Net-zero heat

Long Duration Energy Storage to accelerate energy system decarbonization

LDES
LONG DURATION
ENERGY STORAGE
COUNCIL

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2. It is not their intention that any such form of coordination will be adopted.

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Contents

Preface

We must capture the narrow window of opportunity to achieve a net-zero energy system. The decarbonization of the energy sector needs to accelerate to become aligned with a net-zero pathway that limits global warming to below 1.5°C. However, achieving net-zero emissions by 2050 requires massive development of renewables, new and reinforced infrastructure, and the adoption of new clean technologies. Many challenges compound in this transition, as supply chains need to be scaled up, end-use equipment needs to be adapted, and infrastructure needs to be deployed and reinforced (for example, transmission and distribution electricity grid expansions can take up to 15 years to realize). Immediate action is required to meet emission-reduction targets, limit the impact of climate change, and maximize the opportunities ahead.

As outlined in the 2021 LDES *Net-zero power* report,[1] long-duration energy storage (LDES) offers a low-cost flexibility solution to enable energy system decarbonization. LDES[2] can be deployed to store energy for prolonged periods and can be scaled up economically to sustain energy provision for multiple hours (ten or more), days (multiday storage), months, and seasons. LDES can store energy in various forms, including mechanical, thermal, electrochemical, or chemical and can contribute significantly to the cost-efficient decarbonization of the energy system. Furthermore, it helps address major energy transition challenges such as solar and wind energy supply variability, grid infrastructure bottlenecks, or emissions from heat generation.

This report presents the latest view on the role of LDES in helping achieve Net-zero power and heat by 2050,[3] focusing on the potential role of thermal energy storage (TES) in realizing net-zero heat. It builds on prior LDES Council research and analysis and presents updated cost perspectives based on data from LDES Council members. As a follow-up to previous LDES Council publications, this report focuses on the heat sector, a pivotal component in achieving global decarbonization and climate targets. Accordingly, it also focuses on a particular set of LDES technologies, TES, which can store heat, decarbonize heat applications, and integrate renewables in this sector and the broader energy system.

This report also highlights how an integrated system approach is imperative to cost-efficiently decarbonizing energy systems.[4] Electricity, heat, and hydrogen are becoming increasingly interconnected, driven by the growing uptake of renewable energy and access to technologies that integrate them, such as heat pumps and LDES (Exhibit 1). This creates the need to look at the integrated ecosystem rather than the separate energy sectors to jointly inform cost-optimized energy infrastructure developments. The analyses in this report take interdependencies between power, heat, and hydrogen into account to assess the cost-optimized mix of flexibility solutions needed for the heat and power sectors. It highlights the relationship between power LDES and TES to accelerate the energy transition, and the role that TES can play in decarbonizing heat applications.

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[1] https://www.ldescouncil.com/insights/

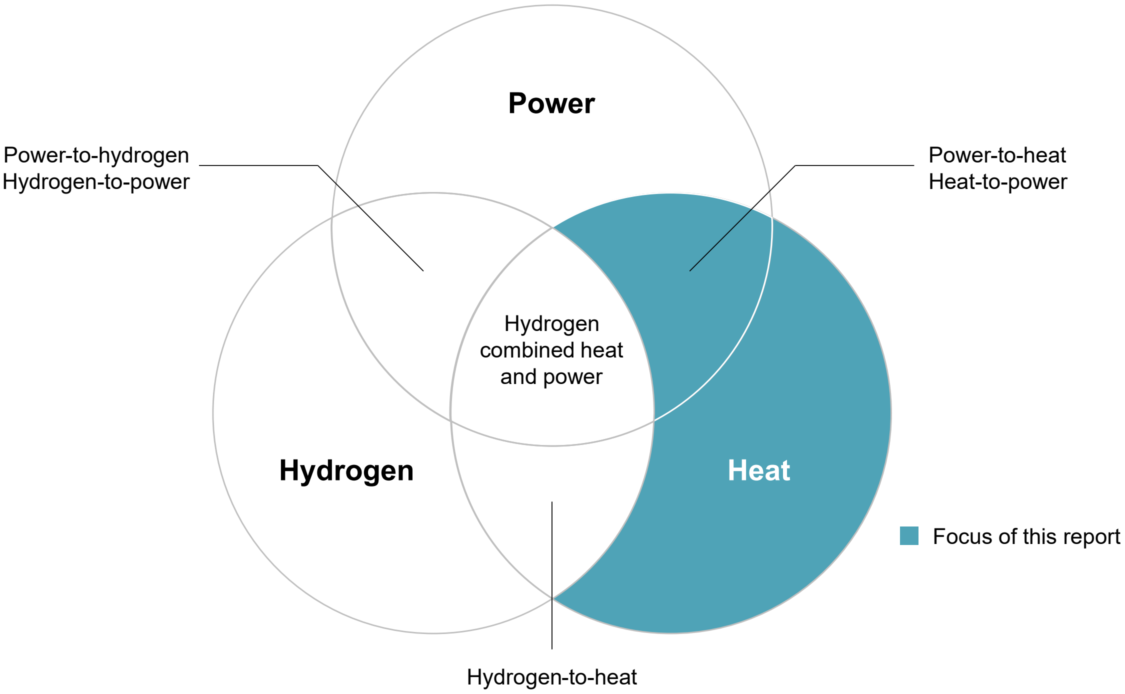
[2] Whenever LDES is mentioned as a technology group, it is defined as a technology storing energy for ten or more hours, as per ARPA-E's definition. When LDES is mentioned in analysis or modeling, the actual duration length is always specified, in line with NREL's recommendation.

[3] It is assumed that the power sector achieves net-zero emissions by 2040, and other sectors by 2050.

[4] The definition of energy system used in this report includes all components related to the production, conversion, and use of electrical energy, heat, and hydrogen. The electrification of the transport sector is included indirectly in the final electricity demand scenario from the McKinsey Global Energy Perspective.

Exhibit 1

Power, heat, and hydrogen interconnections



About the LDES Council

The LDES Council is a global, executive-led organization that strives to accelerate the decarbonization of the energy system at the lowest cost to society by driving the innovation and deployment of LDES and decreasing emissions. The LDES Council was launched at the Conference of Parties (COP) 26 and currently comprises 64 companies.[5] It provides fact-based guidance to governments and industry, drawing from the experiences of its members, which include leading technology providers, industry and service customers, capital providers, equipment manufacturers, and low-carbon energy system integrators and developers.

All technology providers, industry and services customers, capital providers, equipment manufacturers, and low-carbon energy system integrators and developers are members of the LDES Council.

Technology providers

1414° CLEAN SCALABLE ENERGY STORAGE	Electrified Thermal Solutions	e-zinc	MAGALDI	RheEnergise
Ambri	ENERGY VAULT Enabling a Renewable World	Form energy	MALTA	Rye Development
AZELIO	ENERGYDOME Making the Energy Transition happen	HEATRIX DECARBONIZING INDUSTRY	MGA THERMAL	SaltX Technology
Breeze Compressed Air Pipeline Systems	ENERGYNEST	Highview Power®	MINESTORAGE	Stiesdal®
BRENMILLER ENERGY	ENERVENUE	HYDROSTOR	Peniel Impact	STORWORKS POWER
cellcube	ENLIGHTEN	INVINITY ENERGY SYSTEMS	SENS	THERMOWATT
ceres	eos	KRAFT BLOCK	Quidnet Energy	TORC
ECHOGEN power systems	ESS INC CATALYZING A CLEANER FUTURE	KYOTO	redflow	VOLTSTORAGE

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[5] Member count at the time of the release of this report in November 2022.

Industry and services customers	Capital providers	Equipment manufacturers	Low-carbon energy system integrators and developers	
COMPASS datacenters	Breakthrough Energy	ALFA LAVAL	bp	Reliance Industries Limited
EGA الإمارات العالمية للألمنيوم EMIRATES GLOBAL ALUMINIUM	quinbrook infrastructure PARTNERS	Baker Hughes	corre.energy hydrogen based energy storage	
Google		INNIO	EnBW	slb
Microsoft		SIEMENS energy	greenko	TotalEnergies
RioTinto		Sumitomo SHI FW	NEOM نيوم	
SOUTH32		VOITH	Ørsted	

Executive summary

Decarbonizing the global energy system requires an integrated approach to inform optimal energy infrastructure developments in a timely manner. It also requires systemic changes as we move toward energy systems predominantly supplied by variable renewable energy. To realize a 1.5°C scenario by 2050, projections estimate a fivefold increase in total renewables supply and a twofold increase in total electricity demand by that year.[6] Furthermore, there are early signs that power, heat, and hydrogen are becoming increasingly interconnected through sector-coupling technologies like heat pumps, electrolyzers, or hydrogen boilers. This, in addition to the growing share of renewables and electrification, further increases the energy system's complexity. Therefore, an integrated approach could help ensure a cost-optimized and timely energy transition.

LDES offers a clean flexibility solution to secure power and heat reliability. LDES encompasses a range of technologies that can store electrical energy in various forms for prolonged periods at a competitive cost and at scale. These technologies can then discharge electrical energy when needed—over hours, days, or seasons—in order to fulfill long-duration system flexibility needs to shift the increasing variable, renewable energy supply to match demand. This report builds on the 2021 LDES Council *Net-zero power* report by focusing on the role of LDES in realizing net-zero power and heat while expanding on the role thermal energy storage (TES) can play in decarbonizing heat applications.

TES provides an LDES solution to electrifying and firming heat. Decarbonizing the heat sector is crucial for realizing a net-zero energy system by 2050, given that it represents roughly 45 percent of all energy-related emissions today.[7] TES can decarbonize heat applications by electrifying and firming heat with variable renewable energy sources. In addition, it can optimize heat consumption in industrial processes and facilitate the reuse of waste heat or the integration of clean heat sources (for example, from thermal solar).

TES can enable the cost-efficient electrification of most heat applications. TES covers a variety of technologies that can address a wide range of storage durations (from intraday to seasonal) and temperatures (from subzero to 2,400°C). According to the 2022 LDES benchmark results, TES enables cost-efficient electrification and decarbonization of the most widely used heat applications, namely steam and hot air. The benchmark results also indicate that firming heat is very cost-efficient when the final demand is heat.

Some TES technologies are already commercially available with various easy-to-customize uses. To date, the most commonly deployed TES technologies include medium-pressure steam, with various applications, including in the chemicals or food and beverage industries. Additionally, developing technologies will expand the TES solution space with innovative concepts and address temperature needs well above 1,000°C.

TES business cases demonstrate profitability at an internal rate of return (IRR) of 16 to 28 percent, subject to local market conditions. These include optimal physical configurations (access to captive renewables, captive heat, or grid electricity) and market designs (including low grid fees and the remuneration of flexibility). The business case assessments cover a wide range of realistic TES use cases, namely: medium-pressure steam in a chemicals plant (up to 28 percent IRR), district heating supplied by a peaker plant (up to 16 percent IRR), high-pressure steam in an alumina refinery (up to 16 percent IRR), and co-generation in an off-grid greenhouse (up to 22 percent IRR). All market-exposed business

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[6] "Net zero by 2050, a roadmap for the global energy sector," IEA, 2021.

[7] The baseline includes emissions from heating, industrial processes, transport, and other energy sector emissions. It excludes power generation emissions.

cases indicate a supportive ecosystem that acknowledges the value of flexibility, such as ancillary services, would likely be critical to ensuring wide commercial adoption. The business case with behind-the-meter renewable generation shows that TES can already be commercially feasible regardless of external market conditions.

LDES technologies are expected to become increasingly cost-competitive as the market matures. The updated 2022 power LDES cost benchmark solidifies the forecast that LDES costs will decline in the following years, suggesting a 25 to 50 percent overall capital expenditure (capex) reduction of power LDES technologies by 2040. In addition, the 2022 TES cost benchmark indicates that TES capex is also expected to decline by 2040, with an estimated drop of between 5 and 30 percent for power capex and 15 and 70 percent for energy storage capex.

A case study on the port of Rotterdam exemplifies the relevance of LDES for decarbonizing energy hubs while creating system value. The case study represents a typical industrial hub with significant power and heat demand on-site, where a combination of TES and power LDES can play a role in decarbonizing the system. In an industrial location like the port of Rotterdam, the need for industrial heating can fundamentally change the configuration for a net-zero energy system. TES can firm the variable offshore wind supply into a more stable supply of clean heat for industrial heating, including high-temperature heating.

TES could double the global LDES capacity potential in a cost-optimized net-zero energy pathway in line with a 1.5°C scenario. Based on integrated system modeling, TES can expand the overall installed capacity potential of LDES to between 2 and 8 TW by 2040 (versus 1 to 3 TW without TES), which translates to a cumulative investment of USD 1.6 trillion to USD 2.5 trillion. TES enables this additional LDES opportunity by providing a cost-efficient alternative to decarbonizing heat and high-temperature heating applications. This is estimated to reduce system costs by up to USD 540 billion per year while creating broader system value by enabling an accelerated renewables build-out and optimization of grid utilization.

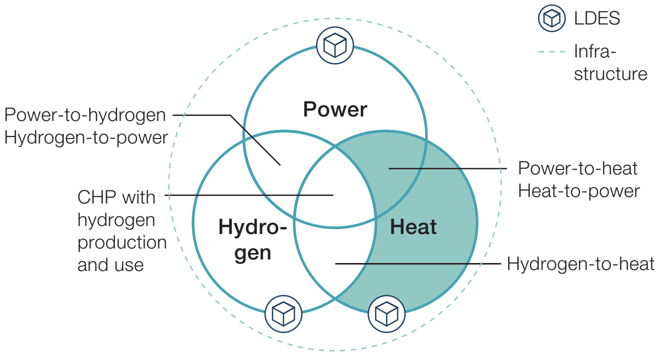
Critical support elements could help drive more TES adoption. A supportive ecosystem that rewards flexibility and promotes a technologically level playing field for flexibility solutions like LDES is critical to accelerating the scale-up of TES. Additionally, increasing awareness and providing support to derisk initial investments is pivotal. Business leaders, policymakers, and investors have an important role to play in unlocking the TES potential by reducing long-term uncertainty and thereby shaping the cost-optimized pathway toward the net-zero energy system of the future.

Net-zero heat

Long Duration Energy Storage to accelerate energy system decarbonization

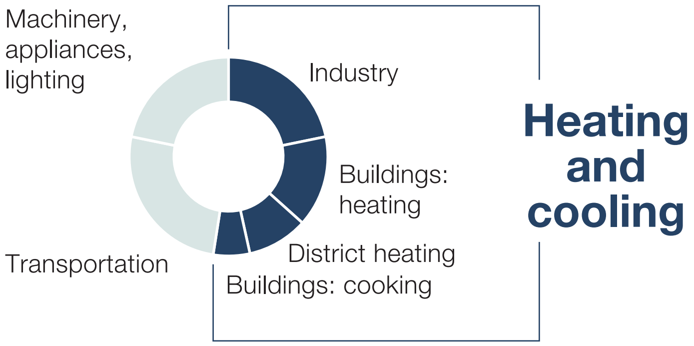
The transition to net zero requires an integrated energy system perspective

Realizing a **cost-optimized transition to net zero** across **all energy sectors** requires significant deployment of **renewables, increased interconnections** between power, heat, and hydrogen, and **supporting infrastructure.** System flexibility will be critical to securing energy system reliability



Heat decarbonization is critical for net zero, as it accounts for ~45% of energy-related emissions

Global final energy consumption by sector



Share of global energy-related CO_2e emissions[1]

20%
from industrial heat

10%
from buildings heat

Long duration energy storage enables a cost-optimized pathway toward net zero

A cost-optimized net-zero pathway could by 2040 result in...

2–8 TW
deployed LDES capacity

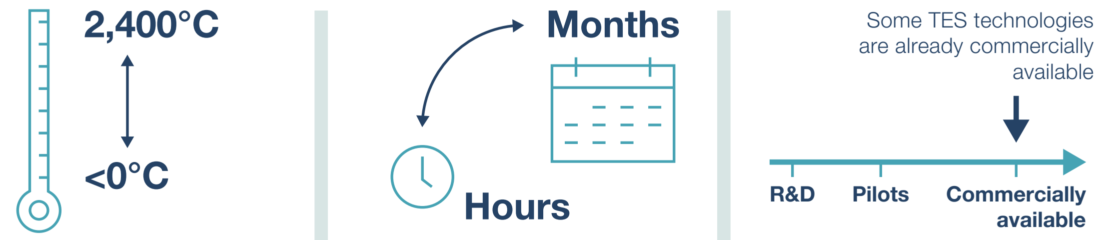
USD 1.7–3.6 tr
cumulative LDES capex investments

up to USD 540 bn
system savings per year

[1] Baseline excludes electricity emissions.

Thermal energy storage (TES) ...

