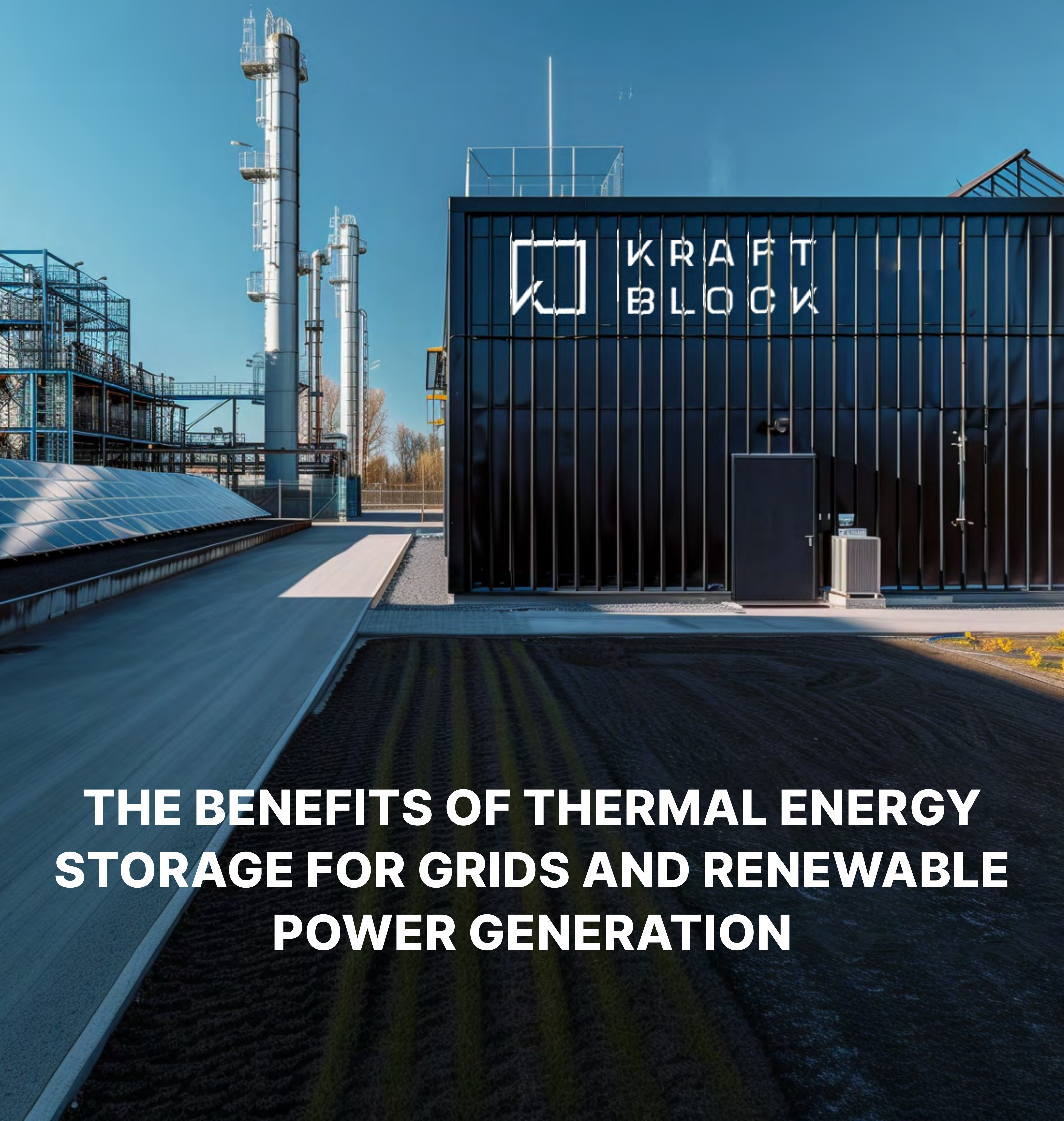
KRAFT BLOCK



THE BENEFITS OF THERMAL ENERGY STORAGE FOR GRIDS AND RENEWABLE POWER GENERATION

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ABOUT THE EDITORS

KRAFTBLOCK

Kraftblock is an engineering and manufacturing company that builds systems to decarbonize heat in industry, district heating and power generation. At the heart of its technology is a unique proprietary thermal energy storage system using a newly invented sustainable material that can withstand temperatures of 1,300 °C. It was founded 2014 by chemist Martin Schichtel and economist Susanne König. Among the important investors are Shell Ventures, Koolen Industries and Finindus.

DWR ECO

DWR eco is a leading consulting agency for market strategies, PR, communication, and politics and sees itself as a strategic mission control centre for entrepreneurial growth, green technologies, and clean investments in the areas of cleantech, ClimateTech, and GreenTech. With an unwavering pioneering spirit and in-depth expertise, DWR eco is the go-to team in politics, the market and the public when it comes to scaling solutions for climate protection, the energy transition, clean mobility, green industry, and the circular economy.

EXECUTIVE SUMMARY

Decarbonizing industrial process heat is one of the most pressing challenges in achieving global net-zero targets. While significant progress has been made in decarbonizing the electricity sector, industrial heat production remains heavily reliant on fossil fuels. However, Thermal Energy Storage (TES) has emerged as a key solution to accelerate the transition to sustainable heat, enhance system flexibility, and provide critical services to the energy infrastructure.

This paper explores the macroeconomic benefits TES offers, particularly in alleviating strain on aging grid infrastructure worldwide. It also demonstrates how TES can be leveraged in key markets, such as the United States, Europe, and Australia, to create economic value for energy consumers. Through this analysis, the paper positions TES as a strategic response to both systemic and industrial challenges.

The paper examines use cases for various stakeholders, including industrial players requiring process heat up to 1,300 °C and utilities that can offer Heat-as-a-Service (HaaS) or use TES for essential grid services like frequency restoration. These use cases underscore TES as a commercially viable solution, outperforming other net-zero heat technologies from both a system and economic perspective.

The growing incidence of negative electricity prices in global markets highlights the need for technologies that enable flexible energy procurement to reduce costs. The analysis shows that implementing TES systems can result in substantial reductions in electricity and heat costs, with monthly savings ranging from 30% to over 150% in extreme price environments like those in Australia.

Finally, the paper emphasizes the importance of integrated planning across grids, flexible energy consumers, and system services to ensure the successful decarbonization of the heating sector. Given current technologies, market trends, and regulatory incentives, TES is expected to play a crucial role in this transition and will attract increasing attention from both regulators and industry leaders in the coming years.

INTRODUCTION

The global electricity transition is making significant progress in some regions of the world. In 2023, renewables accounted for over 44% of the EU's and 21.4% of the US's electricity generation.[1,2] Some US states already have higher shares, such as California with 50.6% renewable power generation.[3] However, the increased penetration of renewable energy sources (RES) poses a number of challenges for grid operators and industrial consumers alike. Intermittent generation leads to supply concerns, volatile energy prices, and grid constraints.

Parallel to electricity, decarbonising heat is a big challenge. While electricity is decarbonising rapidly, heat is still lagging behind. This proofs especially problematic since approximately 50% of final energy demand is heat. Net-zero will therefore remain a distant target if the decarbonisation of heat processes will not pick up pace.

Currently, renewables account for only about 13% of global heat consumption and expected renewable heat developments are insufficient to displace fossil-based heat generation.[4] This dynamic is further reinforced by the rapid growth in industrial heat demand, with China and India alone accounting for 60% of this industrial heat demand growth.[5]

To date, this issue has not been sufficiently addressed and renewable energy for heat generation is only used sporadically. However, a CO_2-neutral heat supply is an important prerequisite for achieving climate targets. The pace of the heat transition must therefore be accelerated significantly in the coming years.

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[1] Eurostat (2024) Renewables take the lead in power generation in 2023 [Online available at: https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20240627-1]

[2] EIA (2024) What is U.S. electricity generation by energy source? [Online Available at: https://www.eia.gov/tools/faqs/faq.php?id=427&t=3]

[3] California Energy Commission (2023) Clean Energy Serving California [Online available at: https://www.energy.ca.gov/programs-and-topics/topics/renewable-energy/clean-energy-serving-california]

[4] IEA (2024) Renewables 2024 [Online available at: https://www.iea.org/reports/renewables-2024]

[5] Ibid.

