity, the approach to cost optimization described above relies on varying only two parameters: curtailment percentage and hours of thermal storage. However, in practice, there are other strategies that can reduce the cost of reliable heat from generation-following thermal batteries beyond the “optimized” configurations modeled here. For instance:

- An industrial facility could choose to keep a small amount of fossil fuel or bioenergy onsite that could be burned in the most difficult conditions (extended periods of low solar and wind generation). For instance, a facility that is prepared to use fuel for just 2 percent of the year (175 hours, or 7.3 days) could procure a battery on the 98 percent reliability curve in Figure 8, which has lower curtailment and storage costs, while enjoying 100 percent-reliable heat output.

- Some industrial facilities do not require steady 24/7 heat and may be able to alter their heat demand to better align with the hourly or seasonal energy supply profile. Such facilities might be able to procure a thermal battery on (or below) the 95 percent reliability curve in Figure 8, substantially reducing costs.
- A facility could sell excess electricity to the grid or another consumer rather than curtailing it, an option discussed in the "Hybrid Battery Configurations" section below.

State of Charge Modeling

Another way to evaluate thermal battery performance is to consider its *state of charge*, i.e., the degree to which the battery is filled with energy. Figure 9 depicts the state of charge for the California (CA) and Texas (TX) batteries discussed above that supply industrial heat with 99 percent reliability. The high level of curtailment for the CA battery is evident from the way its state of charge saturates at or near 100 percent for most of the year. This over-saturation of the CA battery not only leads to curtailment of substantial excess energy but also increases thermal energy losses in the storage medium (since heat loss rate is proportional to the quantity of energy stored in the battery). The TX battery charges and discharges throughout the year—a more efficient utilization of thermal battery technology.

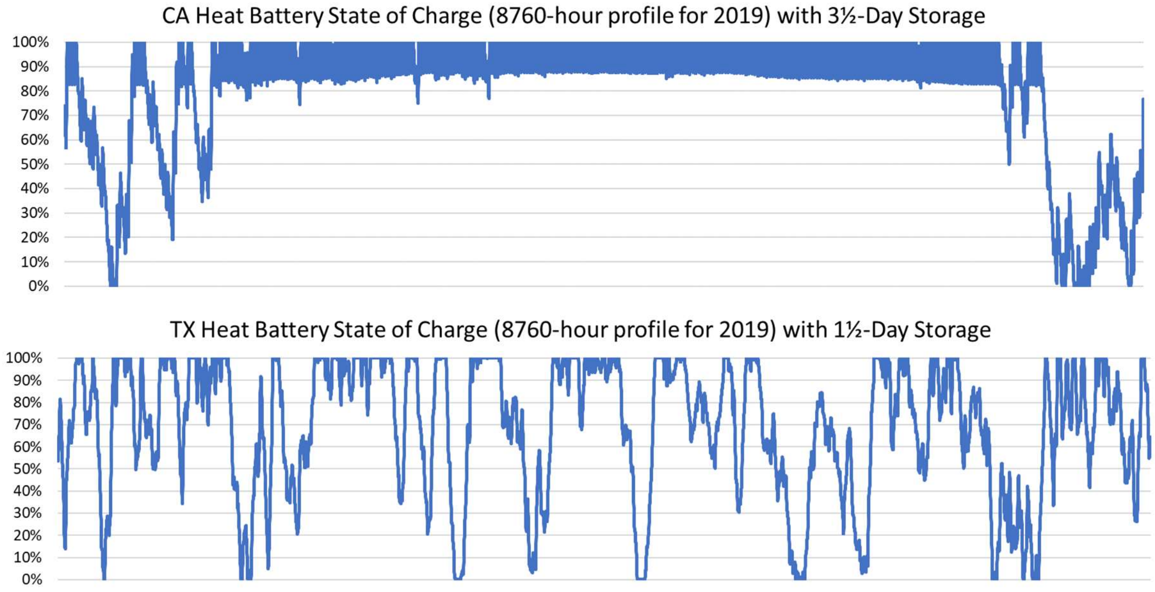

Figure 9. Modeled thermal battery state of charge over 8,760 hours in 2019 in California and Texas locations.

Levelized Cost of Energy

Figure 10 breaks down the final delivered levelized cost of thermal energy (LCOE) for the modeled CA and TX thermal batteries.

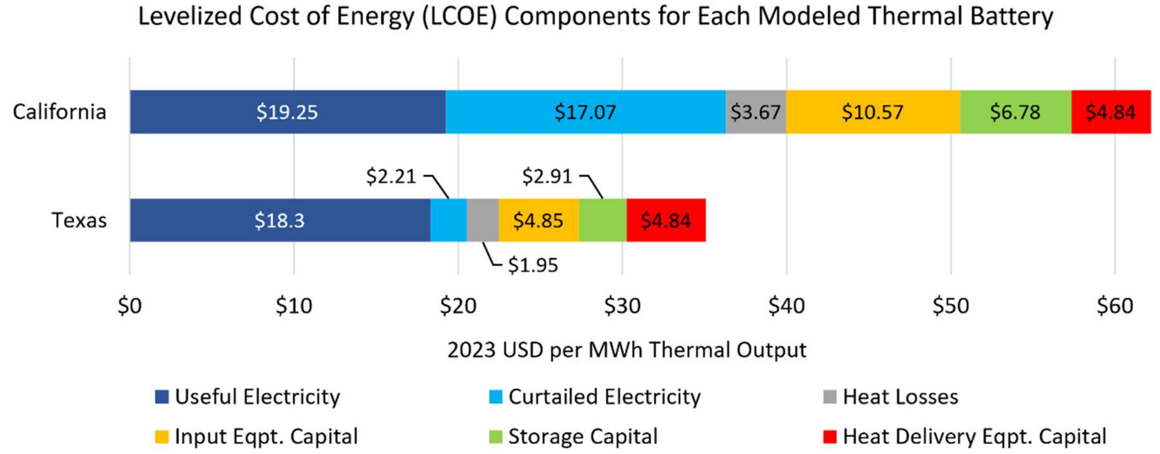

Figure 10. LCOE components for each modeled thermal battery (CA battery with 47.3 percent curtailment and 84 hours of storage, TX battery with 10.7 percent curtailment and 36 hours of storage). Battery capital equipment types are described near the beginning of the "Modeled Industrial Thermal Battery Examples" section above.