... comprises a wide range of technologies



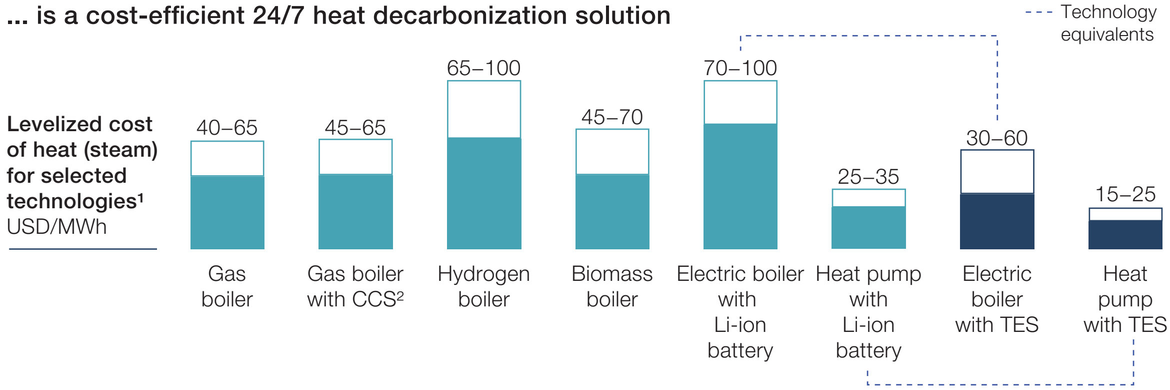
Storage temperature

Storage duration use case

Technical maturity

TES enables electrification of heat applications with different temperature and duration needs

... is a cost-efficient 24/7 heat decarbonization solution



TES makes storing heat more cost-efficient than storing power for heat applications

... can present attractive business cases subject to local conditions. IRRs for selected use cases

	Chemicals plant	Off-grid greenhouse	District heating peaker plant	Alumina refinery
Upside case	28%	22%	16%	16%
Base case	6%		0%	–

TES behind-the-meter business cases can be positive as there are no grid connection fees

... requires enablers to drive broad adoption

✓ **Reward value of flexibility**
- Reduced grid fees
- Ancillary markets

✓ **Create a technologically level playing field across flexibility solutions through**
- Regulations
- Standards

✓ **Increase awareness of TES technologies**
- Pilots
- Demonstration
- Plants

✓ **Derisk initial investments**
- Subsidies
- Guarantees

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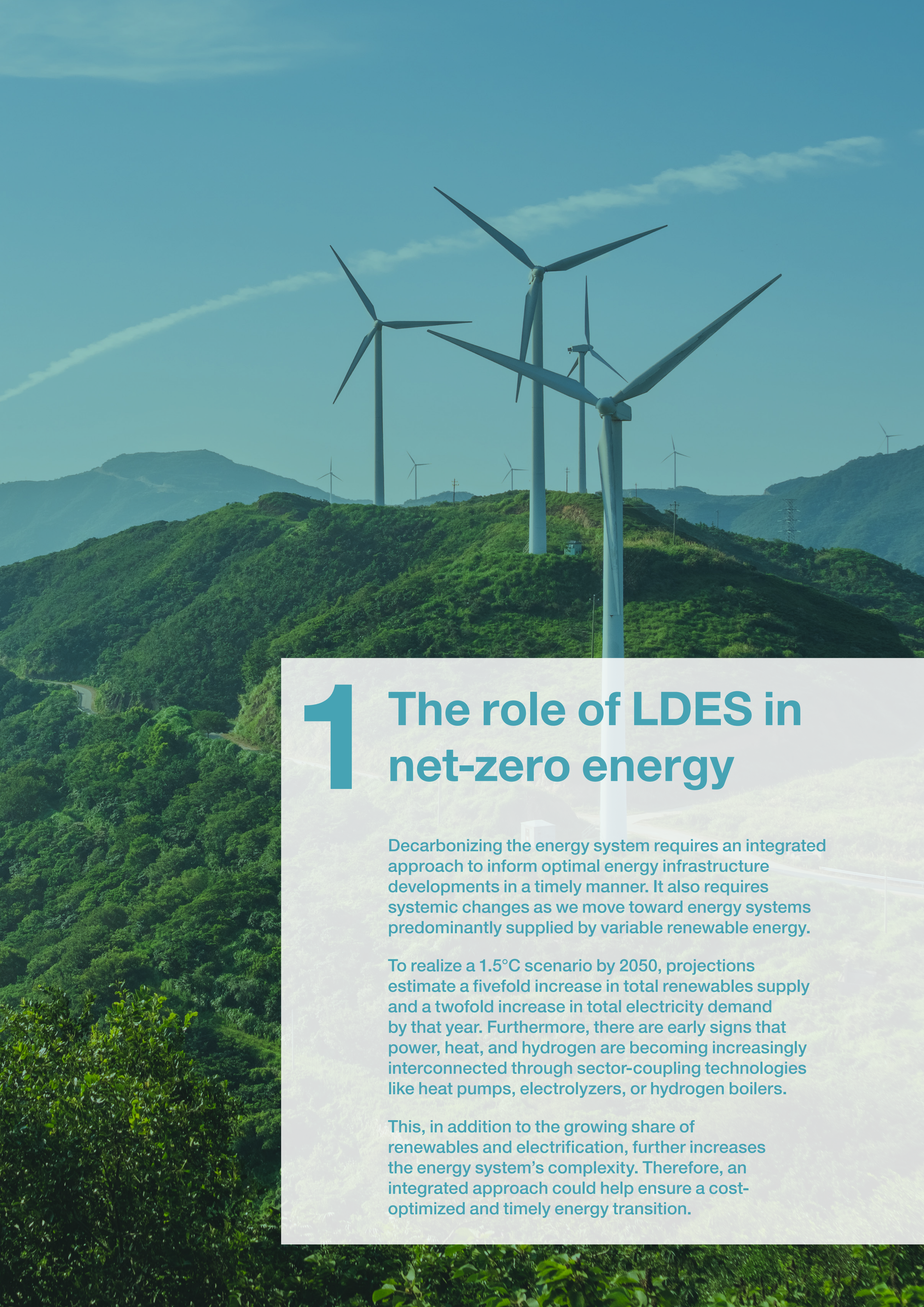
1. Cost ranges reflect fuel prices (gas, electricity, biomass). Includes CO_2 emission costs of USD 100/t.
2. Carbon capture and storage.

Acronyms

Capex	Capital expenditure
CCS	Carbon capture and storage
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
EJ	Exajoules
GHG	Greenhouse gas
Gt CO_2eq	Gigatons of carbon dioxide equivalent
GW	Gigawatt
GWh	Gigawatt-hour
Hz	Hertz
IRR	Internal rate of return
kW	Kilowatt
kWh	Kilowatt-hour
LCOE	Levelized cost of electricity
LCOH	Levelized cost of heat
Li-ion	Lithium-ion
LDES	Long duration energy storage
MPM	McKinsey Power Model
MW	Megawatt
MWh	Megawatt-hour
MWhth	Megawatt-hour thermal
MWth	Megawatt thermal
NPV	Net present value
PV	Photovoltaic
PPA	Power purchase agreement
RTE	Round-trip efficiency
R&D	Research and development
TTF	Title transfer facility
TW	Terawatt
TWh	Terawatt-hour
TES	Thermal energy storage
T&D	Transmission and distribution
WACC	Weighted average cost of capital



1

The role of LDES in net-zero energy

Decarbonizing the energy system requires an integrated approach to inform optimal energy infrastructure developments in a timely manner. It also requires systemic changes as we move toward energy systems predominantly supplied by variable renewable energy.

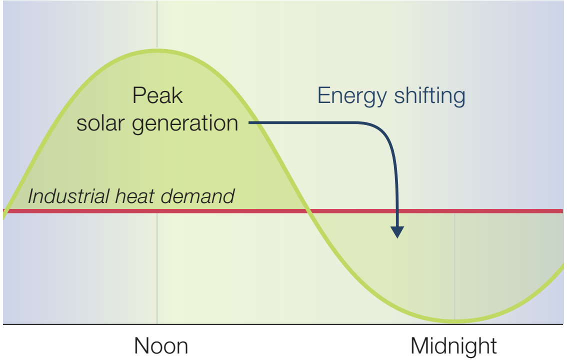
To realize a 1.5°C scenario by 2050, projections estimate a fivefold increase in total renewables supply and a twofold increase in total electricity demand by that year. Furthermore, there are early signs that power, heat, and hydrogen are becoming increasingly interconnected through sector-coupling technologies like heat pumps, electrolyzers, or hydrogen boilers.

This, in addition to the growing share of renewables and electrification, further increases the energy system's complexity. Therefore, an integrated approach could help ensure a cost-optimized and timely energy transition.

A net-zero energy system requires clean flexibility solutions

Achieving net-zero emissions in the energy sector by 2050 is pivotal for limiting global warming to 1.5°C. To keep global warming below 1.5°C compared to preindustrial levels, as called for in the Paris Agreement, greenhouse gas (GHG) emissions need to reach net zero by 2050. The energy sector currently accounts for roughly three-quarters of GHG emissions and holds the key to mitigating the worst effects of climate change.[8] Replacing polluting fossil energy with renewable energy sources like wind or solar and meeting the energy-shifting demand with LDES will help significantly reduce carbon emissions while creating a reliable energy system.

The growth of solar and wind generation is increasing the variability of the energy supply mix and the need for clean flexibility solutions to safeguard energy system reliability. As countries decarbonize, the global share of renewable energy supply is expected to grow dramatically. Net-zero transition scenarios indicate a roughly threefold and fivefold increase in renewable energy supply, with renewables supplying up to 30 and 67 percent of global energy in 2030 and 2050, respectively. Furthermore, electrification is expected to increase, doubling the electricity demand by 2050.[9] Therefore, there is a growing need for clean flexibility solutions that bridge the renewables supply-and-demand gap while securing system reliability. Ensuring renewable electricity matches demand with LDES can help provide the flexibility, security of supply, and resiliency needed to meet global net-zero targets.



Definitions of energy system reliability and flexibility

***Energy system reliability** is the ability of energy systems to deliver energy in the quantity and quality demanded by consumers.*

***Energy system flexibility** is the ability of energy systems to respond to supply-and-demand variations promptly and supports reliability.*

LDES offers a clean flexibility solution that can accelerate renewables build-out

LDES provides energy system flexibility. LDES solutions enable the shifting of energy from times of high supply to times of high demand, thereby helping preserve system balance and securing its reliability. LDES can be deployed competitively to store energy for prolonged periods and sustain energy provision for multiple hours, days, or weeks. Such long-duration flexibility is expected to become essential to firm supply as the share of renewable energy supply increases. LDES can cover various durations driven by technical considerations and economics.

LDES can accelerate the build-out of renewables by optimizing infrastructure utilization. The energy-shifting capability of LDES has multiple system benefits. First, it could reduce energy curtailment and related opportunity costs by facilitating supply-side energy storage. For example, the initial modeling of an alumina refinery use case indicated that LDES could reduce overall generation capacity needs by 15 to 30 percent. Second, it could help improve overall grid utilization through supply-and-demand-side energy storage, reducing stress on the grid. As a result, LDES can be deployed across the electricity grid (for example, at critical corridors at capacity) to accelerate renewables' development. Lastly, LDES can provide other system benefits like stability, with some technologies offering services like inertia provision or frequency regulation.

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[8] United Nations Net Zero Coalition.

[9] "Net zero by 2050, a roadmap for the global energy sector," IEA, 2021.

LDES can support the security of supply

The need to ensure an affordable, reliable, clean energy system has been heightened by recent challenges in the energy sector, which have increased the prominence of energy security on global agendas. Europe is now facing electricity and natural gas prices that are over ten times higher than historical averages, driven by multiple factors such as the war in Ukraine and the rise in global demand following the COVID-19 pandemic.[10] *Global gas markets have also been affected, causing US electricity prices to increase threefold between 2020 and 2022.*[11]

Incorporating LDES can help increase the security of supply and create new use cases for renewable energy. LDES can also unlock new opportunities that are not thoroughly addressed by shorter-duration storage solutions. Examples include: helping increase the share of renewables in the energy mix, providing resilience to unreliable grids at long durations (like at isolated or off-grid locations), enabling cost-efficient 24/7 renewable power purchase agreements (PPAs), or providing stability services to the grid. In addition, TES can support new heating use cases, namely the wider electrification of heat, reuse of waste heat, demand-side management, and lower renewables curtailment.

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[10] Dutch TTF Gas Futures.

[11] U.S. Energy Information Administration (EIA).

There are different options to consider for energy system flexibility

Within the electricity sector, five flexibility options can help match supply and demand:

i. Energy storage, including Li-ion batteries and deployable LDES solutions such as closed loop pumped storage

ii. Dispatchable capacity such as hydropower

iii. Renewable energy curtailment

iv. Transmission and distribution grid expansions

v. Demand-side management

Furthermore, system flexibility is increasingly important in responding to market supply fluctuations.

The heat sector has analogous clean flexibility solutions to the electricity sector, though with clean-heat-specific technologies:

i. Thermal energy storage

ii. Dispatchable capacity like clean-fuel boilers

iii. Robust heating infrastructure like district heating

Integrating the electricity and heat sectors can be critical in enabling clean flexibility. Electricity and heat were historically connected through heat engines in conventional generation plants. Going forward, electricity and heat are expected to become more integrated through higher adoption of power-to-heat technologies, such as heat pumps or electric boilers, and renewable heat-to-power technologies, like concentrated solar power. The increased interconnectedness of the sectors supports their decarbonization and the integration of renewables. Furthermore, solutions that enhance sector integration—like TES—drive flexibility by, for instance, storing energy at times of oversupply and discharging heat at times of undersupply. Given the growing interdependencies of electricity and heat, an integrated perspective is becoming relevant to realizing a net-zero energy system.

KEY TAKEAWAYS

- As the share of variable renewable energy grows steadily, there is a greater need for clean flexibility solutions, like LDES, to secure system reliability.
- LDES is essential for keeping global warming below 1.5°C as it can help accelerate the development of renewables.
- The integration of the energy system through sector coupling improves flexibility, security of supply, and, consequently, system reliability and resiliency.

2

TES as an enabler to decarbonizing heat

Decarbonizing the heat sector is crucial to realizing a net-zero energy system in 2050, given that, excluding power, it represents about 45 percent of all energy-related emissions today.

TES can decarbonize heat applications by electrifying and firming heat with variable renewable sources. In addition, it can optimize heat consumption in industrial processes and facilitate the reuse of waste heat or the integration of clean heat sources.

Most heat applications can be decarbonized through electrification

Heat accounts for about 45 percent of energy-related emissions. Heating and cooling use cases account for more than 50 percent of global energy consumption across all sectors and about 45 percent of global energy-related CO_2 emissions, excluding power (10 Gt in 2019). Industrial applications account for the largest share of heat consumption, at 40 percent of total heat demand, and comprise use cases varying from low- to high-grade heating above 1,500°C. Building heating and cooling is also a significant contributor at around 30 percent of total heat demand,[12] though typically at lower temperatures around or below 100°C. Lastly, heating is used for cooking as well as district heating (Exhibit 2).

Heat applications represent about 45 percent of all energy-related emissions[13]

Industrial heat demand relies heavily on fossil fuels, especially for high-temperature applications. Most industrial heat demand requires either direct hot air or steam at different temperatures for processes such as drying, calcination, or chemical reactions. Overall, 70 percent of industrial heat is still provided by fossil fuels (Exhibit 3). Among the different industrial processes, applications with high temperature heating represent the largest share of emissions and account for about 50 percent of total fossil-fuel-related heat demand. A major driver is the higher energy consumption of these applications, which are mainly supplied by coal, resulting in the high costs of switching to lower-carbon alternatives.

Electrification is a decarbonization solution for most industrial heat applications, including high-temperature processes. There are different options for decarbonizing industrial applications, such as electrification, energy efficiency measures, low-carbon fuels, and carbon capture. In the context of lower renewables costs and higher CO_2 prices, electrification combined with flexibility solutions emerges as an increasingly attractive solution to decarbonize high-temperature industrial processes like chemicals, nonmetallic minerals, or nonferrous metals (Exhibit 4). Other processes, such as steelmaking or cement making, require further research and development or pilots to explore electrification options.

Heat in buildings can also be decarbonized through electrification, subject to local legacy infrastructure. In buildings, heat is mainly used for space and water heating, with 50 percent provided by fossil fuels (Exhibit 5). Several commercially available options for decarbonizing heating and cooling in buildings, such as heat pumps, or rooftop solar, already exist. However, higher upfront costs than conventional solutions currently hinder widespread adoption. For instance, installing a heat pump in the United Kingdom can cost three to seven times more than installing a gas boiler.[14] The widespread adoption of heat pumps also depends on the availability of grid networks that can accommodate a large increase in electricity demand. Similarly, the viability of centralized solutions relies on the availability of legacy pipeline infrastructure. In this case, TES can support the decarbonization of centralized district heating networks by storing energy for weeks or months, depending on accessible technologies, such as underground water.

TES offers a clean flexibility solution to firm heat

Clean flexibility solutions enable the decarbonization of the heat sector via two main options:

i. Shifting to clean alternatives, such as clean electricity, solar thermal, and clean fuels

ii. Optimizing heat consumption, such as reusing waste heat and increasing efficiency

Clean flexibility solutions like TES can support supply-demand matching for both decarboni-

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[12] "Global Energy Perspective 2022," McKinsey, April 26, 2022.