Industrial process heat requires a wide range of temperatures depending on the specific application and industry. Typical temperature ranges are 1) low temperature (0-100 °C) 2) medium temperature (100-500 °C), 3) high temperature (500-1000 °C), and 4) very high temperature (> 1000 °C). Generally higher temperature ranges are more difficult to decarbonise and less technology options are viable solutions. Most solutions rely on large amounts of electricity, e.g., direct electrification. While these solutions can address the negative climate impact of fossil fuels, they often lack the responsiveness required to meet the new demands of a decarbonised electricity grid. This creates new challenges in terms of price spikes, flexibility, and system stability that limit the viability of these solutions.

It is therefore imperative to explore sector coupling technologies that address both the heat and electricity transition. Thermal Energy Storage (TES) can provide heat up to 1300 °C, thus can play a pivotal role in meeting industrial demands while contributing to solving above mentioned macro-economic challenges.

As the dynamics of a decarbonised power sector and industrial heat transition are similar around the world, the findings of the paper are universally applicable.
In particular, the paper focuses on market dynamics in the Europe, the US,
and Australia.

1. CHALLENGE:

DECARBONISING AND ELECTRIFYING HEAT – LEVERAGE SYNERGIES BETWEEN THE GRID AND INDUSTRIAL HEATING

1.1 STATUS QUO OF THE INDUSTRIAL HEAT TRANSITION

Heat is essential for many industrial processes, including fluid heating, distillation, calcination, drying and chemical reactions. These processes operate at temperatures ranging from just above ambient to well over 1300 °C. Globally, industrial process heat accounts for more than 50% of energy demand in key industries such as metals, cement, and glass. However, despite the high penetration of renewables in the electricity sector, almost all industrial process heat is still generated from fossil fuels.

As a result, industrial heating is one of the largest emitting sectors, accounting for about 24% of global energy-related greenhouse gas emissions and final energy consumption.[6] In Europe, emissions from the industrial sector have only decreased by app. 24% since 2010 - far from the targeted net-zero trajectory.[7] In addition, the cost of fossil fuels is rising, with carbon pricing expected to increase steadily over the next decade.

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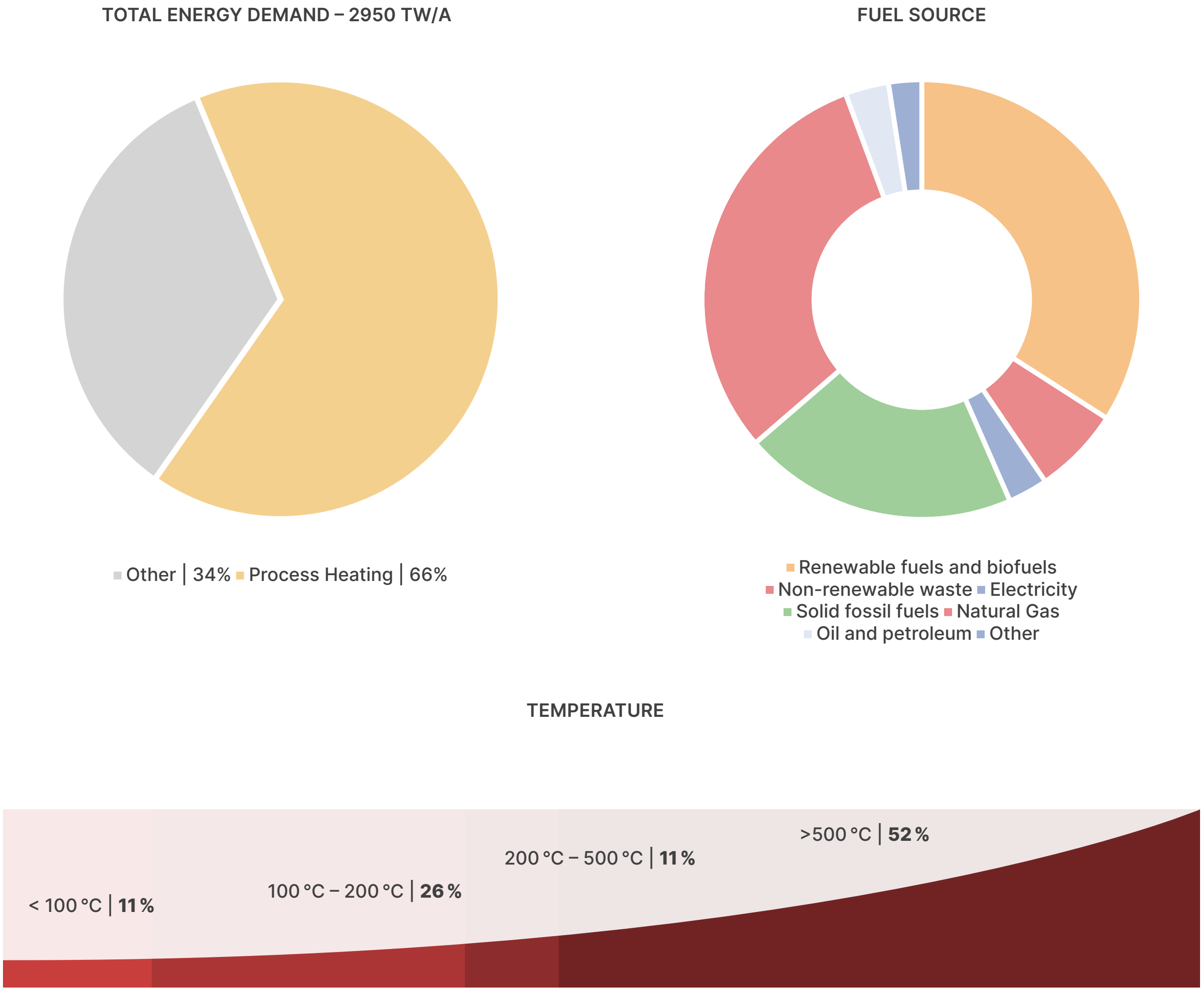
[6] United States Environmental Protection Agency (2023) Global Greenhouse Gas Overview [Online available at: https://www.epa.gov/ghgemissions/global-greenhouse-gas-overview]

[7] Eurostat (2024) Industrial emissions statistics [Online available at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_emission_statistics]

Figure 1: Industrial process heat and fuel source in the EU[8]



Several strategies and technologies have already been developed and are being implemented to decarbonize industrial heat (see Chapter 2). However, electricity-based heat generators are not only technically feasible, but will be the cheapest, most efficient, and locally available decarbonisation vectors in the process heat.

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[8] Own elaboration based on Eurostat (2022) Energy Balances – Gross heat production [Online available at: https://ec.europa.eu/eurostat/cache/infographs/energy_balances/enbal.html?geo=EU27_2020&unit=KTOE&language=EN&year=2022&fuel=fuelMainFuel&siec=TOTAL&details=0&chartOptions=0&stacking=normal&chartBal=&chart=&full=0&chartBalText=&order=DESC&siecs=&dataset=nrg_bal_s&decimals=0&agregates=0&fuelList=fuelElectricity,fuelCombustible,fuelNonCombustible,fuelOtherPetroleum,fuelMainPetroleum,fuelOil,fuelOtherFossil,fuelFossil,fuelCoal,fuelMainFuel]

1.2 DECARBONISATION OF THE ELECTRICITY GRID AS A PREREQUISITE FOR DECARBONISING INDUSTRIAL HEAT

The energy transition think-tank Agora Industry estimates that ~60% of industrial heat applications can be electrified with today's technology.[9] This process relies heavily on a decarbonised power sector that provides a continuous supply of low-cost renewable electricity. The most challenging last third of the journey to a carbon-neutral power grid is yet to come, and as renewable energy generation increases, the strain on aging and insufficient grid infrastructure becomes apparent. While grid operators and governments around the world are attempting to address this challenge through increased investment (e.g., $2.2 billion announced by the US Department of Energy for grids[10]) or regulatory frameworks (e.g., the EU Grid Action Plan[11]), much more demand side flexibility will be needed in the future.

As a result of grid bottlenecks and lacking demand flexibility, the macro- and micro-economic costs associated with network management, negative prices and interconnection queues have increased significantly in recent years. These costs can be substantially reduced by making the energy system more flexible.

COST INDICATOR #1: GRID MANAGEMENT COSTS INDUCED BY CONGESTION

Increasing integration of RES has similar consequences in all markets: grids become congested, and infrastructure proves insufficient to transport the required amount of electricity. As a result, system operators resort to measures such as dispatch or real-time curtailment. Irrespective of the regional footprint, these measures result in system operating costs that are passed on to end users through electricity bills.