The CA battery has higher curtailed electricity and storage capital costs due to its higher curtailment rate and larger number of days of storage. Additionally, the solar-only energy profile results in a need to charge the CA battery more rapidly (during the smaller number of hours when electricity is available). This, in turn, requires larger input equipment, leading to higher input equipment costs ($10.57/MWh in California versus $4.85/MWh in Texas). Finally, heat losses are associated with thermal batteries' 95 percent round-trip energy efficiency and are therefore proportionate to all other costs in the figure, so heat losses have a greater financial impact on LCOE for the CA battery.

However, before concluding that it is more economically advantageous to deploy a thermal battery in West Texas than in California, it is important to consider the cost of locally available alternatives.

Thermal Energy Cost Comparison

A firm interested in building a new industrial facility with the cheapest possible energy inputs may choose one of the most attractive geographies for high-quality renewable energy generation. However, if an industrial facility already exists, or if other factors constrain the choice of site for a new facility (such as access to suppliers, customers, skilled labor, or transport infrastructure), then it is important to compare a thermal battery's cost of energy with other local energy supply options, such as industrial retail rates for electricity and for natural gas.

Figure 11 compares the cost of thermal energy from off-grid renewables and a thermal battery to that paid by an average industrial consumer of grid electricity (without a thermal battery) or natural gas. In both California and Texas, the highest-cost heat comes from grid electricity purchased at the average industrial retail rate. The thermal battery and natural gas are similar in cost, though prices tend to favor gas in Texas. Even though the CA battery provides heat at a higher absolute cost than the TX battery, the CA battery is more cost competitive relative to locally available alternatives, so the California location may be more advantageous than Texas for industrial thermal battery deployment.

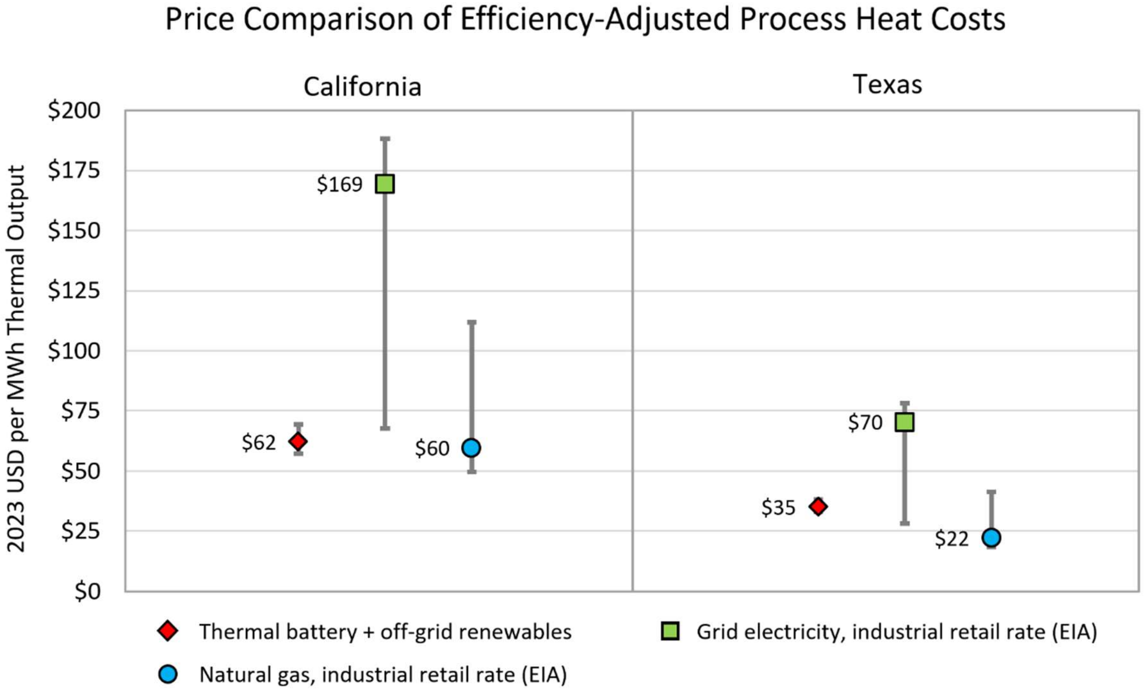

Figure 11. Comparison of cost of heat from thermal batteries (with off-grid generation), from retail electricity, and from natural gas in California and Texas. Error bars on thermal battery costs reflect uncertainty in storage material costs, while error bars on grid electricity and natural gas reflect the range of efficiencies of common electrified and natural gas industrial heating technologies (described below).

For each thermal battery case, average costs are as calculated in Figure 10, while error bars show a range of battery storage medium capital costs from $1.5 to 10 per kWh. Grid electricity and natural gas costs are based on the Energy Information Administration (EIA)'s reported average retail electricity and gas rates for industrial customers in each state. Gas use is assumed to be 75 percent efficient on average,[4] with error bars reflecting the efficiency range between high-temperature industrial furnaces without waste heat recovery (40 percent efficiency) and highly efficient industrial steam boilers with condensate recovery (90 percent efficiency). For retail electricity, the average efficiency is taken to be an electric resistor immersed in a fluid to be heated (approximately 100 percent efficiency). The low-cost error bar represents an industrial heat pump operating at a coefficient of performance of 2.5 (i.e., 250 percent efficiency), reflecting a 75°C increase in temperature, enough to raise room-temperature water (25°C) to its boiling point (100°C). The high-cost error bar represents an induction or electric arc furnace, with efficiency (after heat losses) typically around 90 percent.[xiv]

Note that Figure 11's thermal battery heat costs include both energy and capital equipment (e.g., for a new thermal battery installation), while grid electricity and natural gas costs reflect only efficiency-adjusted energy costs, not capital costs. This is because the largest opportunities for thermal batteries may be to replace existing technology, where capital costs are sunk. However, commercialized gas or electrical heating equipment capital costs are a small fraction of their lifetime costs, so including capital costs for these technologies would not appreciably change Figure 11. For example, the National Renewable Energy Laboratory cites a cost of $53,860 for a 100-horsepower (3.35 million BTU/hr) boiler,[25] which equates to an extra $1 per MWh of delivered heat.