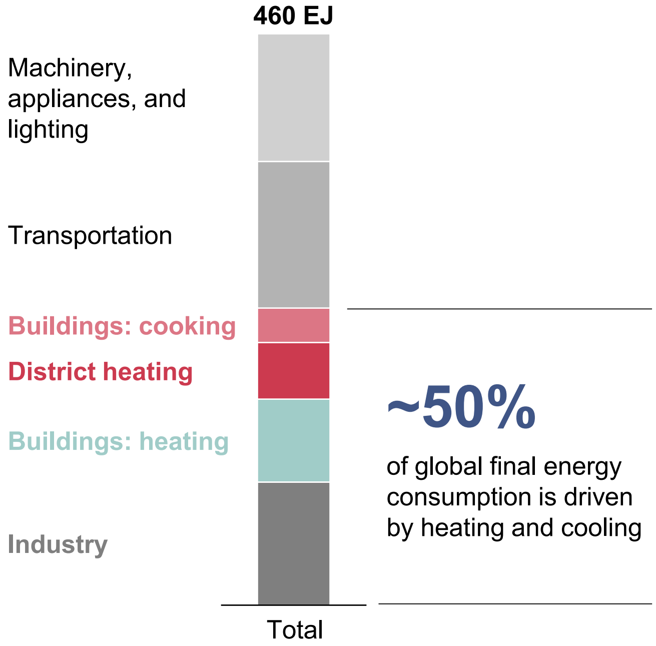
[13] The baseline includes emissions from heating, industrial processes, transport, and other energy sector emissions. It excludes power generation emissions.

[14] "Residential Heat Economics Calculator," IEA. Based on a gas condensing boiler and a ground-source heat pump (upper range) and an air-air heat pump (lower range).

Exhibit 2

50% of global final energy consumption is driven by heating and cooling

Global final energy consumption by sector
Exajoules, 2019



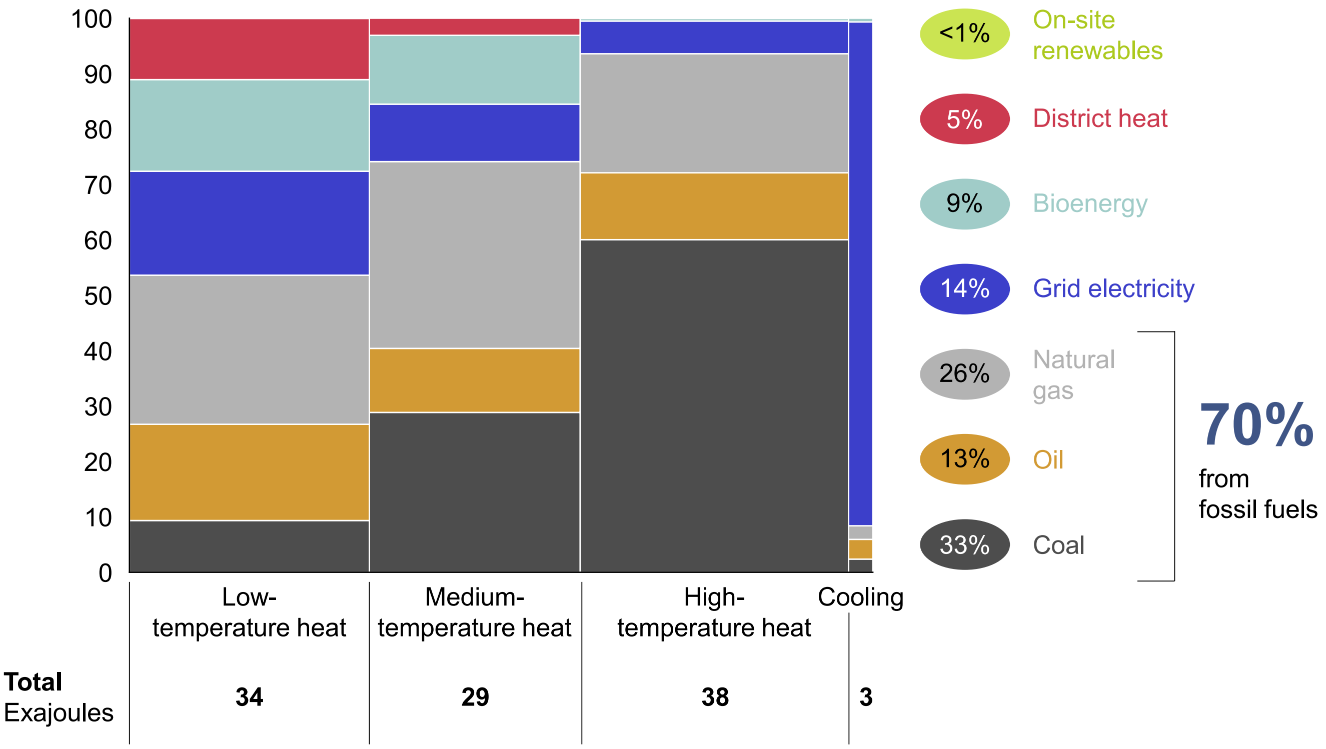
Source: McKinsey Global Energy Perspective

Exhibit 3

At least 70% of industrial heat is generated by fossil-fuel sources

Global industrial final energy consumption by heat temperature
2019, percent

Share of total
Percent

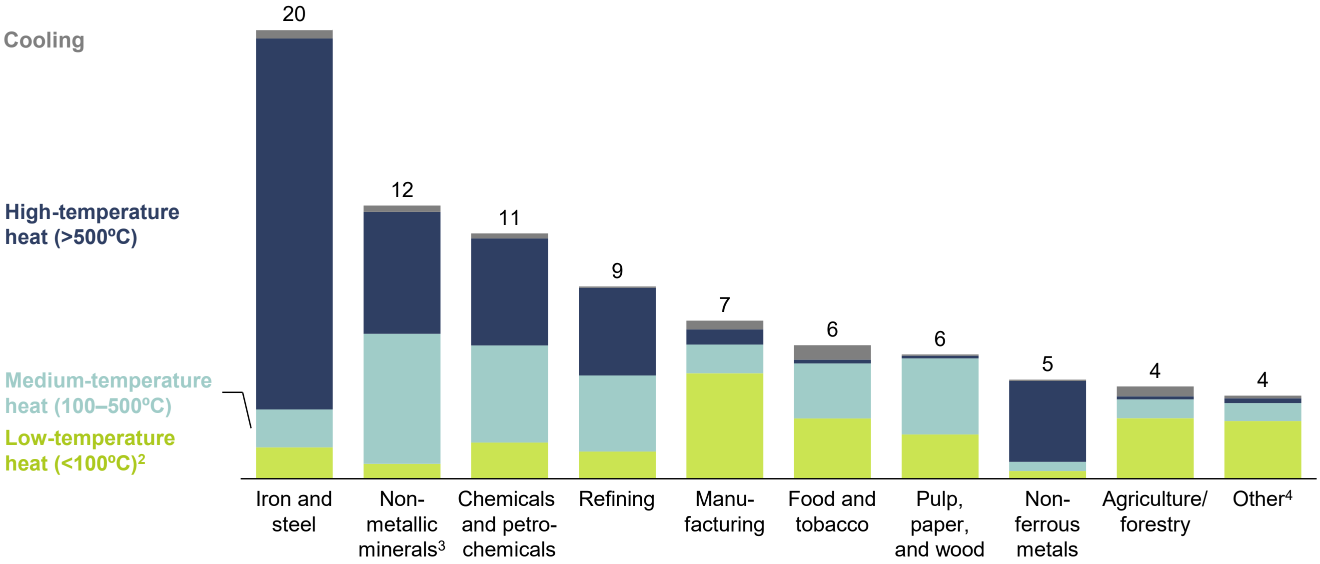


Source: McKinsey Global Energy Perspective

Exhibit 4

Industrial energy consumption is concentrated in high-temperature applications

Global industrial final energy consumption by sector[1]
Exajoules, 2019



1. Excludes ~20 EJ of industrial final energy consumption due to insufficient reporting.
2. Includes hot water and space heating.
3. Includes ceramics, glass, and cement.
4. Includes energy industry own use.

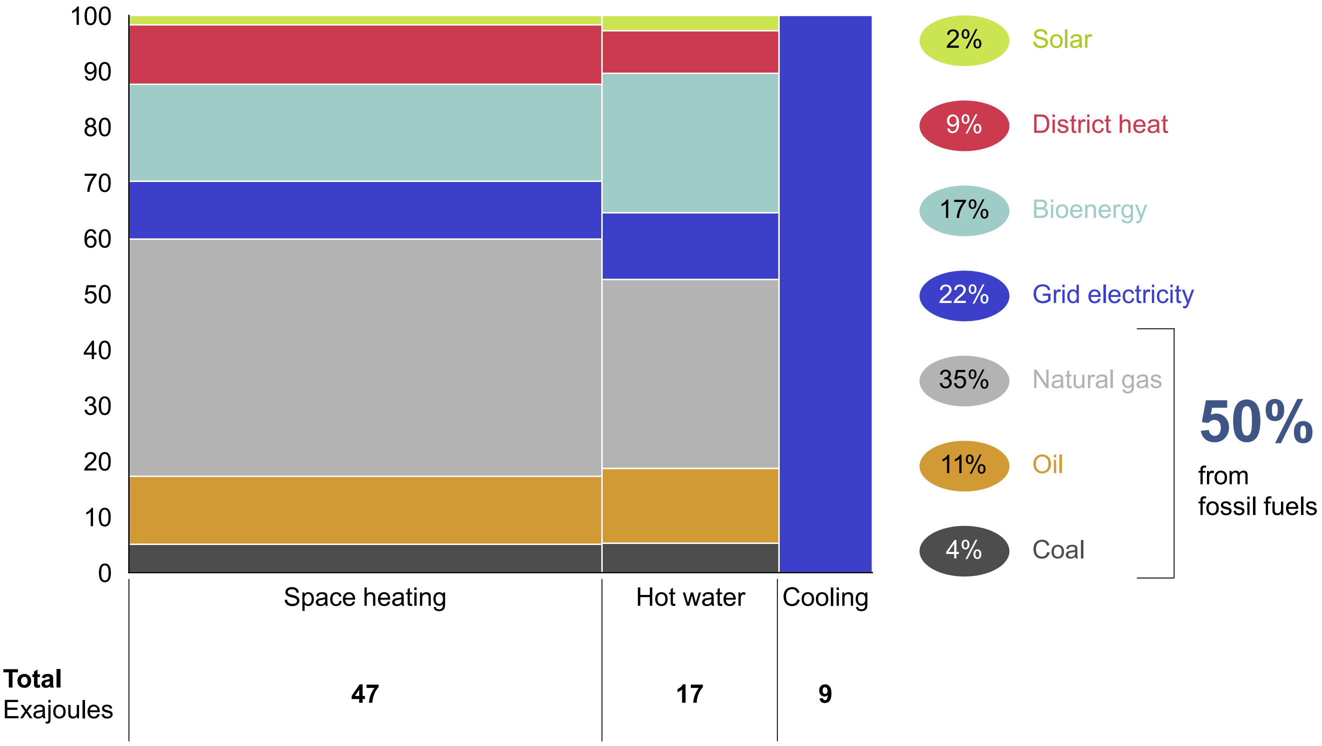
Source: McKinsey Global Energy Perspective

Exhibit 5

50% of buildings' heat is generated by fossil-fuel sources

Global buildings' final energy consumption by use case (all heat-related)
2019, percent

Share of total
Percent



Source: McKinsey Global Energy Perspective zation options. Alternative decarbonization options exist but typically require more significant investments or involve delays in emission reduction.

TES enables cost-effective firming of heat sourced from variable renewable energy. Industrial demand typically follows a constant pattern. Energy supply interruptions—sometimes only lasting minutes—can lead to multimillion dollar losses due to equipment damage and lost production. Similarly, buildings' demand for heating typically follows a pattern that coincides with human activity and has limited flexibility. In regions with a fully decarbonized grid, decarbonizing heat demand through the electricity network is an effective option; however, in most countries, the grid is still reliant on fossil fuels when renewables are unavailable. This makes TES necessary to keep heat loads running on clean energy when the grid cannot provide it.

In addition, TES provides behind-the-meter heat consumption optimization. TES can play multiple roles in optimizing behind-the-meter heat consumption by:

i. Supporting the integration of captive variable energy supply (such as solar energy) for heat

ii. Storing waste heat for later reuse in industrial processes, thereby improving overall process efficiency. TES can also make behind-the-meter heat available for external use, such as in district heating networks

TES complements the coverage of power LDES by firming clean heat. TES enables the long-duration storage of heat supplied by clean electricity or waste heat. Power LDES enables the long-duration storage of electricity. Their optimal use will be determined by multiple factors, such as end-use requirements, with both supporting the use of LDES to decarbonize the energy system.

KEY TAKEAWAYS

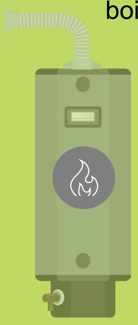
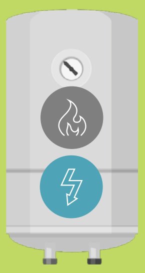
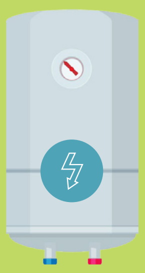
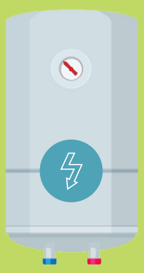
- Decarbonizing heat is a pivotal component for realizing a net-zero energy system, as it accounts for 50 percent of global final energy consumption and 45 percent of all energy-related emissions (excluding power).
- Electrification offers a decarbonization alternative to most industrial heat applications, including high-temperature processes.
- TES enables the firming of heat from variable renewable energy sources and could constitute a key solution for the sector's decarbonization.

TES can be deployed effectively to benefit from variable electricity prices

As global economies transition away from fossil fuels, TES can assist in providing more resiliency and efficiency. In a hybrid gas-electricity setup for steam production, TES can be used to respond to fluctuations in electricity market prices and reduce energy costs. Depending on the energy price profiles, three operating modes are possible for a setup using a gas boiler, electric boiler, and TES (Exhibit 6). First, when gas is cheaper than electricity, the gas boiler provides steam continuously. Second, when the fuel price changes during the day, the operator can switch to whatever is cheapest at any given time, or TES can be charged when electricity prices are low and discharged when they are high. Finally, when electricity prices fall below the equivalent price of natural gas with carbon, steam can be generated via an electric boiler, and TES can be charged and discharged to capture moments of the lowest electricity price.

Exhibit 6

TES can be used by users for optimizing their heat generation based on energy prices

	Energy price scenario		
	Gas is always cheaper than electricity	**Electricity is sometimes cheaper than gas**	**Electricity is always cheaper than gas**
Preferable steam generation technology	Gas boiler 	Hybrid boiler  **OR** Electric boiler/heat pump  ✚ TES 🟥	Electric boiler/heat pump  ✚ TES 🟥 *(Optional)*

3 LDES technologies—cost and competitiveness

TES can enable the cost-efficient electrification of most heat applications, even at high temperatures. TES covers a large spectrum of technologies that can address a wide range of storage durations (from intraday to seasonal) and temperatures (from subzero to 2,400°C).

According to the 2022 LDES benchmark, TES enables the cost-efficient electrification and decarbonization of the most widely used heat applications (i.e., steam and hot air). The benchmark results also indicate that firming heat is more cost-efficient than firming power when the final demand is heat. Furthermore, LDES benchmarks predict significant declines in costs over the next 15 years, making LDES technologies increasingly cost-competitive as the market matures.

The 2022 LDES Council capex benchmark informs the latest Power LDES and TES technology cost perspectives

The 2022 LDES Council capex benchmark provides an up-to-date perspective on LDES technology costs and informs relevant business cases. As with any new technology, competitive costs and performance are critical for widespread adoption that can help achieve societal benefits versus alternatives. For LDES, some key parameters to consider are energy capacity cost (USD per MWh) or energy capex, power capacity cost (USD per MW) or power capex, operation and maintenance cost (USD per MW-year), round-trip efficiency (RTE) for power LDES, and system efficiency for TES. These parameters are covered by the LDES Council cost benchmarks and the following results are presented in this section:

1. **Power LDES.** The 2022 LDES Council capex benchmark presents an updated perspective of the Power LDES capex and RTE of two duration archetypes (8 to 24 hours and 24 hours or more), as presented in the 2021 LDES *Net-zero power* report. The updated benchmark is based on the input from 21 LDES Council technology providers (compared to ten companies taking part in the 2021 benchmark) on cost perspectives regarding a "central" and "progressive" learning-rate scenario (see Appendix A for more details on the methodology). The benchmark results are used later in the economic optimization modeling (see Chapter 5) to approximate the suite of different LDES that could be deployed.
2. **Thermal energy storage.** This report expands the 2022 LDES Council capex benchmark to include TES technologies. The benchmark presents a perspective on TES's capex and system efficiency across four archetypes of heat applications (saturated steam at 1, 10, and 25 barg[15] and hot air at 450°C). This benchmark is based on the input of 11 LDES Council technology providers.

The updated Power LDES benchmark solidifies the view that costs will decline toward 2040

The power capex benchmark indicates that costs could decline by 25 to 50 percent by 2040. Costs could drop to USD 260,000 and USD 1,480,000 per MW for the 8-to-24 hour and 24-hour-or-more archetypes, respectively (Exhibit 7).[16] The power capex, which includes charging and discharging equipment and balance of plant costs, is expected to show an overall decline of around 35 to 50 percent for the 8-to-24-hour archetype and about 25 percent for the 24-hour-or-more archetype.

The energy storage capex benchmark indicates that costs could decline by 25 and 45 percent by 2040. Storage costs are expected to drop to USD 6,000 and USD 22,000 per MWh for the 24-hour-or-more and the 8-to-24-hour archetypes, respectively.[17]

The lower-duration systems are usually optimized to be competitive at shorter durations and higher cycling profiles. This can be seen in the power capex of the 8-to-24-hour archetype. However, this advantage tends to be reduced for longer storage durations as the energy capex becomes the main cost and can differ more significantly across archetypes and scenarios. The energy capex of the 24-hour-or-more archetype can reach considerably lower values than the 8-to-24-hour archetype (around three times lower), making the design of these systems suitable for longer durations due to the lower cycling requirements to generate profits.