In addition, grid congestion results in a significant amount of renewable electricity being wasted, a trend that will worsen in the coming years. The European Union Agency for the Cooperation of Energy Regulators (ACER) estimates that under a business-as-usual scenario, the amount of redispatch could increase from 50 TWh in 2022 to 374 TWh in 2030 and 809 TWh in 2040. The associated costs would increase from €5 billion in 2022 to €11-26 billion in 2030 and up to €103 billion in 2040.[12]

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[9] Agora Industry (2024) Direct electrification of industrial process heat [Online available at: https://www.agora-industry.org/fileadmin/Projects/2023/2023-20_IND_Electrification_Industrial_Heat/A-IND_329_04_Electrification_Industrial_Heat_WEB.pdf]

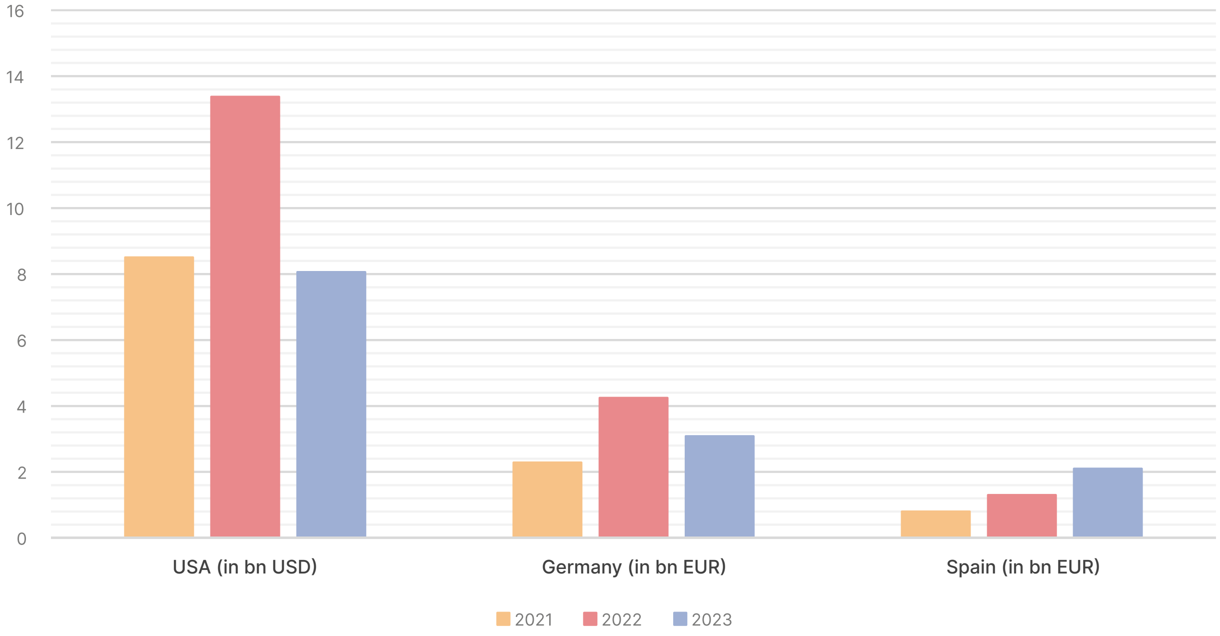
[10] US Department of Energy (2024) Biden-Harris Administration Invests $2.2 Billion in the Nation's Grid to Protect Against Extreme Weather, Lower Costs, and Prepare For Growing Demand [Online available at: https://www.energy.gov/articles/biden-harris-administration-invests-22-billion-nations-grid-protect-against-extreme]

[11] European Commission (2023) Grids, the missing link – An EU Action Plan for Grids [Online available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2023:757:FIN]

[12] Acer (2024) Transmission capacities for cross-zonal trade of electricity and congestion management in the EU [Online availability at: https://www.acer.europa.eu/sites/default/files/documents/Publications/ACER_2024_MMR_Crosszonal_electricity_trade_capacities.pdf]

These issued can be alleviated through energy storage systems such as TES, which provide a flexible and efficient way to store and manage large energy amounts for a customer that does not have already existing demand. This balance of supply and demand reduces the likelihood of congestion. Having said that, flexibility does not replace grid development.

Figure 2: Total grid congestion costs by country[13]



The cost of congestion management is relatively high in the countries shown, but congestion costs decrease in the US and Germany in 2023. This is due to lower electricity prices in 2023 compared to 2022. Despite this decrease in costs, the total number of interventions related to congestion management has increased. As a result, a large amount of electricity is not used in an energy efficient way.

IMPACT OF TES

BALANCING SUPPLY AND DEMAND FOR HEAT GENERATION

Energy storage systems can rapidly respond to fluctuations in supply and demand, providing services like frequency regulation, load following, and peak shaving. This responsiveness enhances grid stability and reduces the need for expensive peaking power plants, which are often required to manage demand spikes.

REDUCING CONGESTION

TES can alleviate congestion by storing energy locally and releasing it when needed, reducing the need for costly transmission expansions and operational adjustments.

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[13] Own elaboration based on Grid Strategies LLC, Bundesnetzagentur, and Aurora Energy Research

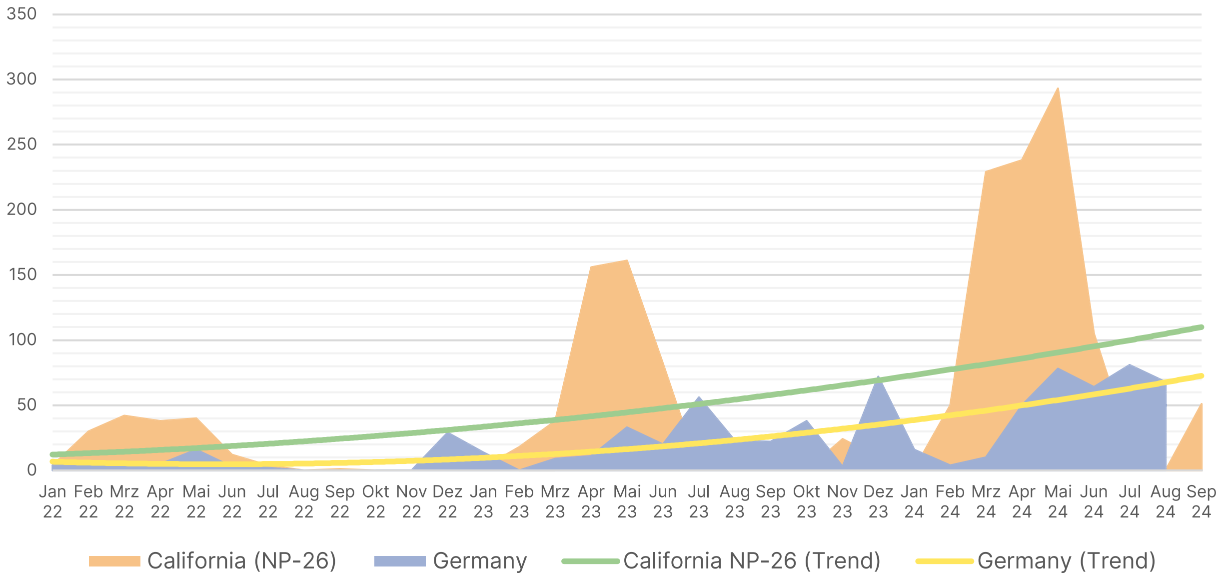
COST INDICATOR #2: NEGATIVE PRICES THREATEN TO UNDERMINE RENEWABLE ENERGY EXPANSION

In recent years, there has been a sharp increase in the number of hours with negative and very low electricity prices. During these periods, there is an oversupply due to high levels of RE generation coupled with low demand. As a result, generators pay electricity traders and consumers to acquire their electricity. This situation is exacerbated by the inflexibility of some RE and fossil fuel plants, which are unable to shut down or reduce generation in response to market signals, and therefore de facto cannot avoid periods of negative or very low prices. TES offers a solution to negative prices by flexibly storing energy thermally when prices are low.

Negative prices are not unique to renewable energy generation. During the Covid-19 pandemic, the price of oil turned negative due to an imbalance between supply and demand. The inability to store this “unwanted” commodity led to negative prices. The case of electricity is somewhat different, as there are market-ready solutions that can prevent periods of negative and very low prices, and also mitigate price spikes in the alternative scenario of high demand and low generation.

Negative prices are not inherently bad from a demand perspective, but they reduce the financial viability of renewables and thus undermine the financial returns from RE investments. This can lead to a drastic slowdown in the current investment momentum in RE projects, threatening the achievement of expansion targets.