Also, note that a generalized model was used to optimize our thermal battery configurations (see the "Reliability and Cost Optimization" section). Engineering optimizations reflecting specific industrial facilities' unique properties and needs could drive costs down further, as could a facility tolerating 98 percent or 95 percent reliability instead of 99 percent. Additionally, more research and returns-to-scale as manufacturing ramps up could reduce thermal battery prices.

The most important message of Figure 11 is that thermal batteries can dramatically reduce the cost of industrial electrification, bringing the costs of producing heat from electricity down to a level that is broadly competitive with continuing to operate existing natural gas equipment. Industrial heat pumps have a similar impact on cost effectiveness, but thermal batteries operate over a much broader temperature range than do heat pumps, dramatically expanding the types of heating processes that can be cost-effectively electrified.[xv]

However, since thermal batteries are not yet definitively the cheapest option, a nudge from policy could help accelerate their deployment. For example, pricing the carbon emissions from gas boilers at $51/ton CO_2 (the federal government's social cost of carbon for 2020 at a 3 percent discount rate)[26] adds around $10/MWh to the delivered cost of heat from natural gas, making the thermal battery more financially attractive. An equivalent effect could be achieved by providing tax incentives for thermal batteries. See the "Policy Recommendations" section below for details on policies to help accelerate the deployment of industrial thermal batteries.

[xiv] There exist less-efficient electrical heating technologies, such as dielectric heating, with efficiency around 70 percent, or lasers, with efficiencies of 30 to 50 percent. However, these electrical heating technologies tend to be used only in specialized or precision applications (e.g., laser cutting and welding) and therefore are not comparable to heat from thermal batteries or natural gas.

[xv] Also, it is possible to charge a thermal battery using a heat pump, which would maximize cost-effectiveness in the low-temperature range.

Price-Hunting Thermal Battery Model Results

At the other end of the spectrum from the generation-following battery, a *price-hunting* thermal battery is connected to the grid and aims to take advantage of fluctuations in electricity pricing. West Texas is particularly well-suited to a price-hunting thermal battery. Electricity is inexpensive in west Texas, as the region has high-quality wind and solar resources combined with inexpensive power from natural gas-fired power plants (due to the proximity to natural gas fields and wellheads). Also, the region suffers from occasional transmission constraints that hamper the export of electricity to other regions, causing gluts of power that make local real-time power prices periodically dip to very low or negative levels. This creates opportunities for a thermal battery to provide significant cost benefits by converting sporadic opportunities for discounted power into a steady stream of low-cost, reliable heat output.

The regulatory environment is also favorable: Texas has some of the most flexible rules for connecting projects to the grid, among the least onerous tariffs for flexible loads, and very accessible real-time price information. Hence, it is one of the most plausible places for price-hunting thermal batteries to be successful.

While reliability of heat output was a key consideration for the generation-following battery, reliability is not a relevant metric for the price-hunting battery, as it is grid-connected, so electricity is always available to the industrial facility (grid outages excepted). Instead, the key parameters determining the financial performance of a price-hunting thermal battery are its charging rate and its storage capacity. The faster a battery can charge, the more fully it can charge in the least-cost hours, rather than needing to partially charge in hours in which electricity prices are less favorable. The more storage capacity a battery has, the longer it can wait for very low electricity prices before charging, enabling it to be more selective about the electricity price it is willing to accept.

For example, suppose a thermal battery needs to supply heat at a steady rate of 1 MW[xvi] to cover its heating loads on a 24/7 basis and has one and a half days of storage (36 MWh). It can fill from empty to a 100 percent charge when prices are low by drawing power from the grid at 3.5 times its steady state output (3.5 MW) for a little over 10 hours (see Figure 12, January 4, from 12:00 am to 10:00 am). If prices remain low, it can remain on standby (with occasional, brief discharges and recharges around small price spikes or dips), stretching its 1.5-day heat supply to last for two days (see Figure 12, from 10:00 am on January 4 – 10:00 am on January 6).

[xvi] This would be 950 kW of heat output after accounting for 95% efficiency of thermal batteries. In this discussion of battery optimization, we ignore batteries' 95% round-trip efficiency, which simplifies the math and does not meaningfully affect the selection of optimum battery parameters (capacity and charge rate). We account for thermal batteries' 95% conversion efficiency in the final prices in Table 2.

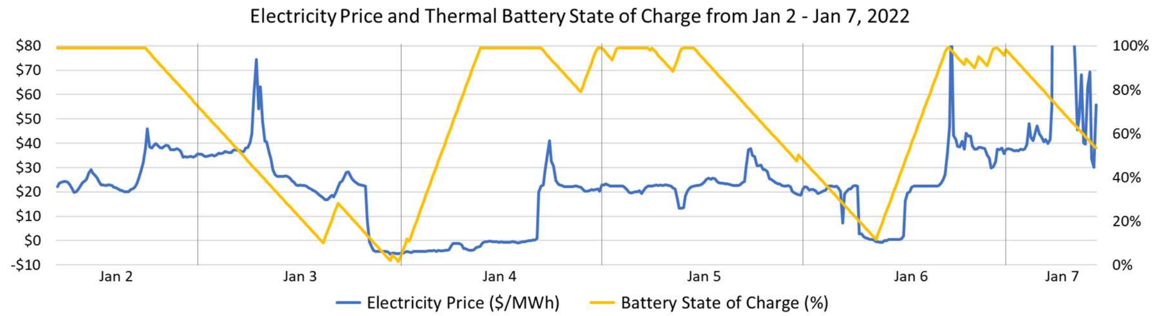

Figure 12. Electricity price and thermal battery state of charge at 15-minute intervals from 8:00 am on Jan 2 – 12:00 noon on Jan 7, 2022.