More submissions provide a broader technology base for the power LDES benchmark. The updated power capex results are based on a higher number of submissions and therefore reflect a broader technology base, making the benchmark more robust. The differences to the 2021 power capex benchmark are mainly driven

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[15] Gauge pressure (pressure in bars above ambient or atmospheric pressure).

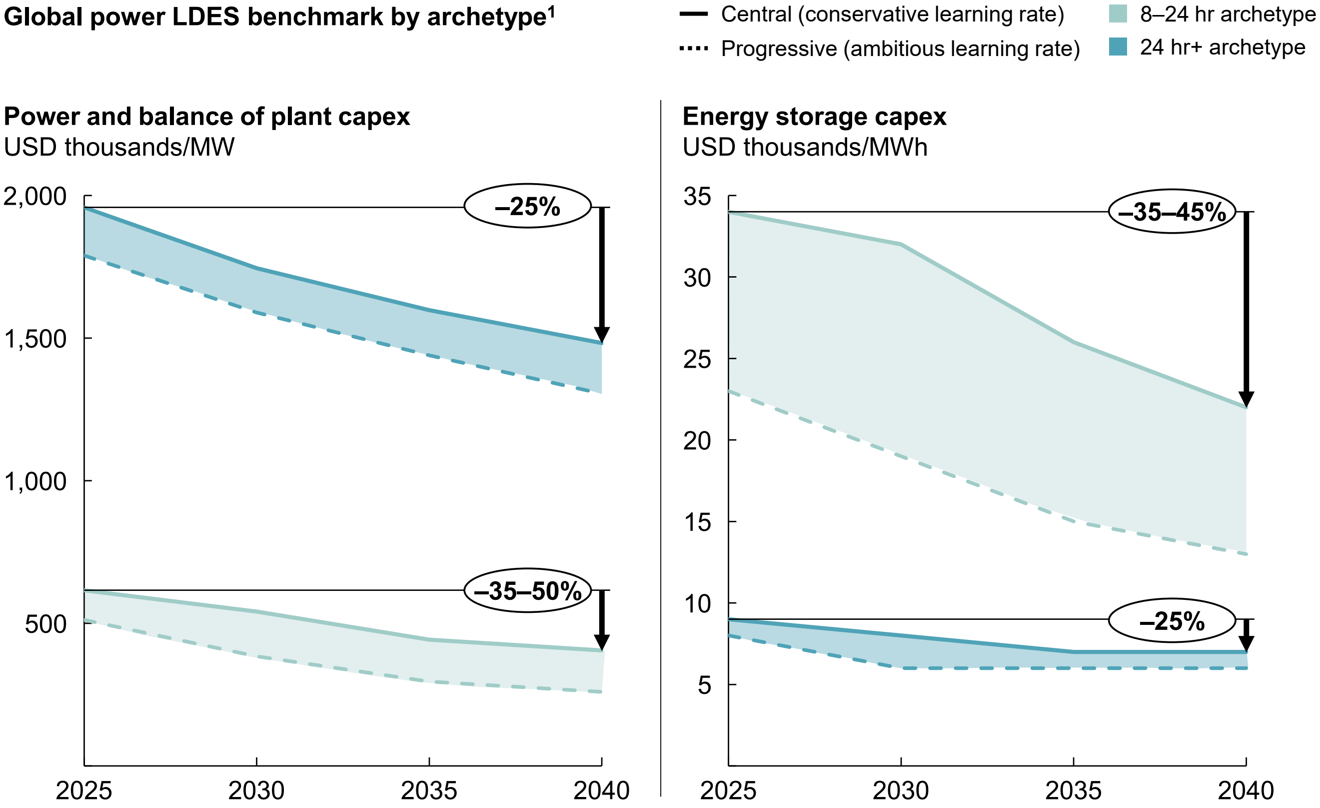
[16] The corresponding numbers from the 2021 LDES Council *Net-zero power* report are USD 380,000 and USD 960,000 per MW, respectively. The difference in costs is expected to be caused mainly by the inclusion of more companies in the top quartile, as the number of contributing companies doubled.

[17] The corresponding numbers from the 2021 LDES Council *Net-zero power* report are USD 4,000 and USD 17,000 per MWh, respectively.

Exhibit 7

Power LDES energy and power capex are expected to decrease by 2040

Global power LDES benchmark by archetype[1]



1. Benchmark data provided by LDES Council members and aggregated into archetypes based on technological properties. All data points are top-quartile cost data within the archetype based on the energy capex.

by the doubled number of submissions from Council members, which increased the number of samples in the top quartile. The same applies to the energy storage capex, as more submissions lead to a larger pool of top-quartile players and the inclusion of a broader range of technologies.

The TES benchmark varies by heat application archetype

TES technologies fall into three categories: sensible, latent, and thermochemical heat. Sensible heat storage stores thermal energy by increasing the temperature of a solid or liquid medium; latent heat by changing the phase of a material; and thermochemical heat through endothermic and exothermic chemical reactions. Within each category, different medium materials with unique characteristics can be used, leading to various operating temperatures and durations. Consequently, different TES technologies will be more suitable for different applications depending on their temperature, scale, storage duration, and other factors, such as heat form, footprint, and process integration.

TES technologies can cover the whole temporal and temperature spectrum of heat needs. Many different materials, such as graphite, rocks, water, and ice, can cover a wide range of temperatures and durations (Exhibit 8). For example, underground water systems such as aquifers, boreholes, and water pits can store heat for months from 0 to 100°C, while graphite systems can store heat at up to 2,400°C. TES technologies—including microencapsulated metals, paraffin waxes, and absorption systems—are in various stages of development, from initial commercial testing and pilot setups to others that are already deployed. Lastly, some TES technologies—such as steel and liquid metals—are at an early stage of development and could expand the availability of TES technologies across temperature and duration ranges, as outlined on pages 28 and 29.

Exhibit 8

TES can support broad temperature ranges and energy storage durations

	Sensible heat	Latent heat	Thermochemical heat
Temperature	**<0–2,400ºC** Most technologies able to span a large range of temperatures	**<0–1,600ºC** Specific temperature ranges served by specific technologies	**0–900ºC** Spans a smaller range of temperatures due to less variety in available technologies
Duration use case	**Minutes to months** Most technologies are able to serve intraday to multiday durations, with several being able to serve monthly durations	**Hours to days** Most technologies serve intraday to multiday durations	**Hours to months** Potential to serve intraday to monthly durations
Technical maturity	**Most commercially available** Most technologies are already commercially available with track records of pilots and use cases	**Some commercially available** Large range of technical maturity, with some already commercially available and others in the R&D phase	**Pilots and R&D stage** Relatively nascent with most technologies in the R&D or pilot phases

TES heat application archetypes are based on temperature requirements. Multiple TES technologies can cover many low-to-high temperature use cases (for example, graphite, ceramics, and microencapsulated metals). TES can thus support the most common industrial use cases, typically involving hot water, steam, or hot air. Heat at less than 100°C (in the form of hot air or water) could, for example, be used in drying processes. Typical steam use cases range from low pressures and temperatures (around 1 barg and 100°C, for instance, in food processing sterilization and cleaning) to higher pressures and temperatures (up to about 100 barg and 320°C, for example, in metal refining, petroleum processing, and industrial steam). Hot gasses are typically used in high-temperature use cases (for example, at temperatures of 800°C to 900°C in ethylene-cracking furnaces).

The TES benchmark accounts for the specificities of different heat applications. Like any other benchmarking, TES benchmarking is a process that compares the costs associated with the production and use of a product to those of leading industry players and proven industry standards. A TES benchmark currently does not exist, so the LDES Council developed one with McKinsey supporting as the knowledge partner. In developing the TES benchmark, it was critical to consider the multiple challenges related to heat systems:

- Various heating capacities and utilities like steam, process air, and hot water are required for different industrial processes.
- Different charging possibilities, such as electric heaters, heat pumps, conventional fuels, and waste heat, are most often system-dependent and usually incomparable.
- Integration costs are site dependent and cannot be compared between projects.
- The total cost of the system is affected by many auxiliary components.

TES categories and temperature and duration use cases and technical maturity

	Storage temperature					
	0°C	100°C	500°C	900°C	1,600°C	2,400°C
	Sub-zero	Low	Medium	High	High+	High++
Sensible heat	*Most technologies able to span a large range of temperatures (e.g., sand, concrete, rocks)*					
Graphite						■
Ceramics, silica, and sand	■	■	■	■	■	
Molten salts			■	■		
Concrete		■	■	■		
Rocks	■	■	■	■		
Steel			■			
Underground water		■				
Water		■				
Latent heat	*Specific temperature ranges served by specific technologies (e.g., ice for subzero, inorganic salts for high temperatures)*					
Microencapsulated metals			■	■	■	
Inorganic salts and eutectic mixtures				■		
Sodium			■	■		
Other liquid metals			■			
Molten aluminum alloy		■	■			
Paraffin waxes, fatty acids		■				
Salt hydrates		■				
Salt-water mixtures		■	■			
Ice	■					
Liquid air	■					
Thermochemical heat	*Spans a smaller range of temperatures due to less variety in technologies available*					
Chemical reaction storage		■	■	■		
Absorption		■				

Storage duration use case			Technology readiness level[1]		
Hours	Days	Weeks	1–3	4–6	7–9
Most technologies able to serve intraday to multiday durations, with several able to serve up to months (e.g., water)			*Most technologies already commercially available with track record of pilots and use cases*		
🟦	🟦				🟩
🟦	🟦				🟩
🟦	🟦				🟩
🟦	🟦	🟦			🟩
🟦	🟦				🟩
🟦	🟦	🟦	🟩		
🟦	🟦	🟦			🟩
🟦	🟦	🟦			🟩
Most technologies serve intraday to multiday durations			*Large range of technical maturity, with some already commercially available and others in the R&D phase*		
🟦	🟦			🟩	
🟦	🟦				🟩
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Potential to serve intraday durations up to months			*Relatively nascent with most technologies in the R&D or pilot phase*		
	🟦	🟦		🟩	
🟦				🟩	

1. Technology readiness levels (TRL) are a measurement system used to assess the maturity level of a particular technology. 1–3 include technologies up to experimental proof of concept; 4–6 include technologies up to demonstration in relevant environment; 7–9 include technologies up to proof in operational environment.

Given the differences in possible charging and discharging of the TES system, this benchmark assumes a system that is charged with an electric heater and discharged either at saturated steam at different pressures (1, 10, and 25 barg) or as hot air at 450°C. Since selected TES technologies can use heat pumps for charging (mainly for steam systems), only the discharging system costs are part of the benchmark. Labor and material costs are factored in to account for all the concrete, piping, electrical, insulation, painting, and supports needed in a space about one meter out from the sides of the equipment. Moreover, it is assumed in the modeling that direct tie-ins to the steam network and hot air ducts are available, as well as equipment up to and including the boiler feedwater pump. Step-down transformers and other auxiliary equipment are excluded from the benchmark.

TES can already be a cost-competitive steam decarbonization solution today

The 2022 LDES Council TES capex benchmark was used to assess the competitiveness of different steam decarbonization alternatives. The LDES Council conducted an industry benchmarking exercise on steam applications based on the latest TES cost estimates drawing on 6,000 data points across technologies and use cases. The primary benchmarking metric used is the levelized cost of heat (LCOH, see appendix A). Benchmarking results indicate that the LCOH for an electric boiler with TES can be around USD 5 to 10 per MWh lower than for a gas boiler. This is mainly driven by lower capex and potential differences in energy prices (such as using behind-the-meter electricity instead of gas), based on three specific approaches to decarbonizing gas boilers:

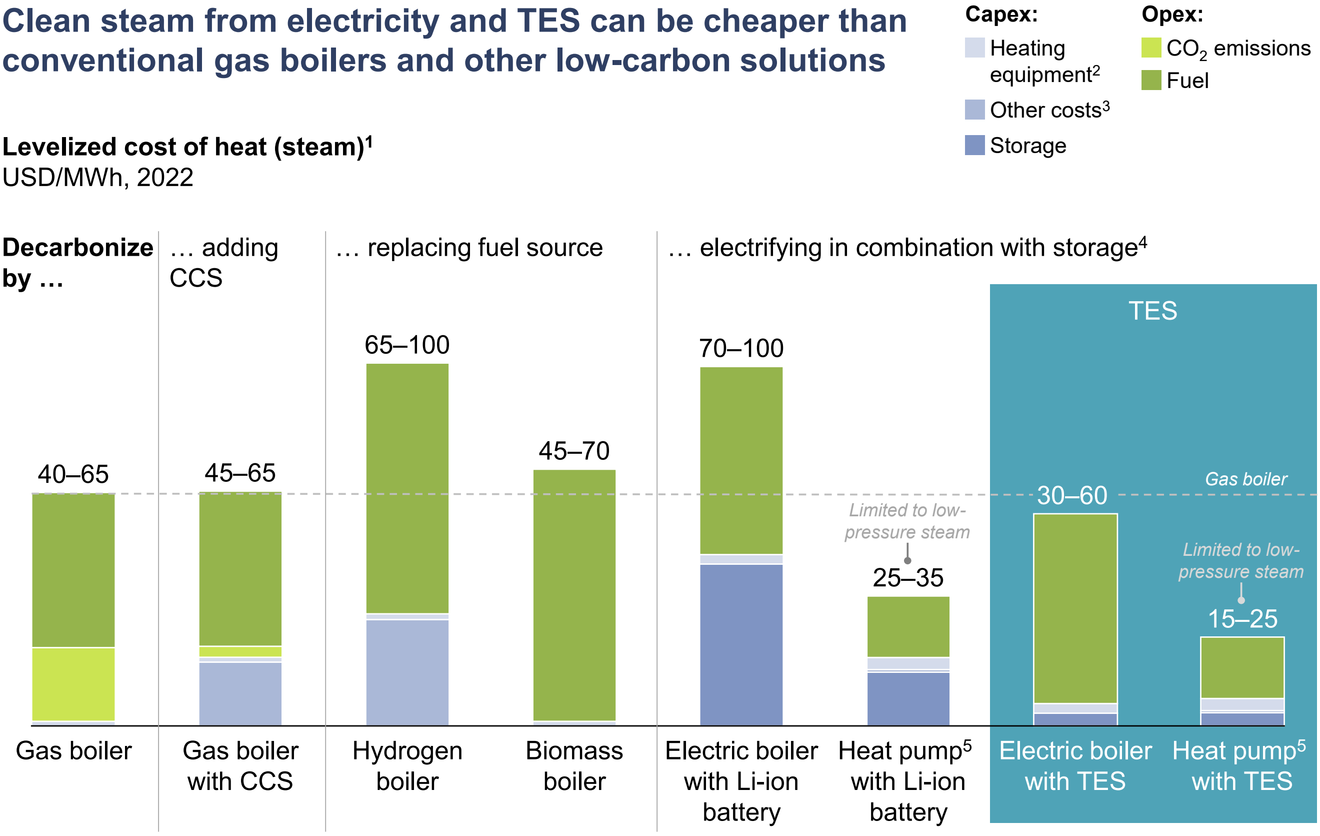
- **Decarbonization through carbon capture and storage can potentially have limited cost advantages.** Adding CCS reduces CO_2 emissions by about 80 to 90 percent. However, it typically increases overall system costs, as benefits from avoided carbon costs or green premiums do not offset the required capital investment for the equipment and continuous expenses for running it.
- **Decarbonization through replacing gas with hydrogen or biomass would likely require significant fuel-cost reductions to be competitive.** Although the value of a full abatement of carbon emissions (around USD 100 per tCO_2) is captured, this is outweighed by high electrolyzer capex and electricity cost for hydrogen (54 to 63 percent higher LCOH than for gas boilers) and high fuel costs for biomass (8 to 13 percent higher LCOH than for gas boilers). Under the current cost estimates, the clean fuels considered are not competitive. A significant reduction of electrolyzer capex through technological improvements or a change in relative fuel costs would be potentially required to achieve cost competitiveness.
- **Decarbonization through electrification can be cost-competitive today, especially in combination with TES.** Two electrification options are considered within this category: electric boilers and heat pumps. These can be used in combination with either Li-ion batteries or TES solutions. The value of electrification with storage is mainly driven by energy costs compared to hydrogen, biomass, and other fuel costs. The regional variability of energy prices means that TES's cost competitiveness might be geographically limited if there is no payment for flexibility provision. Compared with batteries and hydrogen solutions, TES is significantly more cost-competitive due to lower capex over the lifetime of the storage device (25 years for TES versus 10 to 15 years for Li-ion batteries) and higher system efficiency (around 96 percent efficiency for TES, 80 to 85 percent for Li-ion batteries, and 60 to 70 percent for hydrogen electrolyzer) that effectively reduces energy costs. Under current cost estimates, electrification can be cost-competitive if implemented with TES, potentially achieving an LCOH lower than gas boilers (Exhibit 9).

TES enables cost-efficient electrification and decarbonization of heat

Exhibit 9

Clean steam from electricity and TES can be cheaper than conventional gas boilers and other low-carbon solutions

Levelized cost of heat (steam)[1]
USD/MWh, 2022



1. Ranges reflect representative fuel prices. Gas (USD 6–12/mmBTU), electricity (USD 25–50/MWh), biomass (USD 200–350/t). In the hydrogen boiler case, hydrogen production costs amount to USD 2.1–3.2/kg of hydrogen.
2. Boiler, heat pump, and charging equipment.
3. Electrolyzer, CCS.
4. Assumes on-site renewables.
5. High-temperature industrial heat pump. Maximum achievable steam temperature is ~160ºC.