Figure 3: Number of negative price hours in Germany and California (Price zone NP-26)[14]



All markets with a high share of variable renewable generation will see an increasing number of low and negative price hours in the coming years. At the same time, flexible fossil fuel generation will become increasingly expensive. Consumers unable to respond

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[14] Own elaboration based on California ISO, and EPEX Spot

to these market dynamics will be at a competitive disadvantage due to higher energy and hence production costs. Exploiting these price signals will therefore become increasingly important for industrial players around the world.

IMPACT OF TES

ENERGY ARBITRAGE
Storage creates increased demand during periods of negative prices and reduces demand during periods of high prices. It thus balances large price spreads resulting in a net-positive scenario for both generator and consumer. Negative prices are prevailing in today's energy systems e.g., Australia had negative prices 20 percent of the time in 2023.

This effect is especially significant in regions that support renewable energy through a guaranteed payment (strike price) while having a "claw back" mechanism in place for high-price periods. Hence allowing for a market-based price dynamic.

COST INDICATOR #3: INTERCONNECTION QUEUES

Around 3,000 GW of renewable energy projects are waiting in grid connection queues, equivalent to five times the amount of PV and wind capacity to be added in 2022.[15] These queues are largely caused by aging and low-capacity grid infrastructure combined with slow permitting procedures. As a result, the grid cannot facilitate the large number of grid connection requests from renewable energy projects. Interconnection costs have two main components: the direct cost of connecting renewable generation to the grid, and the indirect cost of upgrading the grid to avoid congestion. The former costs are necessary, while the latter are avoidable to a certain extend.

These interconnection queues are expensive for project developers, with the median interconnection cost being USD 46 million per GW, or about a quarter of the installation cost for wind and solar generators.[16] These costs not only divert capital that is critical to the energy transition, but also cause developers to abandon planned projects, putting the energy transition at risk.

Interconnection queues are closely connected to pre-existing grid congestions, grid stability and reliability, and longstanding grid expansion projects. All these issues can be addressed through flexibility options like thermal energy storage.

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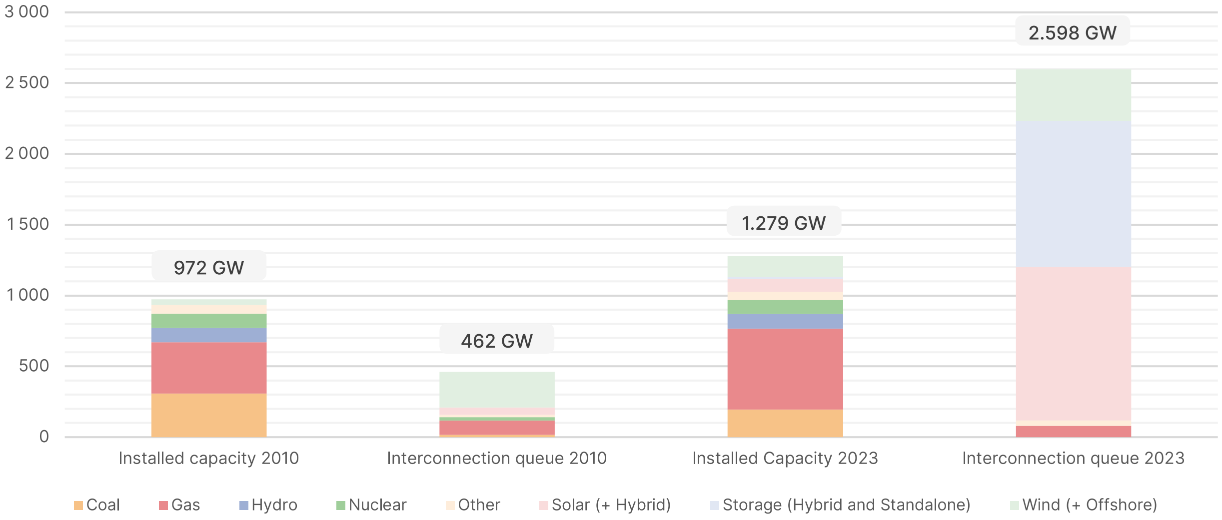
[15] IEA (2023) Electricity Grids and Secure Energy Transition [Online available at: https://www.iea.org/reports/electricity-grids-and-secure-energy-transitions]

[16] Johnston, Sarah, Liu, Yifeu, and Yang, Chenyu (2024) An Empirical Analysis of the Interconnection Queue [Online available at: https://econ-chenyu-yang.github.io/interconnection_queues.pdf]

Figure 4: Generation, Storage, and Hybrid Capacity in Interconnection Queues (USA)[17]



The US case shows that the 'length' of interconnection queues has increased significantly over the last decade. By 2023, the capacity of projects seeking interconnection far exceeds the total installed capacity. This is partly due to the fact that the energy market is becoming more decentralised, with a large amount of small RE project developers entering the market. This dynamic adds to the complexity of interconnection queues as the total number of applications increases and local grid capacities are maxed out. In the US, only ~14% of projects in the interconnection queue are realised.[18] This is partly due to long grid connection times. At current technology prices, these projects represent over $4.4 trillion of potential investment.[19] Interconnection queues therefore threaten to slow down both the energy transition and the economic prosperity of the countries concerned.

IMPACT OF TES

MITIGATING GRID UPGRADES

One of the major costs associated with interconnection is the need for grid upgrades to accommodate new wind and PV projects. Energy storage can help defer,[20] or reduce these upgrade costs by providing grid support services such as voltage regulation, frequency control, and congestion relief. By stabilizing the grid and balancing supply and demand locally, storage reduces the need for expensive infrastructure improvements, lowering the overall cost of interconnection.

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[17] Energy Technologies Area, Berkeley Lab (2024) Generation, Storage, and Hybrid Capacity in Interconnection Queues [Online available at: https://emp.lbl.gov/generation-storage-and-hybrid-capacity]

[18] Ibid.

[19] Ibid.

[20] Storage for Grid Deferral: The Case of Israel (2021) Gal et al. in IEEE PES Innovative Smart Grid Technologies Europe

2. THE CASE FOR THERMAL ENERGY STORAGE

2.1 DECARBONISATION OPTIONS FOR INDUSTRIAL HEATING

The previous chapter made the case for flexibility options such as TES from a systemic perspective. This approach is sound, but ultimately the deployment of a technology depends on the potential financial benefits to purchasers.

There is currently a wide range of technology options competing to support industrial heat decarbonisation. All options have their specific applications and limitations. In particular, temperature range, integration into existing processes, and availability are key criteria to assess when deciding on the best decarbonisation pathway.

Direct electrification of high-temperature heat through electric boilers or induction is currently the most efficient technology option, but it does not provide flexibility and therefore exposes industries to price peaks that often do not coincide with their constant electricity consumption (e.g. heat demand 24h/day). Therefore, complementing direct electrification with TES is a suitable option. However, TES can also function as a stand-alone solution, depending on consumption patterns and production size. As battery energy storage systems proved their value to the grid, especially for short-term use, one must state that TES has only a fraction of the costs of BESS, therefore is a more economical scaling technology.

Another widely discussed solution is green hydrogen, but the lack of infrastructure and uncertain availability and costs dampen the investment perspective for potential consumers. Therefore, the high potential of hydrogen does not necessarily translate into a high level of uptake or a short to medium term contribution to decarbonisation targets. The sector is already well behind its planned decarbonisation pathway[21], so over-reliance on hydrogen as a solution to industrial decarbonisation could lead to missed climate targets due to uncertain availability within the next 10-15 years and significant investment risks.

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[21] IEA (2024) Renewables 2023 [Online available at https://www.iea.org/reports/renewables-2023/heat]

BRIEF COMPARISON OF THERMAL ENERGY STORAGE AND BATTERY STORAGE

While batteries store energy electro-chemically, TES stores energy as heat, mostly as sensible heat, meaning there is a heated material in an insulated storage vessel. While batteries charge and discharge electricity, TES charges heat or electricity and discharges at first heat. The benefits lie in uncritical materials, better efficiency for heat use and longer storage durations. Furthermore, in case of Kraftblock, there is no fixed charging/discharging ratio like batteries have and thus steering the charging power is more flexible.

Compared to green hydrogen and direct electrification, bioenergy is already a widely used option for industrial heating processes, but biomass potentials are limited and competition for feedstock across industries raises concerns about scalability, cost, and environmental sustainability. The respective whitepaper from Kraftblock[22] provides a deeper analysis of net-zero heat technologies.