Optimization of Battery Charge Rate and Capacity

The optimal combination of maximum charging rate and battery capacity is a function of how these factors affect the electricity costs paid by the industrial firm and the capital costs of the thermal battery. Increases in charge rate and battery capacity are worthwhile so long as the resulting reductions in electricity costs more than cover the increased battery expenses (including electricity input equipment and thermal storage medium). For example, Figure 13 illustrates the average wholesale costs of power from the West Texas day-ahead hourly market for an industrial facility using a thermal battery with foresight of future electricity prices.

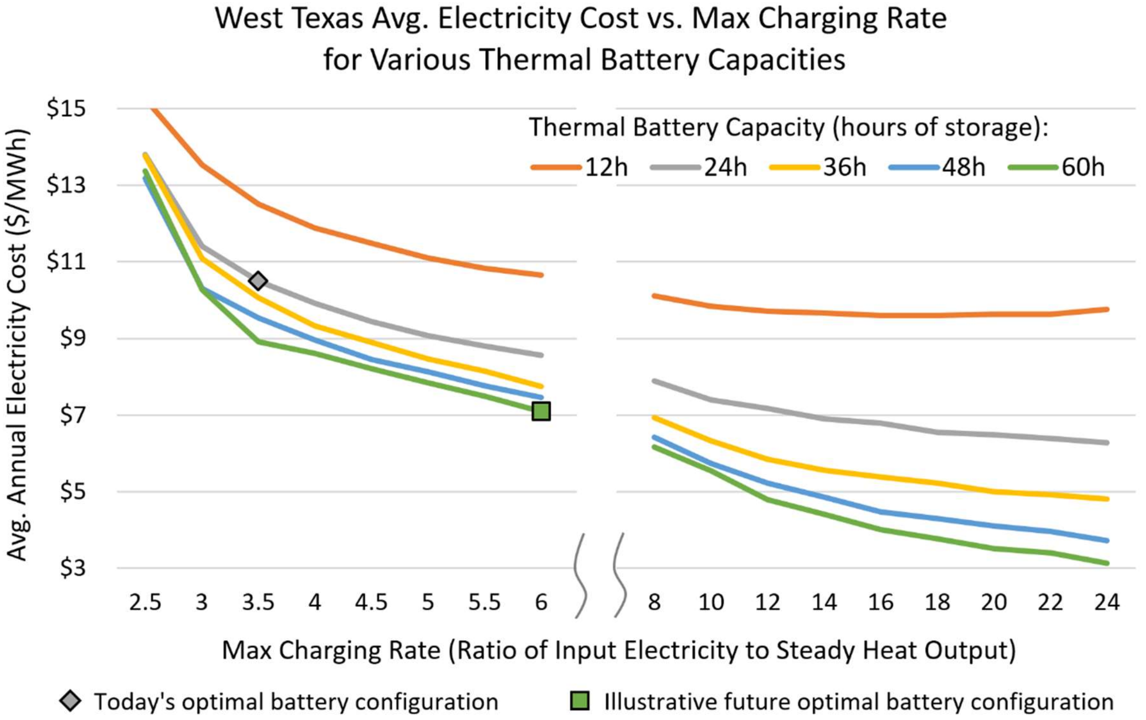

Figure 13. Average electricity cost for an industrial facility as a function of thermal battery charge rate and capacity, using 2020 West Texas electricity prices. The gray diamond indicates the most cost-effective battery configuration based on 2023 thermal battery capital costs (3.5x charge rate, 24 hours of storage), while the green square indicates the most cost-effective battery configuration after future declines in thermal battery capital costs (6x charge rate, 60 hours of storage).

In theory, a thermal battery could achieve a rock-bottom, $3/MWh average cost of wholesale power by combining a very high charging rate (24x the heat output rate) with 60 hours of storage capacity, but this would not be cost-effective after accounting for the capital costs of such a powerful battery. Given a $110/kW cost of capital for electricity input equipment (the same as in the generation-following case above, plus an extra $10/kW in grid connection costs), there is no benefit to pushing the charging rate past 3.5x because the incremental decrease in electricity spending no longer outweighs the incremental spending on input power infrastructure. At that charging rate, given a $5/kWh cost of storage capacity, increasing the battery capacity beyond 24h of storage doesn't deliver enough electricity savings to justify the capital cost. Thus, the optimal configuration is a 3.5x charge rate and 24h of storage capacity, denoted by the gray diamond in Figure 13. The resulting average cost of electricity is $10.50/MWh. In contrast, an industrial facility that purchased wholesale power from the grid evenly in every hour, without a thermal battery, would have paid an average electricity price of $30.80/MWh, roughly three times higher than the facility with the thermal battery.

In the future, thermal batteries may be cheaper due to research and development and returns-to-scale as more batteries are manufactured. Given optimistic future battery costs of $40/kW for electricity input equipment and $1.5/kWh for the storage medium, the optimal configuration becomes a 6x charge rate and 60h of storage, denoted by the green square in Figure 13. This allows the facility to pay an average price of $7.09/MWh for its electricity, less than a quarter of the $30.80/MWh price paid by a similar facility without a thermal battery.

The figures used above are based on 2020 west Texas electricity prices. Repeating the analysis with 2022 prices yields broadly similar results, with a 5x charge rate and 36h of storage being the optimal configuration given today's thermal battery capital costs. The increased charging rate and capacity are justified by higher power prices in 2022. However, the difference in cost-effectiveness between the (5x, 36h) battery and the (3.5x, 24h) battery is minimal. In general, the opportunity cost of having too powerful a battery in a low-price year outweighs that of having too weak a battery in a high-price year, so the (3.5x, 24h) configuration is the best overall choice for this location in west Texas.