TES capex is expected to decline further by 2040

By 2040, power capex is expected to decrease by 15 to 30 percent for steam and 5 percent for hot air. Capex is projected to decrease by between USD 14,000 and USD 44,000 per MWth for steam solutions and around USD 6,000 per MWth for hot air (Exhibit 10). Those costs represent global costs and are provided by diverse LDES Council members. As each member might specialize in a subset of end-use applications, benchmark costs across each technology may come from different technology providers and therefore represent a broad selection of technologies.

As steam and hot air technologies are well known, no significant cost decrease is expected. In the case of hot air, the main discharge option involves a simple solution such as a hot air blower. Hence, the cost reduction does not exceed 5 percent. The technology for steam is also well known; however, the way energy is exchanged between the storage system and the steam can be further optimized, so some improvements are still expected for TES systems. Readers should note that for steam generation, the assumption was made that all the equipment up to and including the boiler feedwater pump was already available on-site and that no additional investment was needed (the detailed benchmarking methodology is included in Appendix A).

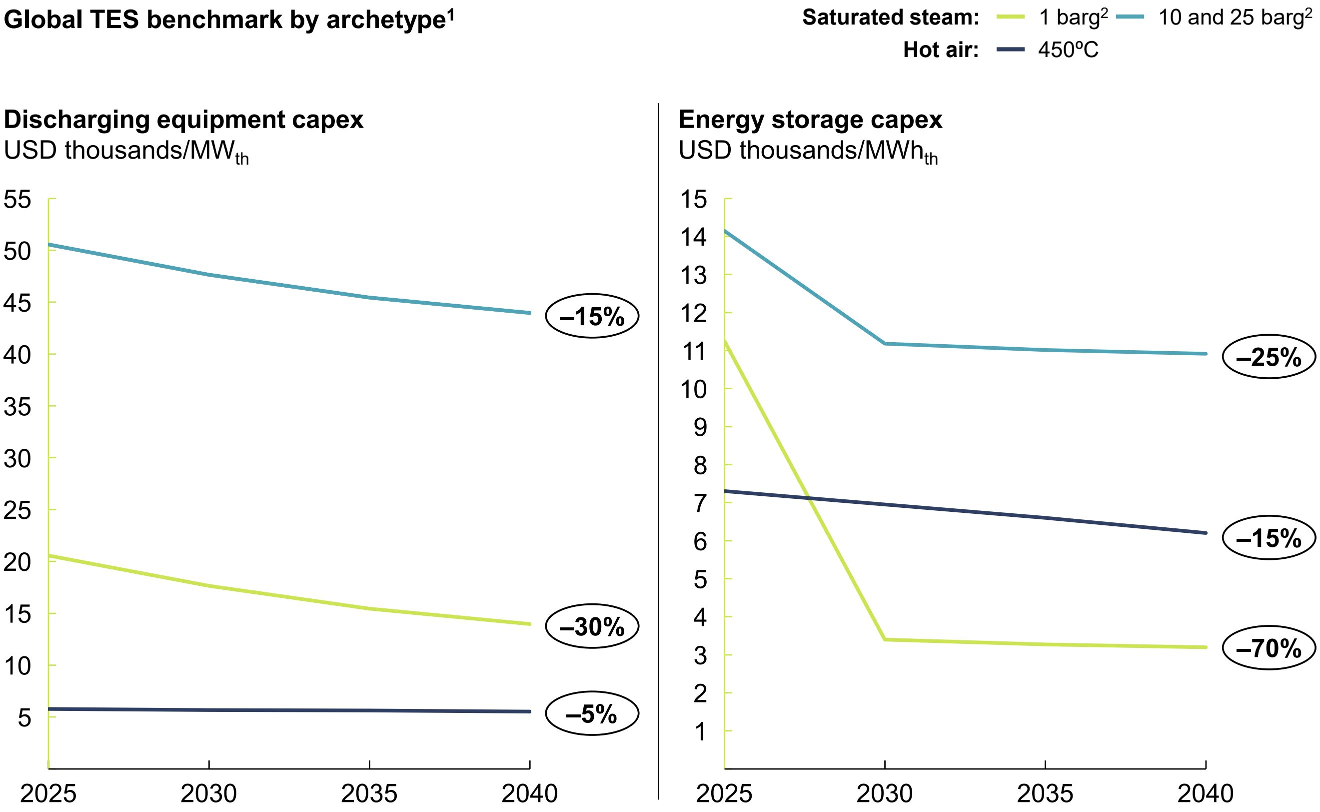
Energy capex is expected to fall between 15 and 70 percent for various types of heat. Costs would go down from USD 7,000 to USD 14,000 per MWhth in 2025, to USD 3,000 to USD 11,000 per MWhth in 2040. Looking across different heat output types, we see cost reductions of up to 70 percent. It is important to note that the pace of reduction observed between 2025 and 2030 is likely driven by the scale-up of technologies that might still be at the level of demonstration or pilot projects today.

> **When the final demand is heat, firming heat is more efficient than firming power**

Exhibit 10

TES energy and power capex are expected to decrease significantly, especially for saturated steam

Global TES benchmark by archetype[1]



1. Benchmark data provided by LDES Council members and aggregated into archetypes based on technological properties. All data points are top-quartile cost data within the archetype. Nominal durations were provided by the technology providers.
2. Gauge pressure (pressure in bars above ambient or atmospheric pressure).

KEY TAKEAWAYS

- LDES technologies are expected to become increasingly cost-competitive as the market matures.
- Under current cost estimates, electrification can be cost-competitive if implemented with TES, potentially achieving an LCOH lower than gas boilers (below USD 30 to 60 per MWh).
- Firming heat is more energy-efficient than firming power when the final demand is heat (57 to 61 percent compared to above 90 percent).

Firming heat is more energy-efficient than firming power when the final demand is heat

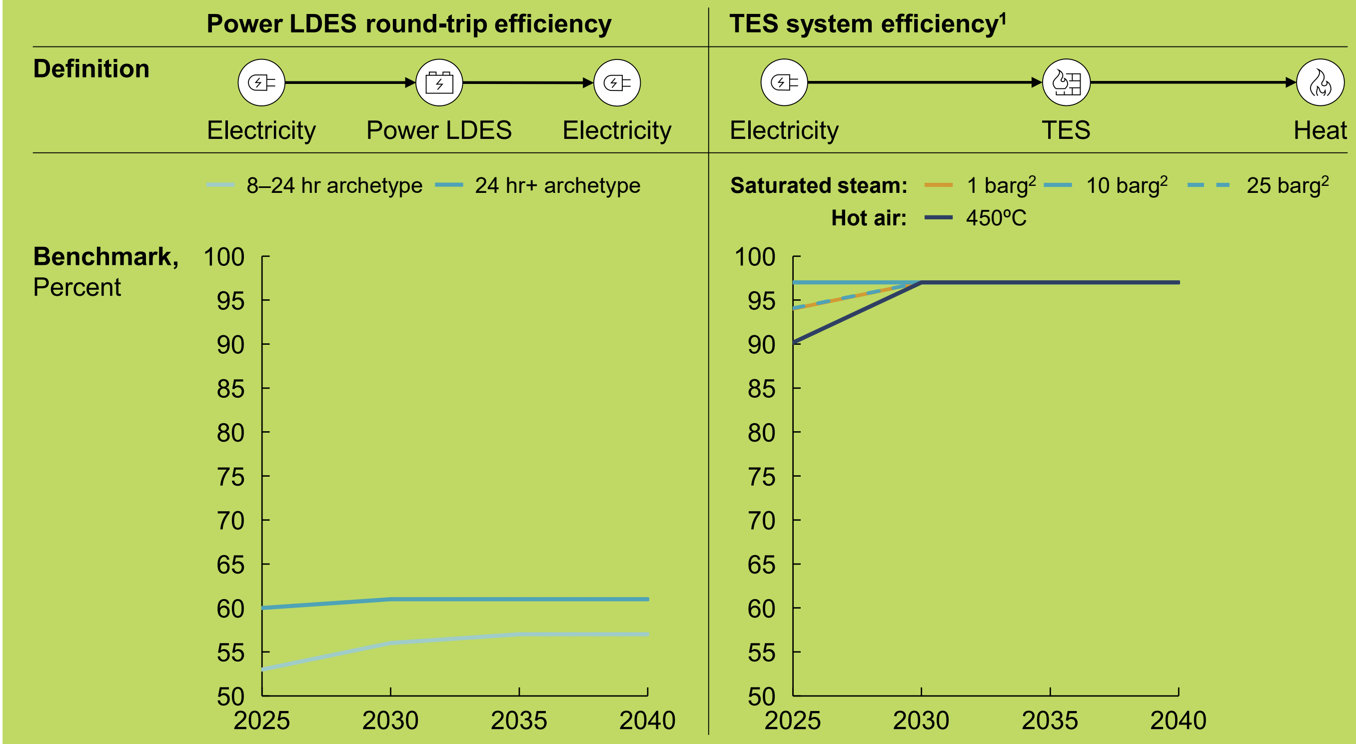
The higher system efficiency of TES makes it an attractive storage solution for heat applications. System efficiency shows how much energy can be retrieved compared to the energy required to charge the system. In the case of power LDES, to generate heat, electricity needs to be retrieved first from the storage at the top-quartile RTE of between 57 and 61 percent. Then, this electricity needs to be converted to heat in a conversion process with a typical efficiency above 95 percent, bringing the overall efficiency to about 54 to 58 percent.

In the case of TES, the electricity is first converted into heat to be put into storage with efficiencies above 95 percent. Then the heat can be discharged directly at efficiencies typically above 95 percent. Because the energy is stored as heat and the conversion losses when going from one type of heat to another are minimal, the overall system efficiency can easily be above 90 percent (Exhibit 11).

Exhibit 11

TES system efficiency is higher than power LDES round-trip efficiency

Power LDES and TES system efficiency benchmark (top-quartile technologies)



1. System efficiency is defined as the product of charging and discharging efficiency.
2. Gauge pressure (pressure in bars above ambient or atmospheric pressure).

4

TES business cases

TES business cases can already be profitable at an IRR of 16 to 28 percent. This is subject to local market conditions such as optimal physical configurations (access to captive renewables, captive heat, or grid electricity) and market designs (including low grid fees and the payment for flexibility).

The business case assessments cover a wide range of realistic TES use cases, namely: medium-pressure steam in a chemicals plant (up to 28 percent IRR), district heating peaker plant (up to 16 percent IRR), high-pressure steam in an alumina refinery (up to 16 percent IRR), and co-generation in an off-grid greenhouse (up to 22 percent IRR). All market-exposed business cases show that a supportive ecosystem that acknowledges the value of flexibility (such as lower grid fees or payments for flexibility or ancillary services) would likely be critical to ensuring wide commercial adoption. The business case with behind-the-meter renewable generation shows that TES can already be commercially feasible, regardless of external market conditions.

The commercial viability of TES depends on local market conditions

The commercial viability of TES depends on access to supportive physical configurations and market designs:

Three possible physical configurations can support TES use cases, covering the infrastructure and connections needed for TES devices to charge:

- **Access to captive electricity supply** from behind-the-meter renewable sources like photovoltaic (PV) solar or wind. These sources can be used to power electric processes and charge TES devices when there is excess generation capacity, thus preventing renewable electricity generation from being stranded and curtailed.
- **Access to captive heat supply** in the form of either waste heat or renewable heat generation. TES devices can enable heat currently wasted in industrial processes to be economically captured, increasing heat utilization. This is particularly true for low temperatures below 100°C. Similarly, captive heat production such as solar thermal plants equipped with TES devices could provide baseload heat and electricity at scale.
- **Access to clean electricity on the market** by connecting to grid infrastructure. In a configuration where a facility is connected to the grid, T&D infrastructure must be capable of accommodating additional loads to charge TES devices on top of baseloads.

There are different market design options that could support TES. As part of a level playing field, these designs can also support other options like fuel replacements or flexibility solutions.

- **Carbon pricing** through carbon markets (such as the EU Emissions Trading System) or penalties can be used to incentivize the adoption of decarbonization solutions, such as TES. By replacing fossil-fuel-based heat like gas boilers with TES solutions, businesses could avoid carbon costs and free up carbon budget that can then be allocated to areas that are tougher to decarbonize.
- **Variable electricity pricing** supports supply-and-demand optimization (for example, through peak pricing) and incentivizes energy system flexibility solutions. The market structure that enables variability in electricity pricing allows such solutions to charge or discharge at economically optimal times (for example, charging at lower prices and discharging at peak prices).
- **Payment for flexibility provision** through markets can optimize system costs by balancing supply and demand. Flexibility solutions could play a potential cost-efficient role in market balancing and can be paid for charging or discharging at specific times. LDES solutions can provide an array of benefits, and as the market evolves, criteria for the additional system services need to be accounted for and credited.
- **Other revenue streams or incentives could be added** to monetize the value of flexibility across the value chain. One example is grid connection costs. Typically, electricity (and gas) markets have financed infrastructure through grid connection fees, assuming a centralized energy system with mostly predictable off-take and supply-side flexibility. As flexibility solutions strengthen the energy system's reliability and affordability, penalizing such technologies through grid connection fees might be counterproductive. Hence, reducing grid fees for such solutions can incentivize their adoption. One practical example is Germany's exemption from grid fees for storage assets during the first 20 years of operation.

Assessment of TES business cases

The assessed TES business cases cover a broad set of representative industrial processes, durations, and temperatures. The case premises and analysis outputs have been verified by LDES Council members and industry players and aim to test multiple physical configurations and market design options, assessing the implications for commercial feasibility and the conditions needed to realize them. The business cases summarized below are developed for fictitious assets that are representative of real-life systems.

The business case assessments include a base and an upside case. Given the dependency on local conditions, TES business cases are tested across several dimensions, resulting in a base and an upside case. The base case focuses on core business case fundamentals, such as required system investment, production cost changes, or emissions savings. The upside case covers potential additional value opportunities deemed relevant for flexibility use cases but potentially challenging to realize, such as payments for decreasing curtailment or the reduction of grid demand-side fees.

> **TES behind-the-meter business cases can already be positive given the limited-to-nonexistent grid dependencies**

TES business case specifications and other applications

Business case 1

Medium-pressure steam in a chemicals plant

IRR

Up to 28%

Specifications

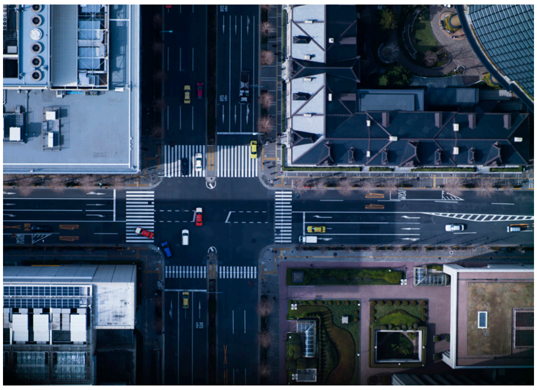
- Steam required at ~25 barg and 330°C
- Currently using a 30 MW gas boiler, which is to be replaced by an electric boiler with TES

Other applications

Other industrial processes:

- Drying
- Humidification
- Cleaning
- Moisturization
- Sterilization and disinfection
- Process heating

Business case 2



District heating using a peaker plant

IRR

Up to 16%

Specifications

- Heated water required at ~10 barg and 120°C
- Currently using a 250 MW peaker gas boiler, which is to be replaced by TES powered by offshore wind

Other applications

Other large island heating networks:

- Industrial complexes
- Residential
- Public schools/universities
- Field hospitals

Business case 3

IRR

Up to 16%

High-pressure steam in an alumina refinery

Specifications

- Steam required at ~104 barg and 325°C
- Currently using a 380 MW gas boiler, which is to be replaced by an electric boiler with TES

Other applications

Other industrial processes:

- Direct drive of equipment (pumps, compressors)
- Process heating
- Steam cracking
- Distillation

Business case 4

IRR

Up to 22%

Co-generation for an off-grid greenhouse

Specifications

- Electricity and 30°C to 40°C heated water required
- Currently using a 2 MW gas boiler and 0.25 MW diesel generator, to be supplemented with TES powered by 2.1 MW captive solar generation

Other applications

Other industries:

- Off-grid mining: low-temperature processing and warm water for labor camp
- Underground ventilation in mines: cooling loads via absorption heat pumps
- Greenhouse cooling, humidity, fresh water, and cooling management
- Poultry and other livestock farming

Business case 1: Medium-pressure steam in a chemicals plant

Implementing TES for medium-pressure steam production can generate positive returns (~6 percent IRR) and could achieve even more with the additional value of flexibility (up to ~28 percent IRR)

BUSINESS CASE 1 HIGHLIGHTS

TES provides a cost-efficient decarbonization opportunity in supporting medium-pressure steam production in combination with an electric boiler. In this business case, TES is considered a highly flexible solution with daily charging cycles and in a European grid connected setting, able to benefit from intraday power price fluctuations. The analysis shows a potential standalone profitable base IRR of up to 6 percent that could increase to 28 percent with additional flexibility value streams. The main base business case drivers include a reduction in operating costs from low electricity prices and benefits from carbon savings.