Figure 5: Comparison of different decarbonisation technologies[23]

DIMENSION/ TECH	TES+P2H	Induction	E-Boiler	BESS+P2H	Bio energy	Green H2
TEMPERATURE	1,300 °C	3,000 °C	500 °C	Dependent	1,200 °C	3,000 °C
ROUND-TRIP EFFICIENCY	~ 95%	~ 90%	~ 98%	80% - 98% minus degradation	~ 33%	<67%
AVAILABILITY	Flexible	Not flexible*	Not flexible*	Flexible	7,000-8000 full load hours	7,000-8000 full load hours
STORAGE LIFETIME	15,000 cycles	n.a.	n.a.	5,000 – 10,000 cycles	n.a.	n.a.
COSTS	🟩	🟩	🟩	🟧	🟧	🟥
INTEGRATION	🟩	🟩	🟩	🟩	🟩	🟥
LAND USE	🟩	🟩	🟩	🟩	🟥	🟧
TLR	8-9	9	9	9	8	8-9
SUPPLY CHAIN RESOURCES	🟩	🟩	🟩	🟧	🟥	🟥

Flexible heating applications such as TES can therefore be an important enabler for the electrification of industrial heating and the ability of the electricity sector to balance supply and demand. Rather than adding to the burden on the grid, flexible TES can respond dynamically to the needs of the grid, procuring electricity primarily when the grid is ‚congested'. In this way, TES can relieve the grid and provide significant benefits compared to other sector coupling technologies. Hence, decarbonisation of industrial heat demand will not be possible without a fully flexible and renewable power sector. Cross-cutting technologies that offer both system and consumer benefits will be essential to achieving global net zero targets.

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[22] Kraftblock (2024) Comparison of Technologies to decarbonize Process Heat in Industries [online available at: https://www.kraftblock.com/blog/comparison-of-technologies-to-decarbonize-process-heat-in-industries]

[23] Own Elaboration based on McKinsey & Company, Systemiq, Fraunhofer ISI, Agora Industry, Berger, NREL, DLR, IEA

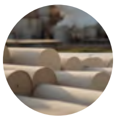
2.2 DOUBLE DIVIDEND: TES SYSTEMS PAVE THE WAY FOR THE ELECTRICITY TRANSITION AND KICK-START THE INDUSTRIAL HEATING TRANSITION

In the following chapters, the paper will discuss how TES can contribute to decarbonisations targets as well as opening up new economic opportunities. These opportunities are closely linked to the volatile electricity prices which need to be leveraged by the industry. Large industrial companies, as well as utilities and energy suppliers, have direct access to electricity spot markets and are therefore able to react to price signals in real time. Smaller companies do not have this access but have the option of indexed or dynamic electricity tariffs. These tariffs still reflect market dynamics and prices and therefore incentivise flexible technologies such as TES.

Kraftblock's Net-Zero Heat System converts electricity in heat and stores it in the Kraftblock storage. It is discharged by blowing cold air into the storage which heats on the material. The discharged air is adapted to the necessary temperature and medium for the industrial process. This allows the use of existing infrastructure in a factory.

Due to the fact Kraftblock's Net-Zero-Heat system can cover temperature ranges from 100 °C to 1,300 °C, it is a viable technology option for decarbonising processes in the following industries:


STEEL AND METALS


PULP AND PAPER


MUNICIPAL UTILITIES AND ENERGY SUPPLIERS


GLASS AND CERAMICS


FOOD AND BEVERAGES


CHEMICALS AND PLASTICS


OIL AND GAS


OTHER INDUSTRIES

2.3 USE-CASES FOR TES – INDUSTRY

LOAD MANAGEMENT

TES can be used in industrial applications to charge electricity when it is abundant and cheap and store it as thermal energy. This electricity can be shifted to predefined hours of use or even 24/7, especially to extort the low prizes and avoid the times of high energy prices. By shifting this load from peak supply (low prices) to peak demand (high prices), companies can achieve significant cost savings.

In the following the paper will discuss different use-cases that only differ in their geographical focus; hence the electricity price signals in the respective market.

1. California (ZP-26) with relatively low electricity prices
2. Spain with great electricity price disparities throughout the seasons
3. Australia (Victoria) with extremely low electricity prices
4. Germany with relatively constant yet high electricity prices throughout the year

All four cases compare a baseline scenario (direct electrification) and a TES scenario (direct electrification + TES). All scenarios assume a constant energy demand throughout the day, culminating in a demand of 50,000 MWh per month. The offtaker is a large industrial company with direct access to the spot market and can therefore react to and benefit from price signals. However, the findings are to a lesser extent applicable to industrial players without direct access to the spot market.

Dynamic or indexed tariffs still transmit market signals to consumers, these tariffs follow spot market signals but do not reflect them 1:1. Consequently, the projected cost savings are similar, but to a lesser extent due to additional components such as retail margins or network charges on top of the wholesale price. The adjustment of industrial demand to price signals is therefore possible and financially sound for players with and without direct access to the spot market.

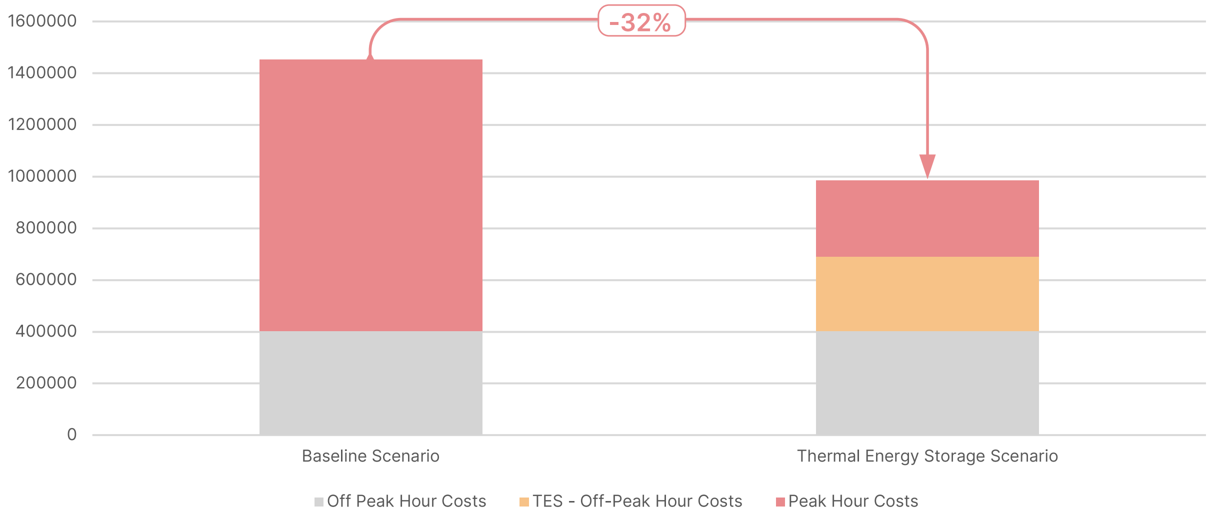
The four reference cases assume a TES storage capacity of 300 MWh, charge and discharge rates of 50 MW, and 2 charge/discharge cycles a day. This TES configuration can shift ~18.000 MWh of peak energy usage to off-peak periods and therefore take advantage of price signals.

All electricity prices reflect official day-ahead spot market rates for their respective regions. Peak prices were calculated as the average of the highest-priced 50% of hours in a month, while off-peak prices were derived from the average of the lowest-priced 50% of hours in the same period. The calculations are solely based on wholesale costs, additional components such as network costs or taxes were excluded.

Starting with the US market, the price spreads in the price zone ZP-26 are noticeable but not huge, therefore cost savings are in the range of about 30% during the analysed month.