Cost Results

Table 2 lists the modeled average wholesale price of heat available on a 24/7 basis from a (3.5x, 24h) thermal battery with price foresight in 2020 and 2022. The cost of delivered heat is the sum of the four rows immediately above it, i.e., the cost of electricity, grid access charges, and the levelized capital cost of the battery itself, adjusted for thermal batteries' 95 percent round-trip efficiency. (Note that the mean electricity price without a thermal battery, in the first row of Table 2, is not the levelized cost of delivered heat from a facility using grid electricity without a thermal battery, as it includes only wholesale power costs and does not include transmission, distribution, and other costs. The levelized cost of heat from grid electricity in west Texas is given in Figure 11 above, at roughly $70/MWh.)

Item	Unit	2020 Value	2022 Value
Mean Electricity Price Without Thermal Battery	$/MWh	$30.80	$62.35
Mean Cost of Electricity with (3.5x, 24h) Thermal Battery	$/MWh	$10.50	$27.18
Grid Access Charges	$/MWh	$5.00	$5.00
Levelized Capital Cost of Thermal Battery	$/MWh	$12.86	$12.86
Thermal Battery 95% Round-Trip Energy Efficiency Penalty	$/MWh	$1.49	$2.37
Levelized Cost of Delivered Heat	$/MWh	$29.85	$47.41

Table 2. Summary statistics for the modeled thermal battery in 2020 and 2022.

Grid access charges include administrative fees, line loss charges, and ancillary services charges. A controllable load aggregator in Texas estimated that these overhead fees for connecting a thermal battery would be around $5/MWh consumed. A price-hunting battery could mitigate that cost by selling ancillary services that aid in grid regulation. These ancillary services provide revenues of $9 to $20/MWh of services provided (not per MWh of electricity consumed).[27] However, ancillary services markets tend to be very shallow (i.e., only a small amount of services are needed), so these revenues could quickly disappear with significant thermal battery deployment.

Regardless of their exact configuration, thermal batteries provide power at a significant discount from the mean real-time prices of power (e.g., at one half to one third of mean prices). In Texas, much of this discount stems from the ability to procure energy when wholesale electricity prices are negative. In these hours, utilities actually pay customers to consume power because it helps with balancing the grid. In both modeled years, the price-hunting thermal battery consumes much of its energy when regional real-time prices are negative and almost all the rest at a discount relative to the mean price.[xvii]

However, even at these low prices, fossil fuels can still be cheaper – for instance, Texas' industrial natural gas retail rate was $22/MWh thermal output (Figure 11). Some of the strategies for cost reduction available to generation-following batteries (see "Further Cost Optimization Approaches" above) could also be used by price-hunting batteries. For example, an industrial facility could burn a small amount of fossil fuel or bioenergy for heat during the most persistent periods of elevated wholesale electricity prices. Or significant reduction in thermal batteries' hardware costs and grid connection fees could make them definitively cheaper than fossil fuels. Alternatively, a carbon price on fossil fuels or a manufacturing subsidy that reduces the cost of the thermal batteries could make up the difference.

Hybrid Battery Configurations

The two configurations we modeled—generation-following and price-hunting thermal batteries—bookend a spectrum. In the middle lie hybrid configurations that connect dedicated solar and wind resources with the battery financially, if not physically, along with options for exporting and importing power from the grid. For example, the generation-following battery could opt to connect to the grid for export only, allowing it to sell excess power and better optimize its supply mix and charging rate to reduce costs. Alternatively, the price-hunting battery could enter into a long-term specialized purchase agreement with local regional renewable generators, making use of the battery's flexibility to negotiate lower and more stable average wholesale power costs than simply purchasing electricity from the real-time market. Hybrid batteries may sacrifice some advantages

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[xvii] Texas's negative-price hours make it an attractive location for thermal batteries, but since thermal batteries always buy electricity in the cheapest hours available, they deliver heat at below-mean prices even in locations without negative-cost hours.

of a pure form arrangement (e.g., forgoing the simplicity of avoiding grid connection processes for the generation-following battery), but in return, they can make use of a larger set of technical options and financial arrangements to further reduce costs.

BENEFITS TO THE ELECTRICITY SYSTEM

The benefits of a thermal battery to the electricity system depend on where it lies on the "generation-following" to "price-hunting" spectrum.

Generation-following batteries mainly benefit society by increasing the amount of low-cost, emissions-free power that can be used for productive purposes without creating increased strain on the existing grid (no extra transmission, balancing resources, etc.). Because they connect to sources with very low operating costs, they create price certainty for their customers, along with a guaranteed zero-emissions profile. If leading facilities move to electrify using this simple approach, this creates a market for electrified industrial equipment, bringing down equipment costs and improving equipment access for other industrial customers. Thus, generating-following projects can serve as early adopters that help increase the scale and drive down the prices of thermal batteries and electrified industrial equipment.

Price-hunting batteries also provide similar benefits to society by consuming power during hours when it is less attractive for other uses and the grid has an excess of electricity that can be supplied to the industrial facility. Price-hunting batteries also allow more variable, renewable power to connect to the grid by virtue of being a flexible load, and the new demand they create is well aligned with periods of abundant renewable energy supply. They provide flexibility services to the grid, e.g., by reducing their electricity consumption at times of stress or unusual weather and increasing consumption where there is excess power available (for example, from renewables and from plants that cannot be easily ramped up and down, such as nuclear plants). These flexibility services may make it easier for utilities to operate a high-renewables grid on a daily basis.