Business case configuration:
A 0.5 GWh TES and 30 MW electric boiler replace a 30 MW gas boiler to provide medium-pressure steam to a chemical, refining, and petrochemical plant in Europe. Electricity is supplied by the grid and TES is used to benefit from intraday price volatility. Key drivers of the business case are cost reductions from fuel replacements and reduced CO_2 emissions.

Profitability assessment:
The base case has a USD 10 million net present value (NPV) with a 6 percent IRR. This is mainly driven by a relatively low capex (approximately USD 30 million) and potentially significant value upsides (USD 125 million across fuel replacements and CO_2 benefits) while being tempered by typical grid demand fees (USD 80 million).[18] The upside case has a USD 125 million NPV with a 28 percent IRR, mainly driven by excluding grid fees (USD 80 million) and accounting for renewable electricity curtailment reduction (USD 35 million).[19] See Exhibits 12 and 13.

Potential business case unlocks:
Two keys unlock support for the **base case:**

- Variable electricity pricing
- Carbon pricing (approximately 27,000 tCO_2eq in annual emission savings)

The **upside case** includes incentives for flexibility. In situations where more captive renewable energy source generation can be placed behind the meter, the upside case might be achieved without additional market mechanisms.

Steam production business case details

Technical specifications	Market parameters	Similar industrial processes
• Baseload operation (>99 percent up-time), with daily TES charging cycles • Steam at ~25 barg and 330°C (260 GWh annual equivalent) • 30 MW electric boiler with 0.5 GWh TES replacing 30 MW gas boiler • Upgrade the 300-km transmission line built to support additional 80 MW of grid capacity to charge the TES • ~47,000 tCO_2 emissions saved annually	• Fossil fuel cost: USD 40/MWh • Renewable electricity cost: USD 25/MWh • Net CO_2 price: USD 100/tCO_2	• Drying • Humidification • Cleaning • Moisturization • Sterilization and disinfection • Process heating

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[18] Average of selected European grid fees used.

[19] RES curtailment is calculated as the value of 50 percent of the electricity used to charge the TES device.

Source: Eurostat

Exhibit 12

Chemicals plant business case diagram

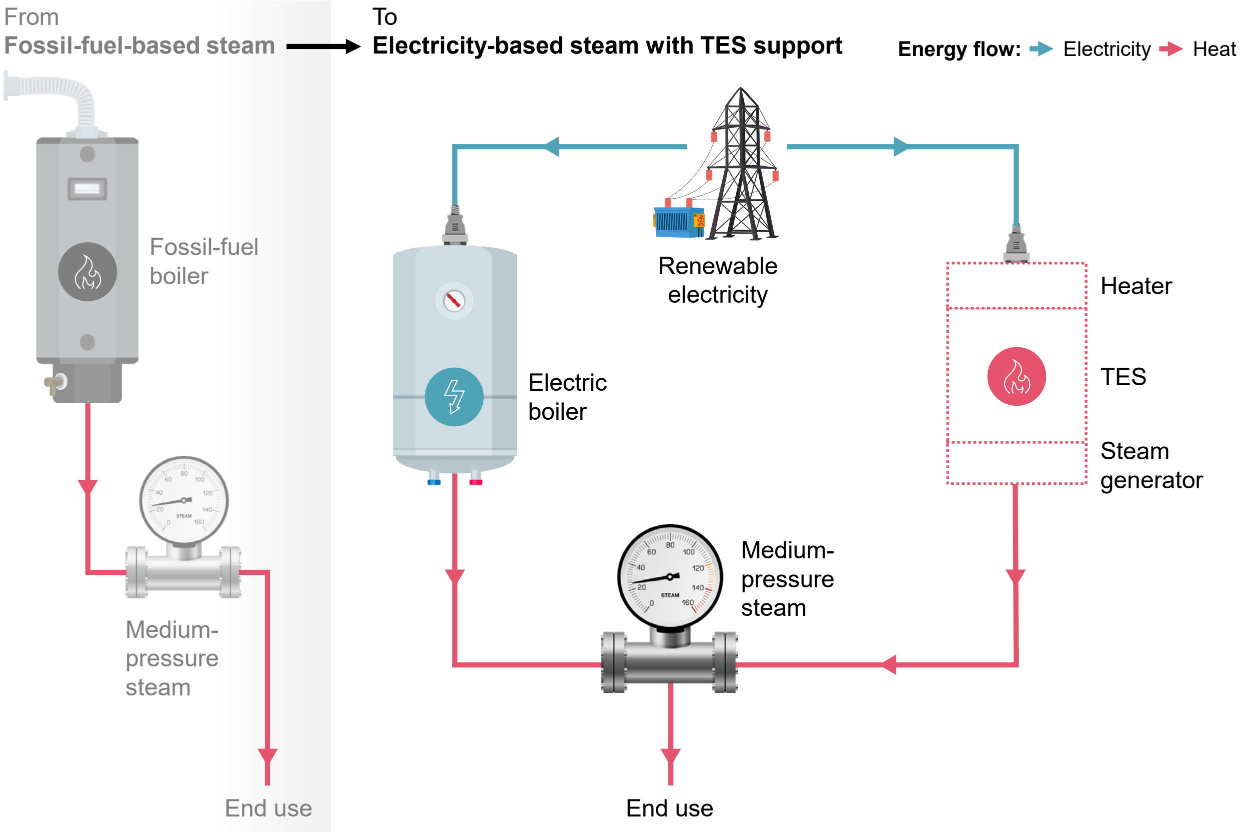
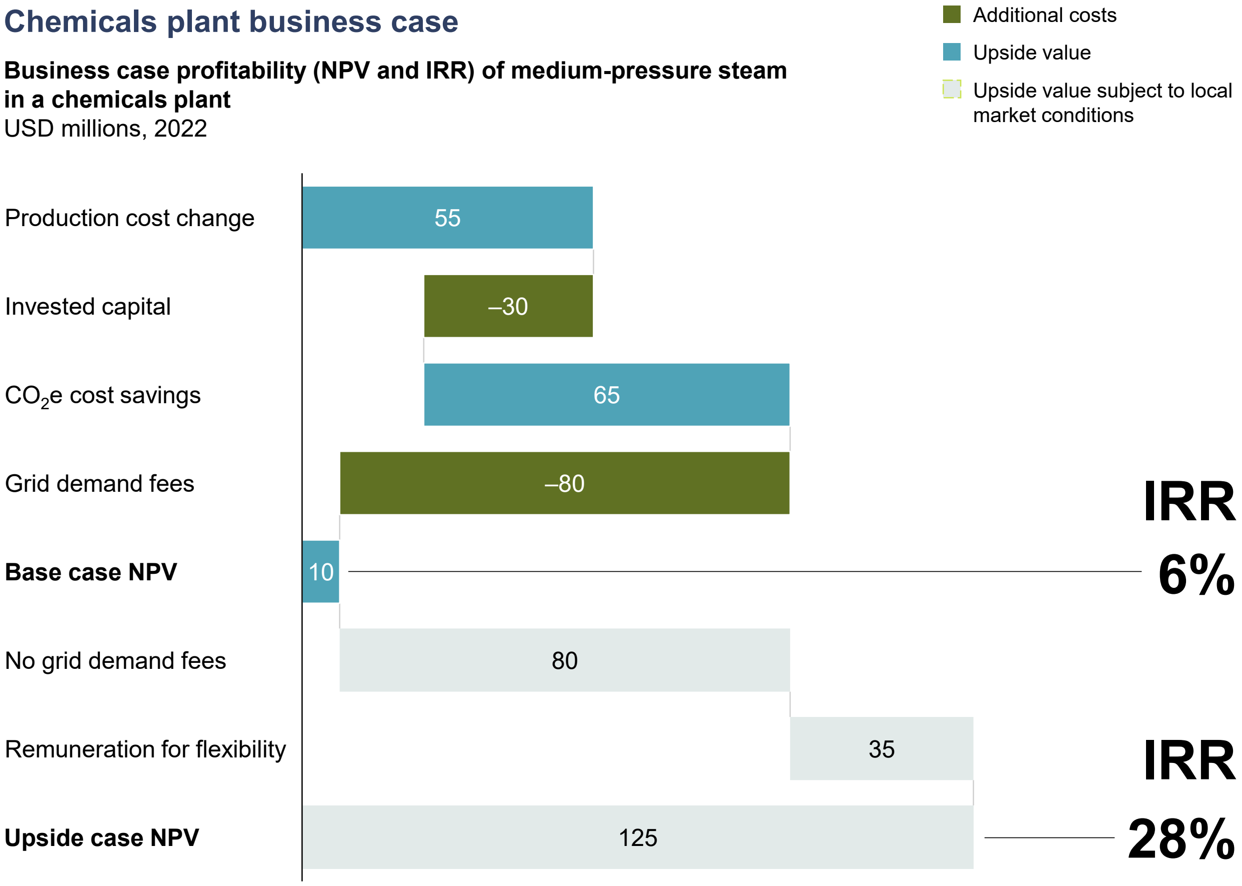


Exhibit 13

Chemicals plant business case

Business case profitability (NPV and IRR) of medium-pressure steam in a chemicals plant
USD millions, 2022



Business case 2: District heating supplied by a peaker plant

Replacing peaker plants with TES can generate positive returns if flexibility is valued (up to 16 percent IRR)

BUSINESS CASE 2 HIGHLIGHTS

TES provides a method of decarbonizing peaker plants to provide hot water in a district heating network. In this business case, TES is considered a flexible grid-connected solution that is used when peak demand for hot water is not met by baseload generation, heavily optimizing charging times to capitalize on low electricity prices from excess renewable electricity generation. The analysis shows that although the base case IRR (0.5 percent) is positive, an additional value stream would be required to increase the return to attractive levels of up to 16 percent. The main base business case drivers include a reduction of production costs (for example, via low electricity prices), benefits from carbon savings, and increasing the value of flexibility (for example, by increasing the number of charging cycles through additional cooling functions).

Business case configuration:
A 4 GWh TES replaces two 125 MW gas boilers (250 MW total) to provide hot water to a district heating network in Europe. TES is used as a flexible asset to benefit from very low pricing due to excess renewable electricity generation. Key drivers of the business case are production-cost reductions from fuel replacements and CO_2 benefits from decreasing emissions.

Profitability assessment:
The base case has a negative USD 40 million NPV with a 0.5 percent IRR. This is mainly driven by value upsides (USD 100 million in fuel replacements and CO_2 benefits); however, high capex costs (USD 95 million) and grid demand fees[1] (USD 45 million) impact the business case. The upside case has a USD 55 million NPV with a 16 percent IRR, mainly driven by adding cooling functionality (USD 20 million), avoiding gas boiler replacement costs (USD 25 million), and excluding grid fees (USD 45 million).[20] See Exhibits 14 and 15.

Potential business case unlocks:
Two key unlocks could help support the **base case:**

- Variable electricity pricing
- Carbon pricing

In addition, the **upside case** would likely include:

- Rewarding flexibility (for example, by reducing grid fees and via remuneration for flexibility)
- Optimizing TES timing and operations (for example, by timing the implementation of TES with the replacement of gas boilers and increasing TES utilization)
- In situations where more captive renewable electricity generation can be placed behind-the-meter, an upside case might be achieved without additional market mechanisms

District heating business case details

Technical specifications	Market parameters	Applicability to large island heating networks and backup functions
• Peak demand operations with ~40 TES charging cycles annually • Heated water required at ~10 barg and 120°C (140 GWh annual equivalent) • 4 GWh TES solution replacing two 125 MW gas boilers (250 MW total) • 650 MW charging and 220 MW discharging • ~33,000 tCO_2 emissions saved annually	• Fossil fuel cost: USD 40/MWh • Renewable electricity cost: USD 5/MWh • Net CO_2 price: USD 100/tCO_2	• Industrial complexes • Residential • Public schools and universities • Field hospitals

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[20] Selected European grid fees included.

Source: Eurostat

Exhibit 14

District heating peaker plant business case diagram

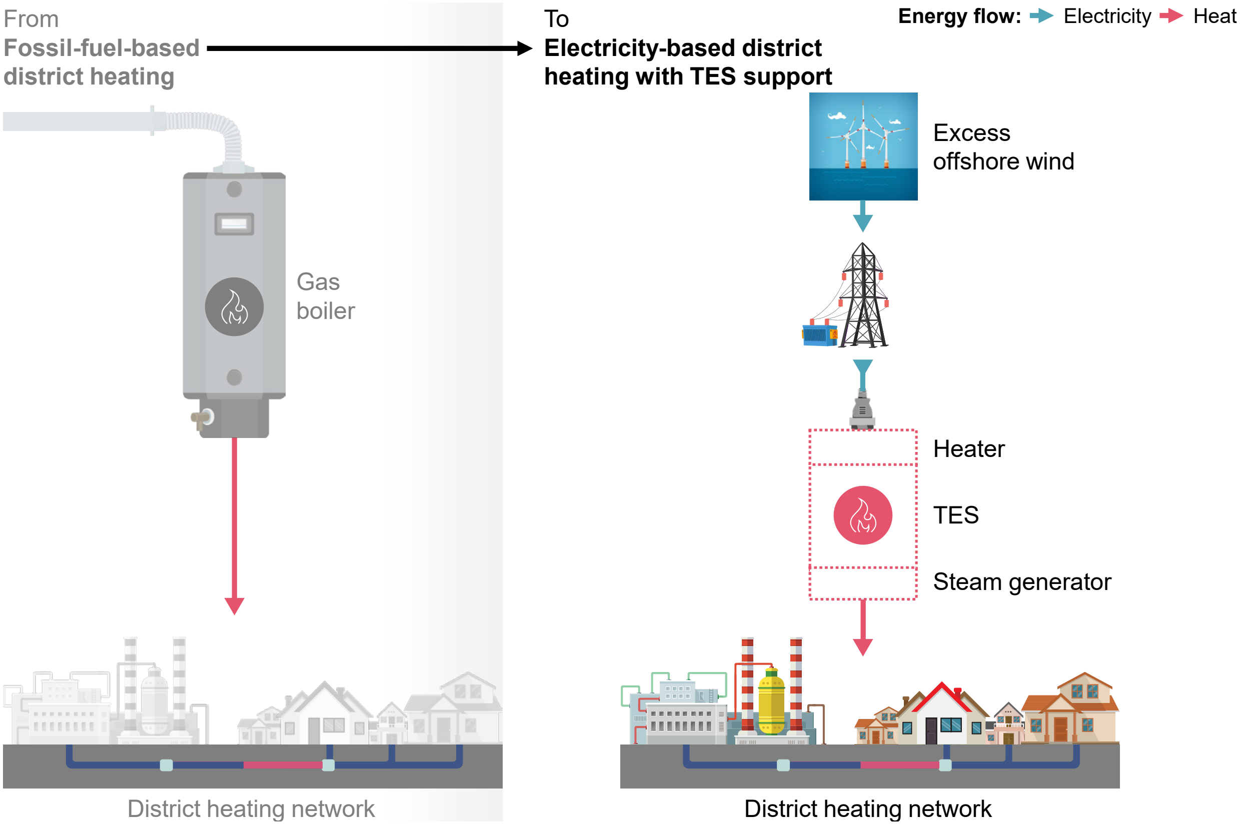
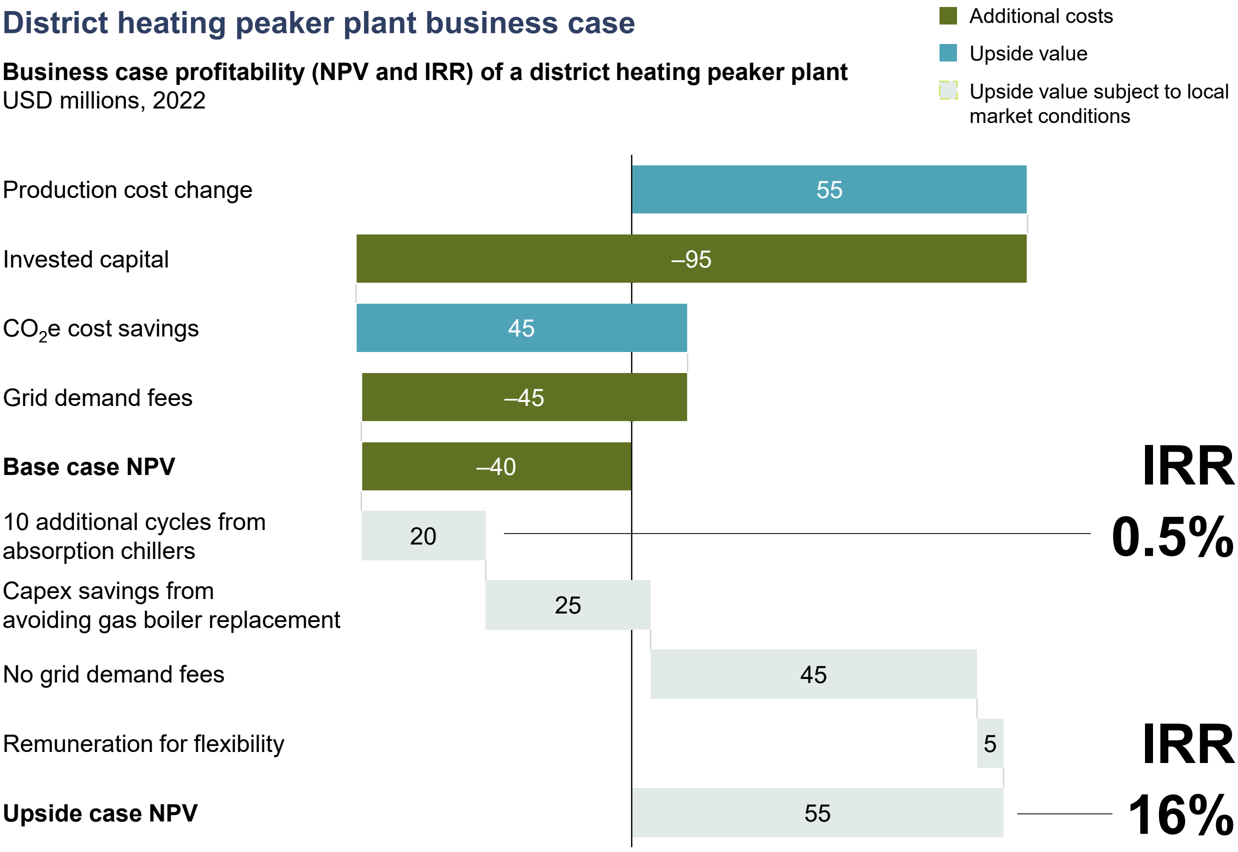


Exhibit 15

District heating peaker plant business case

Business case profitability (NPV and IRR) of a district heating peaker plant
USD millions, 2022



Business case 3: High-pressure steam in an alumina refinery

Implementing TES for high-pressure steam production can generate positive returns if flexibility is valued (up to 16 percent IRR)

BUSINESS CASE 3 HIGHLIGHTS

TES provides a method of decarbonizing an alumina refinery by providing high-pressure steam. In this business case, TES is considered a highly flexible solution (with daily charging cycles) in a European grid-connected setting where renewable electricity prices are slightly higher than fossil fuel prices. The analysis shows that additional flexibility value streams on top of a base business case would be required to create a positive return (16 percent IRR). The main business case drivers needed are benefits from carbon savings and rewarding flexibility. The latter could be done, for example, through reducing fees for electricity transmission (grid demand fees) and effectively acknowledging that TES can become a grid asset, and not an additional burden on the grid.