CASE 1: CALIFORNIA ZONE ZP-26 | September 2024

– PEAK Ø 42,01$/MWH – OFF-PEAK 16,08$/MWH



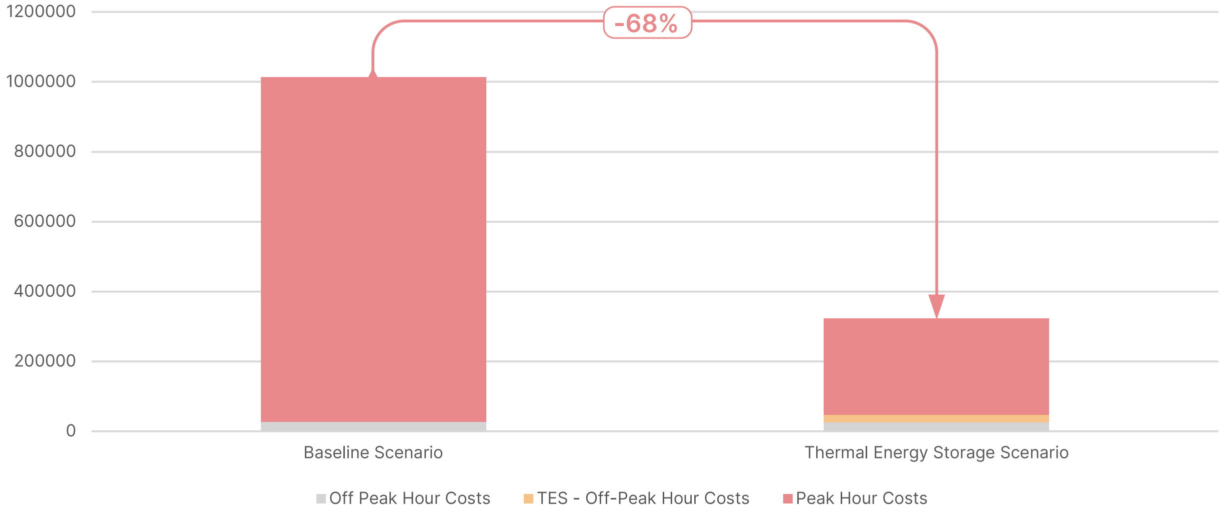
ASSUMPTION	
BASELINE SCENARIO (NO THERMAL ENERGY STORAGE)	THERMAL ENERGY STORAGE SCENARIO
OFF-PEAK HOUR COSTS: **25,000 MWh at 16.08 $/MWh** **= 402,000 $**	OFF-PEAK HOUR COSTS: **25,000 MWh at 16.08 $/MWh** **= 402,000 $** **18,000 MWh (TES) at 16.08 $/MWh** **= 289,440 $**
PEAK HOUR COSTS: **25,000 MWh at 42.01 $/MWh** **= 1,050,250 $**	PEAK HOUR COSTS: **7,000 MWh at 42.01 $/MWh** **= 294,070 $**
TOTAL: **1,452,250 $**	TOTAL: **988,510 $**
SAVINGS **Energy Cost Difference: 463,740 $**	

While the use case focused on an in-depth analysis of September 2024, the findings are applicable throughout the entire year. Using the same methodology, the most expensive 50% of hours in 2023 averaged an electricity price of $92.66/MWh, while the least expensive 50% averaged $23.68/MWh. Similar trends were observed across all subsequent use cases, although the results are less robust due to the charging and discharging times of the TES systems and uneven spreads of negative hours. Therefore, the paper focused on a single month to ensure an accurate representation of the cost savings.

The Spanish electricity market displays different price dynamics, whereas day-ahead prices are relatively high during winter and summer months and dip during spring. Therefore the paper will next establish a scenario based on Spanish electricity prices in March 2024.

CASE 2: SPAIN | March 2024

– PEAK Ø 39.4 €/MWH – OFF-PEAK 1.1 €/MWH



ASSUMPTION

BASELINE SCENARIO (NO THERMAL ENERGY STORAGE)	THERMAL ENERGY STORAGE SCENARIO
OFF-PEAK HOUR COSTS: **25,000 MWh at 1.1 €/MWh** = 27,500 €	OFF-PEAK HOUR COSTS: **25,000 MWh at 1.1 €/MWh** = 27,500 € **18,000 MWh (TES) at 45 €/MWh** = 19,800 €
PEAK HOUR COSTS: **25,000 MWh at 39.4 €/MWh** = 2,750,000 €	PEAK HOUR COSTS: **7,000 MWh at 39.4 €/MWh** = 275,800 €
TOTAL: 985,000 €	TOTAL: 323,100 €

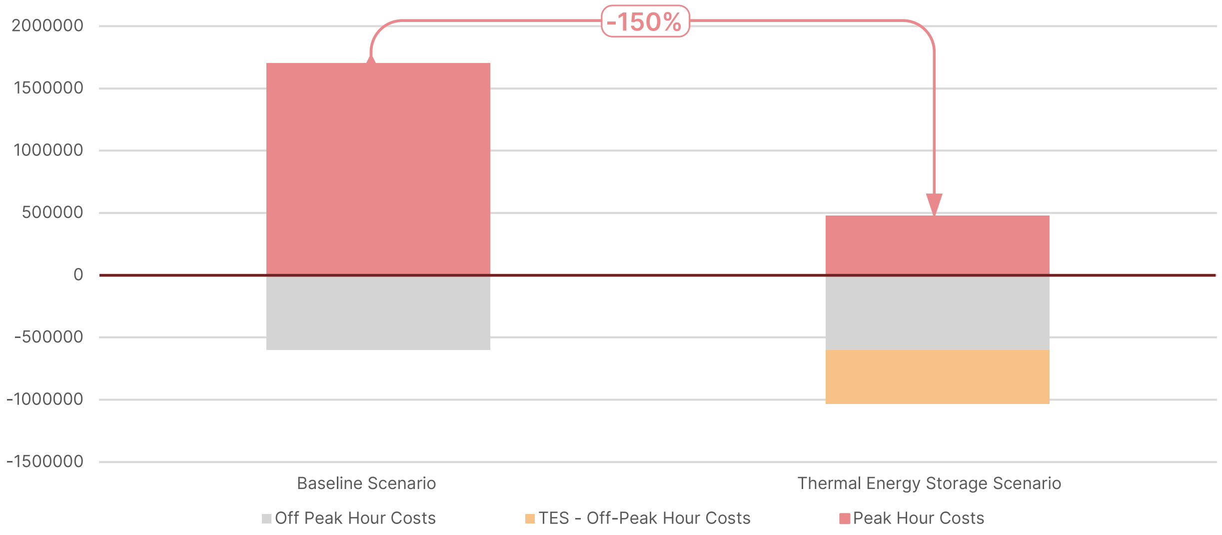
SAVINGS
Energy Cost Difference: 689,400 €

The Spanish example shows that TES systems are especially advantageous in regions with period of very low or below zero prices. The proper reaction to market signals allows for cost savings of up to 70% in Spain.

Next, we want to present an “extreme” scenario based on the Australian electricity market, which experience large numbers of negative prices.

CASE 3: AUSTRALIA - VICTORIA | January 2024

– PEAK Ø 68,2 AU$/MWH – OFF-PEAK -24 AU$/MWH

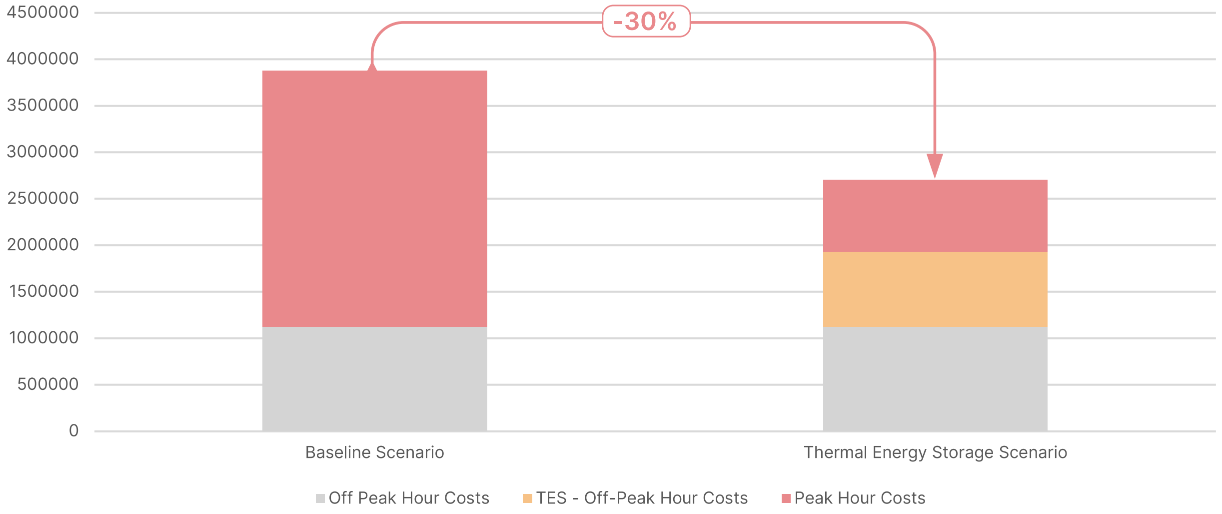


ASSUMPTION	
BASELINE SCENARIO (NO THERMAL ENERGY STORAGE)	THERMAL ENERGY STORAGE SCENARIO
OFF-PEAK HOUR COSTS: **25,000 MWh at -24 AU$/MWh** **= -600,000 AU$**	OFF-PEAK HOUR COSTS: **25,000 MWh at -24 AU$/MWh** **= -600,000 AU$** **18,000 MWh (TES) at -24 AU$/MWh** **= -432,000AU$**
PEAK HOUR COSTS: **25,000 MWh at 68,2 AU$/MWh** **= 1,705,000 AU$**	PEAK HOUR COSTS: **7,000 MWh at 68,2 AU$/MWh** **= 477,400AU$**
TOTAL: **1,105,000 AU$**	TOTAL: **-554,600 AU$**
SAVINGS **Energy Cost Difference:** 1,659,600 AU$	