Price-hunting thermal batteries can also reduce net peak load on the grid (i.e., peak load after subtracting generation from variable resources like wind and solar), lessening the need for dispatchable, fuel-burning generation, as well as transmission and distribution infrastructure. Today, around 2,940 petajoules (PJ) of fossil fuels are burned to heat industrial boilers and 3,195 PJ are burned to provide other forms of industrial process heat in the U.S. each year (Figure 1). These fossil fuels could be replaced by about 820 TWh of electricity,[xviii] equivalent to 21 percent of total U.S. electricity use in 2021.[28] This demand is not spread evenly throughout the year. Accounting for intra-week and seasonal variance in industrial electricity demand (Figure 4, Figure

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[xviii] This assumes that the average efficiency of combustion boilers (including heat losses) is 80 percent and that they can be replaced by industrial heat pumps operating at an average efficiency of 250 percent. It also assumes that the efficiency of non-boiler combustion-based process heating is 60 percent and can be replaced by a mixture of electrical technologies (electric resistance, induction, dielectric heating, etc.) operating at an average efficiency of 95 percent.

5) and a 14 percent reserve margin,[29] the required increase in capacity would be 146 GW, equivalent to 13 percent of total U.S. capacity in 2022.[6] Based on temperature requirements, thermal batteries could theoretically serve more than 90 percent of that demand (Figure 3), shifting it to non-net-peak hours. This requires a much smaller build-out of new power plants and other infrastructure, saving money and avoiding difficult legal and environmental issues associated with siting and building new grid infrastructure.

Note that when price-hunting thermal batteries serve new demand or electrify heat previously provided by fossil fuels, there is a net increase in annual electricity demand. To maximize the battery's flexibility benefits for the grid, the new demand should be accompanied by new electricity supply. Even if the battery's consumption profile is well-matched with low market prices, without new supply, electricity prices could go up. For example, Texas has recently seen increased electricity costs associated with substantial new flexible load from crypto-mining firms.[xix] Because crypto-mining is a new activity without a long track record, developers of electricity generation assets are reluctant to enter into long-term power purchase agreements (often 10-25 years in duration), as they do not trust the crypto-mining firm will be around to fulfill the terms of the agreement. As a result, few if any crypto miners have signed contracts for new electricity supplies, so new supply was not deployed to accompany the new load and electricity prices rose. In contrast, industrial facilities that consume heat from thermal batteries tend to make good long-term counterparties in power purchase agreements as many manufacturers have long track records, and the lifetime of industrial equipment is measured in decades. Therefore, renewables developers can be comfortable signing power purchase agreements with industrial thermal battery users. This dynamic illustrates one way in which industrial facilities with thermal batteries can create a strong market signal for new renewables.

Ultimately, thermal batteries in generation-following mode make it easier for industry to access low-cost, renewable energy while meeting industrial needs for reliable heat delivery. Meanwhile, batteries in price-hunting mode can utilize the least-valuable tranche of grid power, leaving the remainder to more time-sensitive applications, while making it easier for utilities to balance the electrical grid, integrate additional renewable energy, and reduce reliance on dispatchable generation. Hybrid arrangements have the potential to optimize social benefits by drawing on the best aspects of generation-following and price-hunting modes.

It may take some time for electricity tariffs to be updated to properly reward industries for providing flexibility services and peak demand reduction. Decarbonizing industry is urgent and must not wait until tariff reform is done. Fortunately, off-grid, generation-following projects and regions that expose industries to electricity prices that vary by hour based on grid needs (as in Texas) provide a starter market that can begin to bring down equipment costs and shift industry to clean energy today.

[xix] Crypto-mining refers to obtaining some types of cryptocurrency by using computers to perform math operations that allow the cryptocurrency to function as a decentralized network, such as verifying cryptocurrency transactions.

BENEFITS TO INDUSTRIAL FIRMS

Generation-following thermal batteries improve the reliability of heat delivery for industrial facilities that can access cheap, off-grid wind and solar generation. Firms that might otherwise have been unwilling to rely on off-grid renewable energy due to concerns about reliability might view it as a practical energy supply option when paired with a thermal battery.

Price-hunting thermal batteries dramatically reduce the cost to industry of buying grid electricity for industrial heating purposes by allowing that electricity to be procured in the lowest-cost hours. They may also enable firms to operate through grid outages if the firm has on-site backup generation, a system to convert stored heat back to electricity, or electricity storage sufficient for auxiliary (non-heat) systems such as blowers and conveyor belts.

Both types of thermal battery help industries to stop burning fossil fuels. In addition to the societal benefits of reduced conventional and climate pollution (i.e., improved public health and reduced climate damages), this has financial benefits for the industrial firm, including:

- Reduced exposure to fossil fuel price volatility
- Improved ability to market products to environmentally conscious buyers
- Ability to sell products to governments under green public procurement programs, wherein the government pays a premium for cleanly-produced products
- Avoidance of present or future carbon pricing costs
- Avoidance of tariffs based on embedded carbon, such as the European Union's Carbon Border Adjustment Mechanism, when selling goods into covered markets
- Ease of compliance with existing and future emissions and energy efficiency standards
- Reduced need for cooling water, exhaust treatment technologies (such as particulate filters), and cleaning and maintenance of combustion equipment
- Improved workplace health and safety
- Reduced insurance premiums due to lowered risks to workers and property and, potentially, due to a reduction in the quantity of insured capital equipment

POLICY RECOMMENDATIONS

Industrial thermal batteries can accelerate the decarbonization of industry and help the U.S. achieve its climate goals, while supporting competitive domestic manufacturing. However, it will take roughly 30 GW_{input} with 360 GWh of thermal battery capacity to replace every 100 TWh (~450 PJ of fuel) of industrial process heat with clean power. These are huge amounts, and hence, they present significant opportunities for the economy and the environment. Therefore, policymakers should consider using public policy to accelerate the adoption of industrial thermal batteries. Broadly speaking, two types of policy are well-suited to this task: financial incentives (including direct funding, tax credits, and low-cost financing) and updating electricity pricing and electricity system plans to value flexibility services and facilitate grid-connected industrial facilities with heat storage.