Business case configuration:
A 6.6 GWh TES and 380 MW electric boiler replace a 380 MW gas boiler to provide high-pressure steam to an alumina refinery in Europe. TES is used as a highly flexible asset, though it is assumed that renewable electricity prices are slightly higher than prices for fossil fuels in this region. Key potential drivers of the business case are CO_2 benefits from reducing emissions and rewarding flexibility (for example, through reducing grid demand fees or remunerating avoided electricity curtailment).

Profitability assessment:
The base case has a negative USD 825 million NPV. This is mainly driven by a negative operating cost change (USD 260 million), capex needed (USD 375 million), and grid demand fees[1] (USD 1,040 million),[21] though CO_2 benefits bring some value (USD 845 million). The upside case has a USD 635 million NPV with a 16 percent IRR, mainly driven by excluding grid fees (USD 1.04 billion) and accounting for renewable electricity curtailment reduction (USD 425 million).[22] See Exhibits 16 and 17.

Potential business case unlocks:
Two keys unlock support for the **base case:**

- Variable electricity pricing
- Carbon pricing

The **upside case** could be supported by the following unlocks:

- Rewarding flexibility (for example, reduced grid fees, remuneration for flexibility)
- In situations where more renewable electricity generation can be placed behind the meter instead of sourcing electricity from the grid, there are no grid fees in the first place, and therefore an upside case might be achieved without additional market mechanisms

Alumina refinery business case details		
Technical specifications	**Market parameters**	**Applicability to other industrial processes:**
• Baseload operation (>99 percent up-time), with daily TES charging cycles • Steam at ~104 barg and 325°C (260 GWh annual equivalent) • 380 MW electric boiler with 6.6 GWh TES replacing 380 MW gas boiler • Upgrade 300 km transmission line built to support additional 980 MW grid capacity • ~600,000 tCO_2 emissions saved annually	• Fossil fuel cost: USD 20/MWh • Renewable electricity cost: USD 25/MWh • Net CO_2 price: USD 100/tCO_2	• Direct drive of equipment (pumps and compressors) • Process heating • Steam cracking • Distillation

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[21] Average of selected European grid fees used.

[22] Renewable curtailment is calculated as the value of 50 percent of the electricity used to charge the TES device.

Source: Eurostat

Exhibit 16

Alumina refinery business case diagram

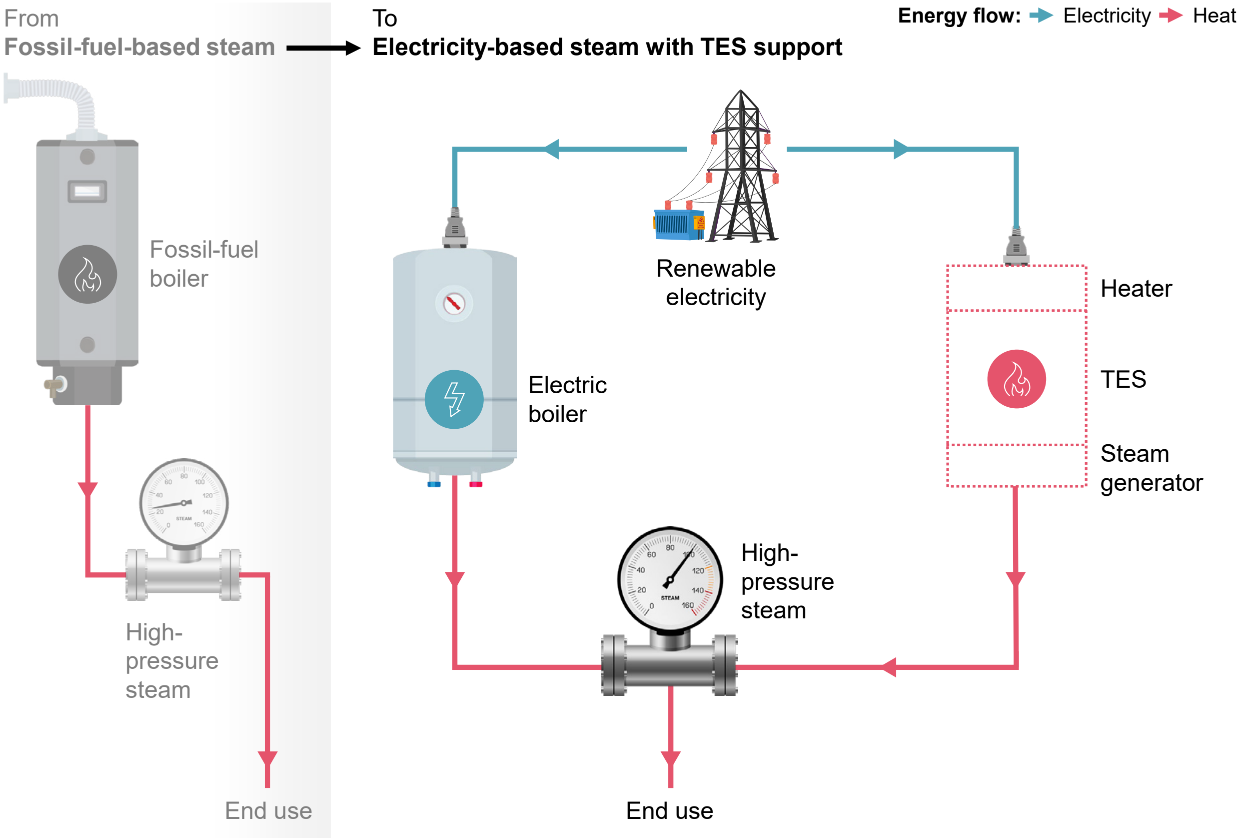
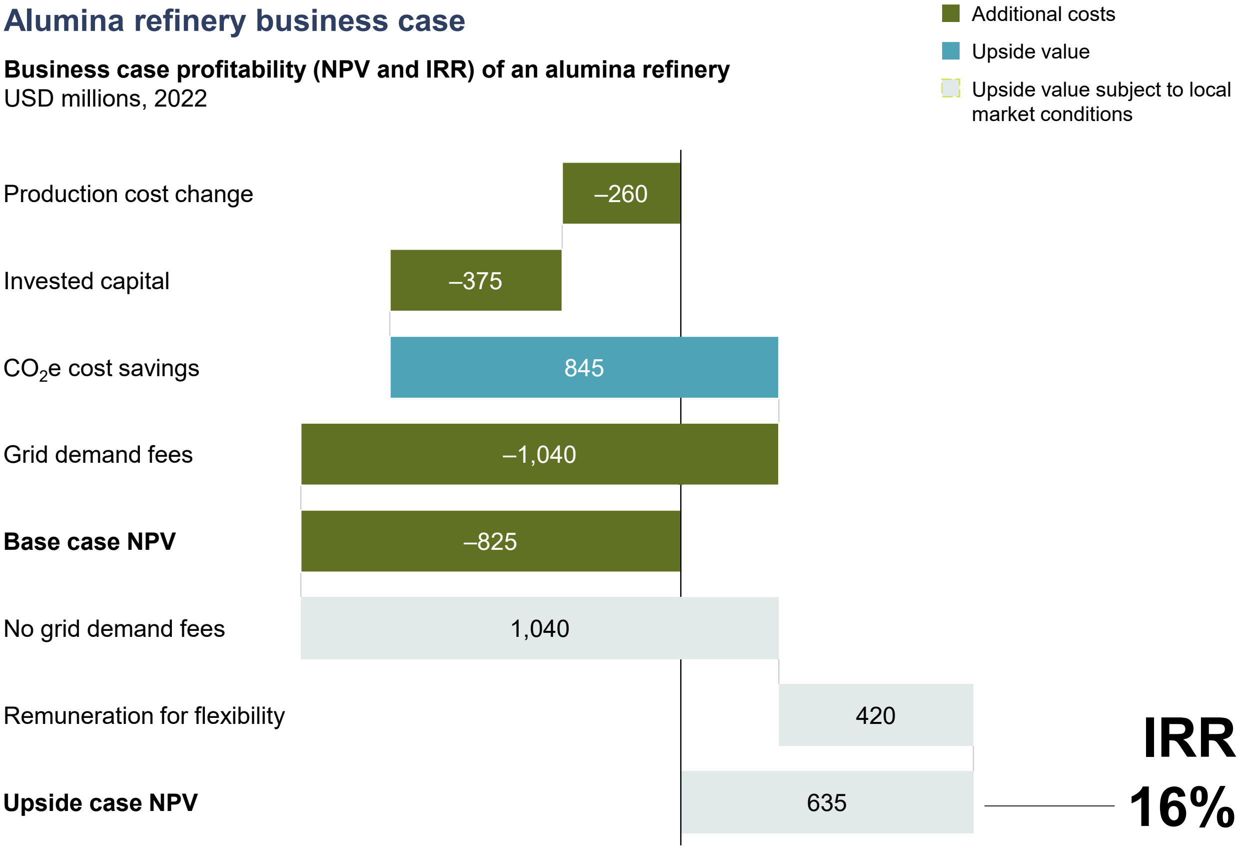


Exhibit 17

Alumina refinery business case

Business case profitability (NPV and IRR) of an alumina refinery
USD millions, 2022



Business case 4: Co-generation for an off-grid greenhouse

Implementing TES with co-generation in an off-grid setting can produce positive returns (up to ~22 percent IRR), regardless of the additional value of flexibility

BUSINESS CASE 4 HIGHLIGHTS

TES provides a cost-efficient decarbonization opportunity to support co-generation (electricity and heat usage) in an off-grid setting with captive solar. In this business case, TES is considered a high flexibility solution with daily charging cycles to uptake captive solar energy and electrify heat production in a sub-Saharan Africa off-grid setting. The analysis shows a potential standalone profitable base business case of up to 22 percent, driven by reduced production costs and low electricity prices as well as benefits from carbon savings.

Business case configuration:
An 11.4 MWh TES and 2.1 MW solar PV system supplement a 2.0 MW gas boiler and a 0.25 MW diesel generator to provide electricity and warm water to an off-grid greenhouse in sub-Saharan Africa. TES is used as a highly flexible asset to maximize the capacity factor[23] of captive solar and electrify heat production. In the summer months, the combination of TES with solar can meet all heat and electricity demands. In the winter months on the shortest and coldest days, this might be supplemented with a gas boiler and diesel generator as backup options. Key potential drivers of the business case are production cost reductions from fuel replacements and CO_2 benefits from reducing emissions.

Profitability assessment:
The base case has a USD 1.6 million NPV with a 22 percent IRR. This is mainly driven by a significant contribution of value upsides (USD 3.6 million in fuel replacement and CO_2 benefits) while being tempered by the relatively significant capital investment (USD 2.0 million). See Exhibits 18 and 19.

Potential business case unlocks:
Two keys unlock support for the **base case:**

- Behind-the-meter renewable generation: benefits from captive solar generation and maximizing the capacity factor of solar panels, resulting in low electricity unit price
- Carbon pricing

Off-grid greenhouse business case details

Technical specifications	Market parameters	Applicability to other industries
• Seasonal demand loads with daily TES charging cycles • Warm water at 30° to 40°C and electricity (equivalent to 1,850 MWh of electricity and 2,200 MWh of heat annually) • 11.4 MWh TES solution and 2.1 MW solar PV system supplemented with a 2.0 MW gas boiler and 0.25 MW diesel generator • ~2,000 tCO_2 emissions saved annually	• Fossil fuel cost: USD 40/MWh • Net CO_2 price: USD 100/tCO_2	• Off-grid mining: low-temperature processing and warm water for labor camps • Underground mine ventilation: cooling loads via absorption heat pumps • Greenhouse cooling, humidity, and freshwater management • Poultry and other livestock farming

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[23] Capacity factor is defined as the amount of time energy is being produced as a percentage of total time in a day.

Exhibit 18

Off-grid greenhouse business case diagram

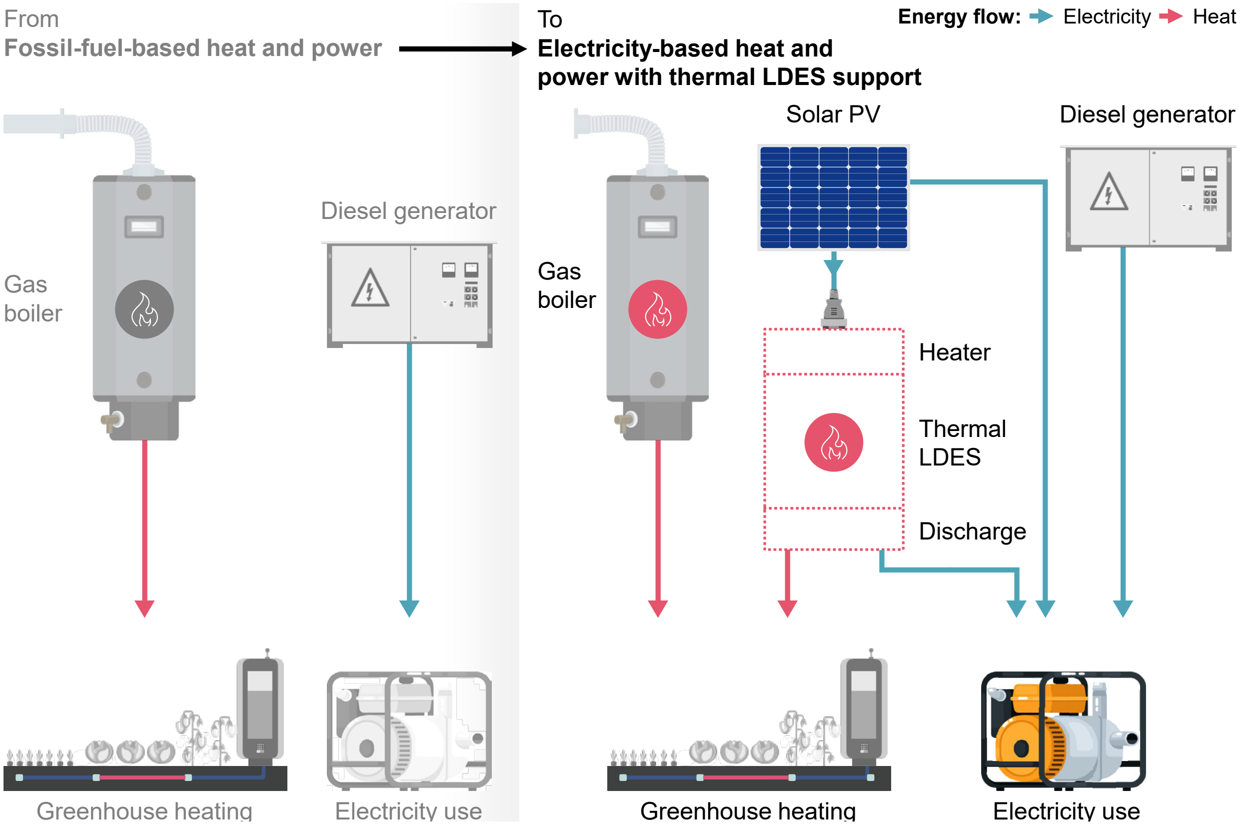
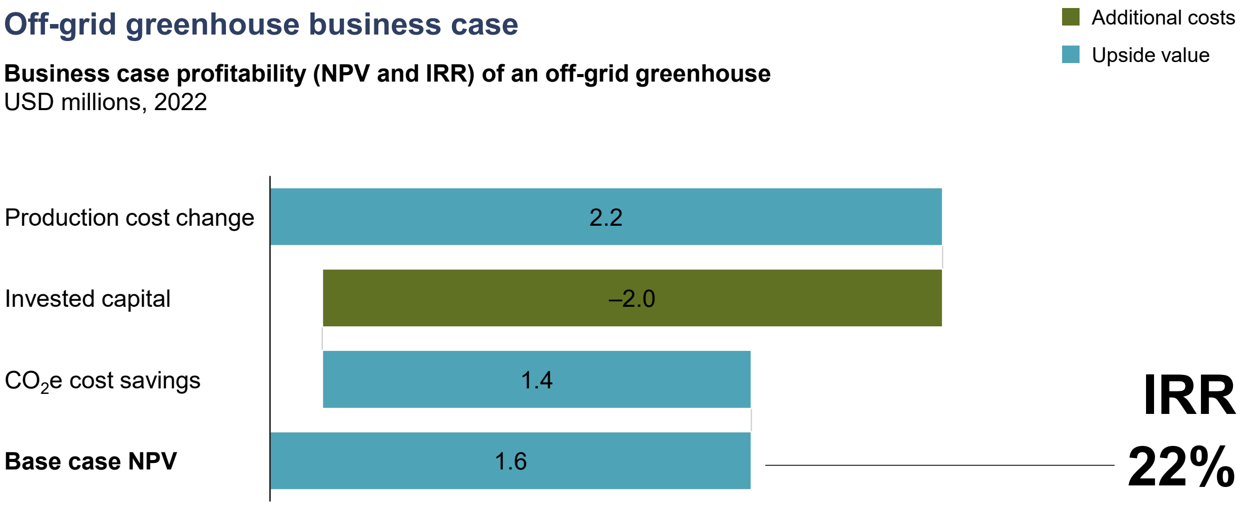


Exhibit 19

Off-grid greenhouse business case

Business case profitability (NPV and IRR) of an off-grid greenhouse
USD millions, 2022



KEY TAKEAWAYS

- TES for medium-pressure steam production can generate ~6 percent IRR and up to ~28 percent IRR with the additional value of flexibility.
- Replacing peaker plants with TES can generate returns up to 16 percent IRR if flexibility is valued.
- TES for high-pressure steam production can generate up to 16 percent IRR.
- TES with co-generation in an off-grid setting can generate up to ~22 percent IRR, regardless of the additional value of flexibility.