Australia is somewhat of an outlier compared to other electricity markets in that periods of negative prices are the norm rather than the exception. These negative prices persist for a variety of reasons, largely due to high levels of PV generation and very inflexible coal-fired generation, which contributes to oversupply. Periods of e.g. negative AU$300/MWh are therefore common, whereas negative prices in the EU or the US tend to be closer to 0.

CASE 4: GERMANY | July 2023

– PEAK Ø 110 €/MWH – OFF-PEAK 45 €/MWH



ASSUMPTION

BASELINE SCENARIO (NO THERMAL ENERGY STORAGE)	THERMAL ENERGY STORAGE SCENARIO
OFF-PEAK HOUR COSTS: **25,000 MWh at 45 €/MWh** = 1,125,000 €	OFF-PEAK HOUR COSTS: **25,000 MWh at 45 €/MWh** = 1,125,000 € **18,000 MWh (TES) at 45 €/MWh** = 810,000 €
PEAK HOUR COSTS: **25,000 MWh at 110 €/MWh** = 2,750,000 €	PEAK HOUR COSTS: **7,000 MWh at 110 €/MWh** = 770,000 €
TOTAL: 3,875,000 €	TOTAL: 2,705,000 €

SAVINGS

Energy Cost Difference: 1,170,000 €

Despite its relatively high share of renewable generation Germany experiences relatively high electricity prices compared to other EU Member States. Furthermore, day-ahead prices are on average relatively stable throughout the year. Nonetheless, the discrepancy between Peak and Off-Peak electricity costs leads to considerable cost savings.

It is important to note that the scenario described represents optimal use of the TES system, which is not always possible in reality. Nevertheless, energy cost reductions of more than 30% are possible with the TES configuration described. Despite the greater price differences between European regions, the benefits of TES systems remain comparable in regions where electricity prices are more uniform. In general, TES systems offer a greater cost advantage in markets where there is a significant price disparity between peak and off-peak electricity prices. This is evidenced by the use-cases of Spain and Australia.

The scenarios described are all based on a TES with a storage capacity of 300 MWh, so price peaks cannot be completely avoided. However, further energy cost reductions are possible with larger storage capacities, up to the point where process heat can be fully supplied by the TES using low- and negative-cost electricity.

The trend towards periods of low or negative electricity prices will continue in the coming years, and periods of (ultra-)low prices will become more frequent. In addition, dynamic and indexed tariffs are becoming increasingly popular and will gain greater acceptance and regulatory support in the coming years. This will strengthen price signals of power spot markets and increase exposure to price volatilities for a wide range of a consumers. Hence, the benefits of TES are not limited to large industries with access to the spot market.

2.4 USE-CASES FOR TES – UTILITIES

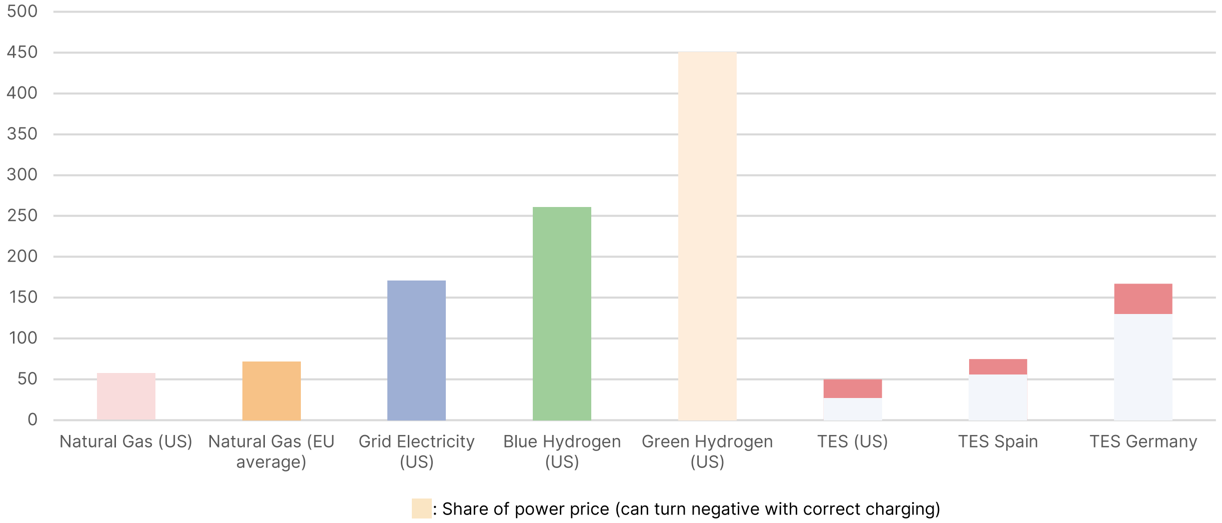
HEAT-AS-A-SERVICE (HAAS)

Heat-as-a-Service is becoming an increasingly interesting business model which is similar to the described load management use-cases above. The difference lies in the ownership of the TES system. In the HaaS business model it is the energy service provider rather than the end-consumer who has ownership over the heat generator. This is especially relevant for industrial offtakers which cannot bear the capital costs of TES systems or want to decouple capital allocation from their decarbonisation efforts to focus on their core business.

Through this model the offtaker still has the advantage of low-carbon heat supply through the TES, enabling the decarbonisation of industrial processes. The contract of the HaaS model usually entails a stable price over a longer period of time giving the offtaker a price guarantee for the heat supply. In return for the CAPEX investments of the heat provider, it can derive profits through the above-described load management use-case and charge the TES system during low/negative price periods while selling at a stable preestablished price.

The provider of heat, hence the owner of the TES asset, does not need to be a utility company but can also be the operator of renewable generation assets like a solar park. Therefore, the operator of the RE asset can integrate a TES system in their asset and sell heat directly to the offtaker through a private wire. The function of the TES can therefore be similar to a conventional battery storage with the added benefit that the TES system can store energy significantly longer than battery systems, providing more flexibility on the market through possible larger timeframes to shift the energy. Depending on the specific case batteries and TES are not per se mutually exclusive and can be used complementary.

Figure 6: Levelized cost of heat (€/MWh)[24]

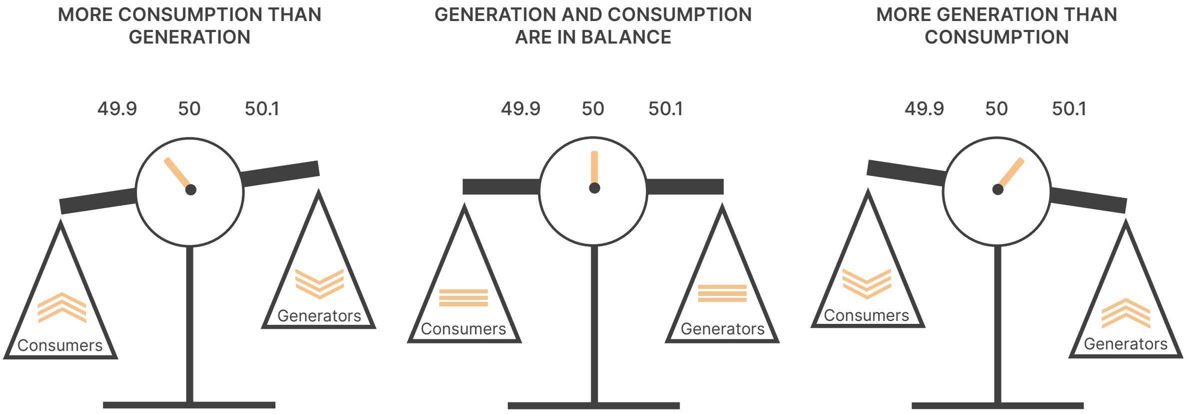


Since the heat generation costs for the TES system are fluctuating, while the selling price is stable, the TES operator can make considerable profits.