Financial Incentives

One of the most straightforward methods of supporting electrification of industrial facilities and thermal batteries is by helping to cover some of the costs of new or retrofitted facilities. This support could originate at the local, state, or federal levels of government. For instance, U.S. cities and states routinely offer industrial firms subsidies worth hundreds of millions or billions of dollars in return for new capital investment and job creation in their communities.[30] Cities and states could require that industrial facilities adopt electrified heating technologies and thermal batteries to qualify for these subsidies.

Some U.S. states have programs that help promote in-state industrial development. For example, the Empire State Economic Development Fund assists industrial and manufacturing businesses that wish to build or renovate facilities in New York State,[31] and Connecticut's Manufacturing Innovation Fund provides financial support to businesses involved in technologically advanced manufacturing in Connecticut.[32] State-level programs to support businesses have traditionally focused on developing a state's manufacturing economy and providing jobs. A goal to accelerate the transition to sustainable industry could be added to the mandate of existing state-level industrial development programs, or states could establish new funds that focus exclusively on sustainable manufacturing.

The federal government supports industrial decarbonization projects through the new Industrial Efficiency and Decarbonization Office (IEDO) within the Department of Energy. IEDO provides funding, technical assistance, and workforce development to support low- and zero-carbon thermal process technologies, including electrification of process heat.[33] In its first year of operation, IEDO announced $174 million in funding opportunities.[34] IEDO may choose to direct a portion of its funding to support industrial thermal battery deployment.

Another relevant funding source is the Office of Clean Energy Demonstrations (OCED), a part of the Department of Energy established in 2021 as part of the Bipartisan Infrastructure Law. OCED's Industrial Demonstrations Program provides $6.3 billion in funding for projects that abate emissions from industrial activities, including those that reduce emissions in medium- and high-temperature heat generation.[35] Industrial thermal batteries qualify for these funds.

The Inflation Reduction Act (IRA) has the potential to significantly increase available funding for electrification of industrial process heat and thermal batteries. For example:

- IRA section 13501 provides $10 billion in funding for the Advanced Energy Project Credit and expands its eligibility to include re-equipping an "industrial or manufacturing facility with equipment designed to reduce GHG emissions by at least 20 percent through the installation of low- or zero-carbon process heat systems."[36] Upgrading a facility to use electrified heat and a thermal battery (which allows facilities to purchase electricity at those times when renewables provide the highest share of grid electricity) meets this definition.

- IRA section 50161 allocates $5.8 billion to a new Advanced Industrial Facilities Deployment Program, which supports the purchase, installation, retrofits, or upgrades to industrial facilities to use “advanced industrial technology.”[36] This term is defined in the Energy Security and Independence Act of 2007 section 454(c)(1)(B) to include “technologies and processes that achieve emissions reduction in medium- and high-temperature heat generation, including through electrification of heating processes.”[37] Electrification of industrial process heating at medium-to-high temperatures, with or without thermal batteries, would qualify for this funding.

Although industrial electrification projects and thermal batteries qualify for this funding, many other sorts of industrial technologies also qualify, and it will be up to implementing agencies to allocate funds to specific projects or manufacturers. Therefore, regulators’ awareness of the benefits of electrified process heat and thermal batteries can be an important factor in how much funding these projects receive.

In addition to direct funding from legislative provisions or Department of Energy programs, the federal government provides substantial support to clean manufacturers in the form of tax credits. Among the most relevant for thermal batteries is another IRA provision:

- IRA section 13502 establishes an Advanced Manufacturing Production Credit (45X) that provides rebates to manufacturers of specific clean energy-related technologies (such as solar panels and battery modules). For battery modules that do not use *cells* (a cathode and an anode separated by an electrolyte), the credit amount is $45 per kWh of battery capacity.[36]

Tax credits are often described by policymakers in relatively broad statutory language. The Internal Revenue Service (IRS) must then interpret the legislation, accounting for the intent of Congress, and translate it into detailed regulations, rules, and procedures.[38] Therefore, the way in which the IRS interprets legislation can enhance or diminish a tax credit’s ability to achieve specific policy outcomes. The IRS should confirm that a thermal battery qualifies as a “battery module” under IRA section 13502, identify appropriate system boundaries for stationary storage systems,[xx] and provide guidance on how to calculate power and capacity values for useful thermal output.[xxi] The

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[xx] Depending on the configuration of the system, the battery’s input electrical equipment, the thermal storage medium, and the heat output equipment may constitute a single “battery module,” which might facilitate estimation of its efficiency and the kWh of deliverable energy stored in the battery.

[xxi] The $45/kWh credit should ideally be based on the thermal energy storage capacity of the battery directly. However, if the IRS determines that the $45/kWh credit amount is based on the *electrical* storage capacity of a battery, the IRS should specify an approved method of converting thermal kWh to equivalent kWh of electrical storage, such as using the Carnot cycle efficiency or the efficiency of an average U.S. steam turbine. For each 100 kWh of thermal storage, these conversion methods would result in a capacity of 22 to 44 kWh of electrical storage equivalent.[39] Applying the $45/kWh credit to unadjusted thermal storage capacity would reduce levelized heat output costs by $27/MWh-thermal, while applying the credit to an adjusted storage capacity of 22 or 44 kWh would reduce levelized heat output by $6/MWh-thermal or $12/MWh-thermal respectively. These discounts can be compared to total levelized costs of $35 to $62/MWh-thermal in Figure 10.

resulting certainty would help industries make investment decisions. This tax credit would defray the cost of deploying this technology at scale, accelerating the transition to clean industry and helping the U.S. achieve its climate goals.