FREQUENCY RESTORATION RESERVE

Frequency restoration services are used to maintain the stability of the electricity grid by balancing supply and demand in real time. This is necessary to ensure that the grid frequency remains within a specified range, 50 Hz in most regions and 60 Hz in the Americas and parts of Asia. If the grid exceeds a threshold of about +/- 0.2 Hz, a brown-out or blackout can occur.

Figure 7: Balance between electricity generation and electricity consumption



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[24] Own elaboration based on: Gilbert, Tristian, and Menon, Akanksha and Dames, Chris and Prasher, Ravi (2023) Heat source application-dependent levelized cost of decarbonized heat [Online available at: https://www.sciencedirect.com/science/article/pii/S2542435122005645] & Systemiq (2024) Catalysing the Global Opportunity for Electrothermal Energy Storage [Online available at: https://www.systemiq.earth/electrothermal-energy-storage/]

During times of widespread fossil generation in centralised power stations and low penetration of renewables, the need for flexibility was rather low. Nowadays, with increasing penetration of renewables, flexibility is essential for a functioning power sector due to the higher intermittency and lower predictability of generation. To procure the necessary flexibility, auctions are held where flexibility providers can offer their capacity and energy. In return, they receive a payment consisting of two main components:

1. capacity payment (availability of reserve capacity) and
2. energy payment (actual activation of reserves).

Energy storage, in particular thermal energy storage, can provide downward flexibility by providing increased consumption in times when frequency regulation is needed.

Utilities can offer their TES asset to be part of the automatic frequency reduction reserve (aFFR). This provision of flexibility is remunerated; the remuneration is as flexible as the flexibility asset itself, with prices ranging from €1/MW per hour to €129/MW per hour depending on the season and time of day in 2023. On average, the capacity price was at ~15 €/MW per hour.[25] In the case described, the 300 MWh TES system provides aFRR (down) for 30 minutes per day at full capacity. This results in an additional annual revenue of €164.250.

ASSUMPTION

TES CAPACITY:	**300 MWH**
(DIS-)CHARGE:	**50 MW**
RESPONSE SERVICE:	**AUTOMATIC FREQUENCY RESTORATION RESERVE (DOWNWARD)**
OPERATION DURATION:	**30 MINUTES AT FULL CAPACITY / DAY**
RENUMERATION:	**AVERAGE 15 €/MW PER HOUR (WIDE PRICE SPREADS FROM 1 €/MW PER HOUR TO 129 €/MW PER HOUR)**

BENEFIT

ADDITIONAL ANNUAL REVENUE: 164,250 €

As the penetration of renewables increases, traditional power plants that were used to provide frequency response services are being pushed out of the wholesale merit order. This reduces the availability of and need for flexibility. Additionally further assets such as coal or nuclear are being phased out within the next decade, therefore further increasing the need for flexibility options.

[25] Julien Jomaux (2024) European power reserves: part 2 - aFRR (and how solar is impacting it) [Online available at: https://gemenergyanalytics.substack.com/p/european-power-reserves-part-2-afrr]

3. POLICY TRENDS DRIVING THERMAL STORAGE ADOPTION

Moving away from a fossil fuel in dispatchable power generation and industrial heating is still widely perceived as an economic and technological risk. Today, however, industrial players can draw on a range of commercially available technologies that offer solutions to these two critical challenges of the energy transition. More importantly, the key role of these technologies is being leveraged and de-risked by policy trends and new revenue streams for flexibility services.

3.1 INDUSTRIAL HEAT INCENTIVES

POLICY LEVER	REGION	STATUS	EXPLANATION / CONTEXT
INDUSTRIAL DECARBONISATION ACCELERATOR ACT	EU	ANNOUNCED	→ Channel investment in infrastructure and industry, in particular energy intensive sectors
EMISSION TRADING SYSTEMS	EU / UK	IN FORCE	→ Companies need to buy emission allowances that gives them the right to emit a certain amount of CO_2. This system incentivises decarbonisation efforts by reducing the cost disparity between net-zero and fossil-based assets
GREEN LEAD MARKETS / GREEN PUBLIC PROCUREMENT / ECODESIGN REGULATION	EU	FRAMEWORK IN PLACE	→ Leverage public procurement to drive market demand for greener products
CARBON CONTRACTS FOR DIFFERENCE	GER / UK EU	IN FORCE UPCOMING	→ Financial instruments designed to promote climate-friendly production processes in energy-intensive industries by compensating for the additional costs associated with these processes
INFLATION REDUCTION ACT	USA	IN FORCE	→ $6 bn for competitive grants for industrial technologies (retrofits or new equipment) designed to accelerate GHG emission reductions in industrial processes → Tax credits for investments in advanced energy projects that reduce GHG emissions by at least 20%
INDUSTRIAL ENERGY TRANSFORMATION FUND	UK	IN FORCE	→ Designed to help businesses with high energy use to cut their energy bills and carbon emissions through investments in energy efficient and low-carbon technologies

3.2 FLEXIBILITY SCHEMES

Next to regulatory incentives focused on the adoption of low-carbon heating, a variety of levers exist to further boost system flexibility, specifically, energy storage technologies.

POLICY LEVER	REGION	STATUS	EXPLANATION / CONTEXT
BALANCING ENERGY MARKET (RAM) E.G.,AUTOMATIC FREQUENCY RESTORATION RESERVES (AFRR)	EU COUNTRIES & UK	IN FORCE	→ Auctions to procure capacity for frequency response services
FLEXIBLE GRID CHARGES	GER	ANNOUNCED	→ Increase industrial demand-side flexibility through reduced grid charges
DEMAND SIDE MANAGEMENT TARGETS	EU	ANNOUNCED	→ EU Member States need to include demand-side resources in all planning, policy, and major investment decisions above a certain threshold. Concrete targets on DMS and flexibility are expected to follow in most regions.

These regulatory trends and remuneration opportunities will strengthen the market momentum for TES systems and are expected to increase in the coming years. TES, with its systemic and private benefits, is therefore not only a viable option for industries and utilities but will also gain increasing traction due to its systemic benefits.

4. CONCLUSION

Thermal energy storage presents a great opportunity for the energy landscape, offering significant benefits both from a system-wide perspective as well as for individual industrial users. As the global energy transition accelerates towards more sustainable and renewable energy sources, this momentum has not fully reached the process heat sector. The sector is still falling short of its sector-specific contribution to climate targets; this trajectory is not expected to change anytime soon.

The paper emphasised the need for unlocking the synergies of sector coupling technologies in order to have a successful twin transitions of both heat and electricity transition. The electricity grid serves as the backbone of global net-zero ambitions but is unable to stem the challenges ahead. Flexibility is therefore not only necessary but mandatory for a successful energy transition.

From a system perspective, TES contributes to grid stability by effectively managing the intermittency of renewable energy sources like solar and wind. By storing excess thermal energy during periods of low demand or high renewable generation, TES can release energy when it is most needed, thus balancing supply and demand. This capability reduces the reliance on fossil fuel-based peaking plants, cutting greenhouse gas emissions and lowering the overall carbon footprint of energy production. Moreover, TES enhances the flexibility of electricity demand, thus enabling a more dynamic and resilient energy infrastructure that can adapt to fluctuations in energy availability and consumption.

For individual industrial offtakers, TES offers compelling advantages in terms of energy cost savings, operational efficiency, and sustainability. By utilizing TES, industries can reduce their peak energy consumption, leading to lower energy bills and reduced exposure to volatile energy prices. TES also allows for greater operational flexibility, enabling industries to optimize their energy use and align it with production schedules, maintenance windows, or other strategic priorities. Furthermore, the adoption of TES supports industries in meeting their sustainability goals by reducing their carbon emissions and increasing their use of renewable energy.

In conclusion, the widespread implementation of TES is not just a technological innovation but a strategic imperative for both energy systems and industrial sectors. By addressing the challenges of energy storage and distribution, TES plays a pivotal role in the transition to a sustainable energy future. It empowers energy systems to be more resilient, flexible, and environmentally friendly while providing industrial offtakers with the tools to enhance competitiveness, reduce costs, and achieve sustainability targets. As the energy landscape continues to evolve, the integration of TES will be crucial in shaping a more sustainable and efficient future for all stakeholders involved.

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