Lastly, in addition to direct funding and tax credits, governments can support manufacturers by improving their access to low-cost financing (i.e., loans). Access to affordable financing is particularly important for newer technologies that may be unfamiliar to traditional lenders, who are risk-averse and may be reluctant to loan money for facilities that plan to employ novel technologies or processes. The Department of Energy's Loan Programs Office can provide direct loans to innovative clean energy projects, can co-lend with a private lender, or can provide loan guarantees (an agreement to repay a loan should a borrower default), which can help projects to secure private financing.[40] Industrial thermal energy storage (among other industrial emissions reduction technologies) is specifically identified as eligible for support under Title 17 Innovative Clean Energy provisions.[41]

At the sub-national level, a number of states have established green banks, funding entities that use loans, loan loss reserves, loan guarantees, bond sales, and other tools to improve access to low-cost financing for clean energy projects. Green banks use these tools to attempt to magnify the effects of public money by leveraging private capital. The amount of support they provide can be substantial. For instance, from 2012 to 2021, the Connecticut Green Bank mobilized $1.85 billion in private investment into qualifying projects using $288 million in green bank funds.[42] To date, green banks have mostly focused on energy retrofits of homes and commercial buildings (heat pumps, boilers, etc.), as well as renewable energy infrastructure, such as rooftop and community solar. However, green banks are well-positioned to fund industrial electrification and thermal batteries, which could contribute to their states' economies while cutting emissions.

Electricity Tariffs and System Operator Rules

To the extent that thermal batteries interact with the power grid, electricity pricing, connection costs, and operating rules will impact their financial viability. Today, the economics of industrial electrification via thermal batteries are finely balanced against competing fossil-fueled energy supply, so even small differences in grid-related tariffs, costs, and rules could make or break project economics. It is important that these elements be structured to recognize the value of thermal batteries in improving grid asset utilization (i.e., using grid assets when they are least necessary), thus lowering costs for other consumers.

At the national scale, the Federal Energy Regulatory Commission (FERC) approves charges that loads must pay for capacity costs, transmission costs, ancillary services, and the like, some of which are based on quantity of electricity consumed (MWh), while some are tied to peak demand. A thermal battery is not a typical behind-the-meter load due to its flexible operation, and in the case of a hybrid battery configuration (i.e., with its own renewable generation as well as a grid connection), the battery-equipped facility may sometimes export electricity to the grid and sometimes draw from the grid. FERC should recognize that because a thermal battery draws electricity at times when the grid has excess capacity, it places little strain on electricity generation, transmission, or distribution assets and therefore should receive discounted grid charges. For hybrid batteries, fees should be based on actual consumption of grid electricity, not on the battery's rated capabilities, which may be higher but are largely served by off-grid generation assets.

Independent system operators and their stakeholder groups, with FERC's approval, should open dockets to study the costs and benefits of flexible loads like thermal batteries, continuing work that has already started to negotiate new kinds of arrangements with flexible data center loads (which are far less flexible than thermal batteries). While off-grid renewable generation dedicated to individual industrial projects is a good starter market that can help achieve technology cost declines, having many siloed generation assets is not optimal for society, as it forgoes benefits that can be gained from optimizing the electric system as a whole. Therefore, in the long term, it would be best if most generation-following thermal batteries become grid-connected (hybrid) batteries. However, there are barriers to connecting new renewable generation to the grid, such as an interconnection queue, which currently can impose costly delays of three to five years before new renewables may connect to the grid. Interconnection queue processes should recognize the likely operating modes of thermal batteries, i.e., that a grid-connected battery will only charge during times of abundant electricity and deliver electricity to the grid at times of greatest need, facilitating grid management and resilience, so they may require less scrutiny than pure renewables projects without thermal storage.

State-regulated vertical utility monopolies might not be open to competition from behind-the-meter generation and might be reluctant to offer specialized tariffs that value flexibility and price-hunting. This would be unfortunate, as flexible, behind-the-meter loads that can export power to the grid during the most valuable hours can be an asset for utilities and their customers. Public utility commissions (PUCs) should create a new rate class that reflects the lower cost to serve flexible loads. They should also examine rules for direct access to the grid, open dockets to study structural barriers to entry for thermal batteries, and ensure that the monopoly franchise (i.e., regulated utilities' rights to deny other firms permission to transmit power across any public right-of-way) does not stymie industrial electrification and thermal battery deployment. These measures need not come at the expense of utilities. It costs less to serve thermal batteries, so a lower rate class can nonetheless preserve utility profit margins. Additionally, thermal batteries create new electricity demand that is coincident with renewables production, helping electric utilities increase their revenue and take market share from fossil fuels, even as they make grid regulation easier. PUCs should encourage utilities to facilitate and potentially earn from grid-connected thermal battery deployment.

CONCLUSION

Thermal batteries are a promising and under-appreciated technology that can facilitate industrial electrification and a faster transition to clean industry. Modern thermal batteries supply heat at temperatures as high as 1,500 to 1,700°C, enough to satisfy more than 90 percent of the industrial process heat demand that is today met with combustible fuels. Thermal batteries can be operated cost-effectively in two modes (or a hybrid of the two). Generation-following batteries enable industrial firms to convert variable generation into reliable, 24/7 process heat, allowing them to rely on off-grid wind and solar while benefitting from low prices. Price-hunting, grid-connected batteries charge when electricity is abundant and low-cost, saving money for industrial customers while helping system operators to balance the grid. This spectrum of approaches gives industrial firms access to cheap, electrified heat, helping to close the gap between electricity costs and fossil fuel costs.

A range of financial policies, including direct funding, low-cost financing, and confirming thermal batteries' eligibility for the Advanced Manufacturing Production Tax Credit (45X), are crucial tools to encourage industries to pursue electrification rather than continuing to burn fossil fuels. Reforming electricity tariffs to value the flexibility services that these batteries provide and removing other hurdles to their deployment are important enablers of industrial thermal battery projects.

With the right policy environment, thermal batteries can promote clean and competitive U.S. industry, enhance U.S. technological leadership, and reduce conventional and GHG pollution from industrial fossil fuel combustion. Policymakers should seize this opportunity to invest in U.S. manufacturing in a way that promotes public health and contributes to the U.S.'s climate goals.

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