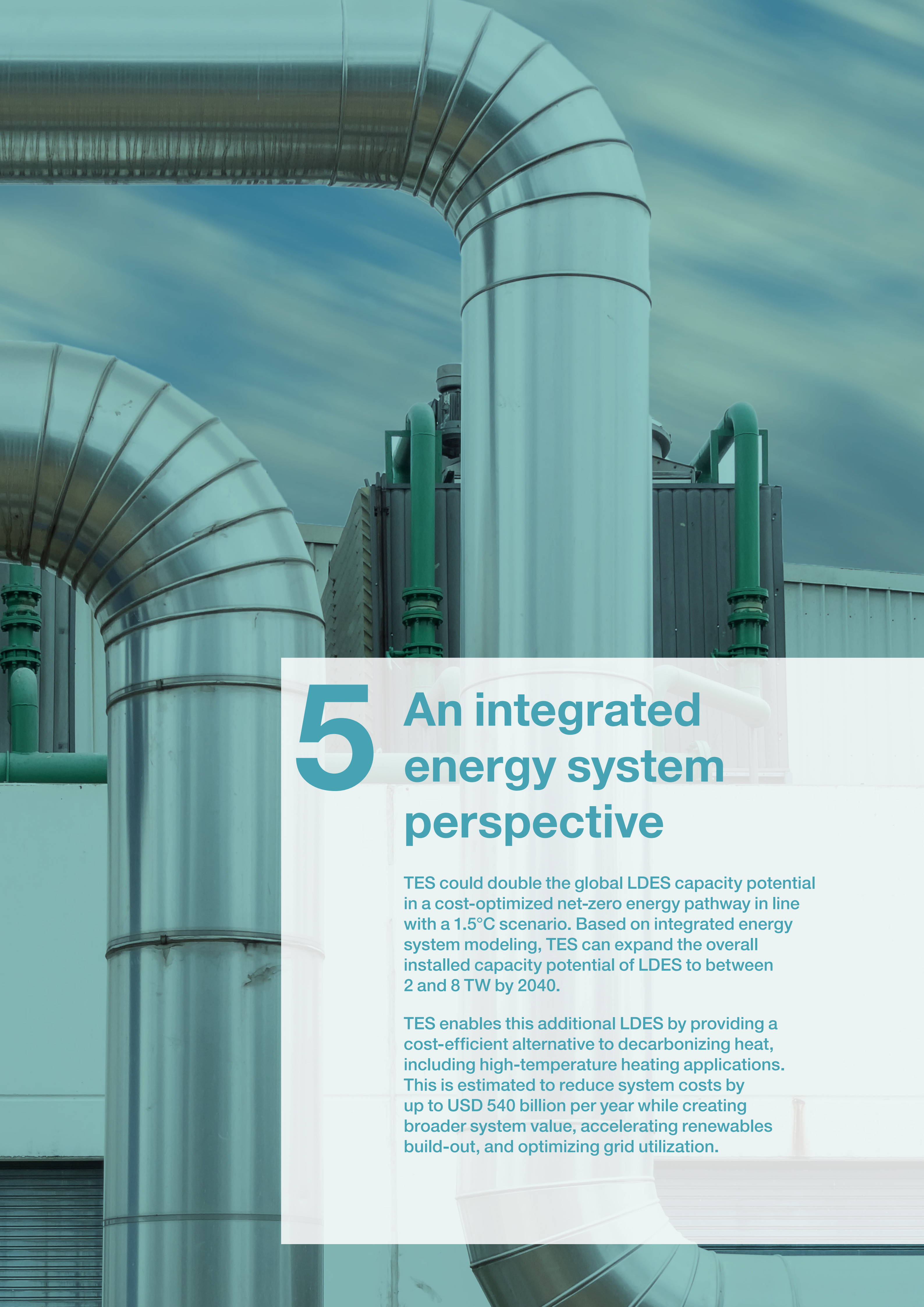
Case study: The port of Rotterdam

The port of Rotterdam case study shows how LDES can integrate and decarbonize complex energy systems while creating system value. As one of the largest industrial clusters and ports worldwide, the port of Rotterdam, located in the Netherlands, brings together a broad spectrum of heavy-industry use cases like refineries and heating networks. In addition, the coastal location provides direct access to a potential abundance of offshore wind. With significant power and heat demand on-site, there is a role for both power LDES and TES use. In combination with electric heating systems (for example, boilers and heat pumps), TES can firm up the variable offshore wind supply into a more stable supply of clean heat for industrial heating, including high-temperature heating.

In an industrial location like the port of Rotterdam, the need for industrial heating can radically change the configuration for a net-zero energy system. Considering that heat electrification with TES could be a competitive decarbonization option—especially for direct wire connection to renewables—it might become a technology of choice for achieving significant decarbonization targets. If all heat demand in the port becomes electrified by 2040 and is served by TES, it would require a storage capacity of between 65 and 90 GWh for systems providing 12 to 16 hours of storage. The land footprint of TES is estimated to be 30 to 45 hectares, which would not be a constraint as it represents less than 0.5 percent of the port of Rotterdam's total 12,600 hectares.

All the involved stakeholders could benefit from TES and contribute to its deployment. All stakeholders have an opportunity to play an important role in realizing an optimized energy system that includes TES, as they represent different perspectives:

1. Offshore wind developers are typically focused on ensuring their offshore wind farms are integrated and connected to relevant off-takers, including industrial heat off-takers. Connecting their variable electricity supply with LDES solutions such as TES could optimize off-take and increase asset value.
2. Industrial energy off-takers are typically focused on ensuring an affordable, reliable, and increasingly clean energy supply, with a limited impact on their industrial processes. Combining variable clean electricity supply with LDES solutions could help support their focus, and the combination with TES would likely enable cost-efficient solutions for their heating and decarbonization pathways.
3. Policymakers in this space are typically focused on ensuring optimal societal decarbonization outcomes, considering options for a supportive policy environment and potentially beneficial financial instruments. Governments could support TES use cases by ensuring a level playing field for flexibility solutions across power and heat. The development of such cost-competitive solutions may help, in turn, reduce infrastructure costs such as upgrading the electricity network, which might have otherwise required public investment support.



5

An integrated energy system perspective

TES could double the global LDES capacity potential in a cost-optimized net-zero energy pathway in line with a 1.5°C scenario. Based on integrated energy system modeling, TES can expand the overall installed capacity potential of LDES to between 2 and 8 TW by 2040.

TES enables this additional LDES by providing a cost-efficient alternative to decarbonizing heat, including high-temperature heating applications. This is estimated to reduce system costs by up to USD 540 billion per year while creating broader system value, accelerating renewables build-out, and optimizing grid utilization.

LDES can potentially meet the clean flexibility needs of future energy systems

The role of integrating LDES depends on local market conditions. To explore the need for LDES technologies across different geographical setups with varying local energy supply and demand, three different market archetypes have been considered:

i. Balanced markets, with similarly sized wind and solar capacities, such as Central Europe or the United States

ii. Solar-heavy markets, dominated by solar PV, such as Southern Europe or the Middle East

iii. Wind-heavy markets, such as Northwest European countries with significant shore-lines

For all three system types, several scenarios were analyzed considering:

i. Li-ion only

ii. Li-ion and power LDES

iii. All technologies

As observed in Exhibit 20, solar-heavy markets have a higher need for shorter duration flexibility than other scenarios, as supply fluctuations are predominantly intraday. In contrast, wind-heavy markets show the highest demand for LDES to cope with wind output fluctuations, which can last for days or even weeks. Systems with a balanced supply mix might be able to tackle more of the electrical demand variability with complementary wind and solar generation profiles, but ultimately the storage demand would be impacted by the overall electricity and heat demand.

Both power LDES and TES play a potentially critical role across market archetypes in an optimized energy system pathway to net zero. In a Li-ion battery only scenario, Li-ion batteries would cover both short- and long-duration needs with average discharge durations of up to 12 hours. In the other two scenarios that include LDES technology options, LDES is seen as the most cost-efficient solution for longer durations, reducing Li-ion average discharge durations to around four hours. This is explained by typical power LDES discharge costs being between 75 and 95 percent lower for 8-to-24-hour and 24-hour-or-more discharge durations, respectively. In a scenario with all relevant technologies, including TES, TES provides additional flexibility and increases overall LDES potential.

TES could accelerate the decarbonization of most heat use cases. Heat pumps can already outperform gas boilers in low-temperature applications in the short term and this technology becomes even better when coupled with TES. In contrast, high-temperature heat has historically been challenging to electrify due to high electricity costs. However, TES changes the economics of electrification by

The transition to clean energy requires an integrated energy system approach

The uptake of variable renewable energy, together with the increased electrification, is creating strong interdependencies across the energy system. The findings presented in this report are based on an integrated energy model that explores the most cost-optimized route to achieve a net-zero energy system,[24] considering sector coupling and the use of LDES, including TES, among other flexibility solutions. The optimization function of the model minimizes system costs to achieve net-zero emissions in the power sector by 2040, and in other sectors by 2050. The main inputs to the model comprise technology costs (including the latest LDES Council data) and projected electricity and heat demand profiles. While absolute demand figures are more challenging to predict, core insights of this effort are relative capacity additions and retirements across technologies.

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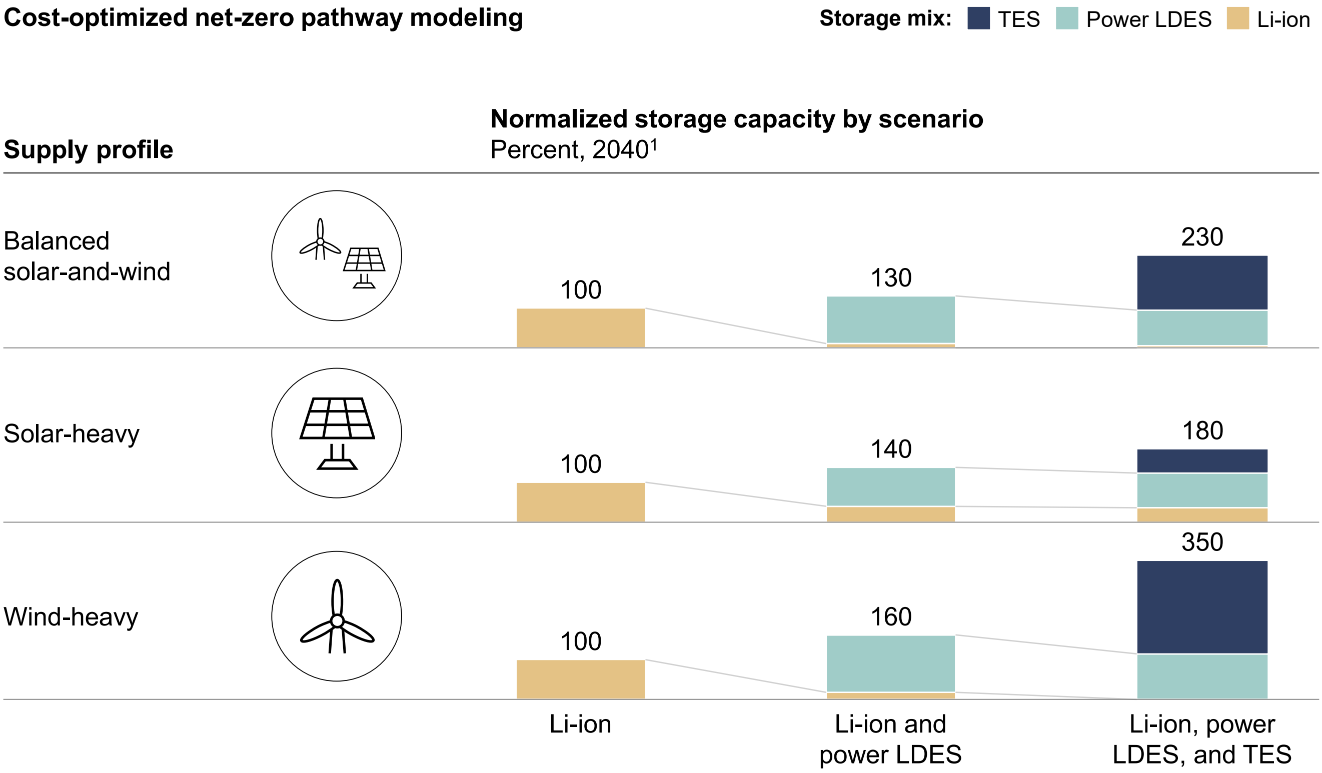
[24] The definition of energy system used in this report includes all components related to the production, conversion, and use of electrical energy, heat, and hydrogen. The electrification of the transport sector is included indirectly in the final electricity demand scenario from the McKinsey Global Energy Perspective.

Exhibit 20

The uptake of TES depends on the profile of renewable generation in the system

Cost-optimized net-zero pathway modeling

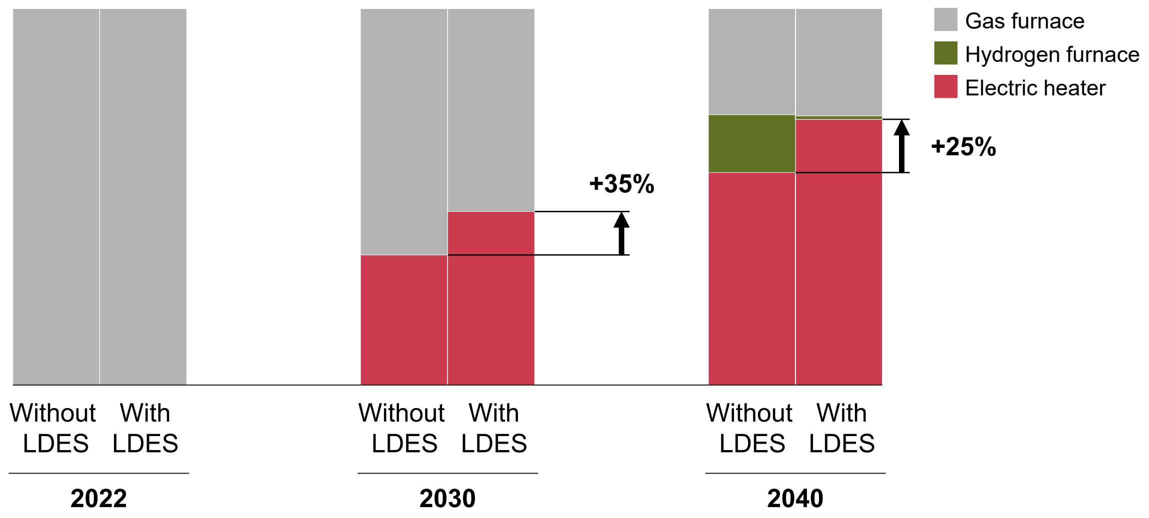


1. Power storage capacity normalized to Li-ion capacity.

Exhibit 21

LDES can significantly improve the economics of electrified high-temperature heat

High-temperature heat supply mix development over time
Share in percent



Note: The “without LDES” scenario includes Li-ion only. The “with LDES” scenario includes Li-ion, power LDES, and TES.

enabling access to electricity when the cost is low and converting it to heat that can be used later. Exhibit 21 shows that TES can accelerate the electrification of high-temperature heat and displace gas by 26 to 34 percent.

A net-zero pathway presents a 2 to 8 TW LDES capacity opportunity by 2040

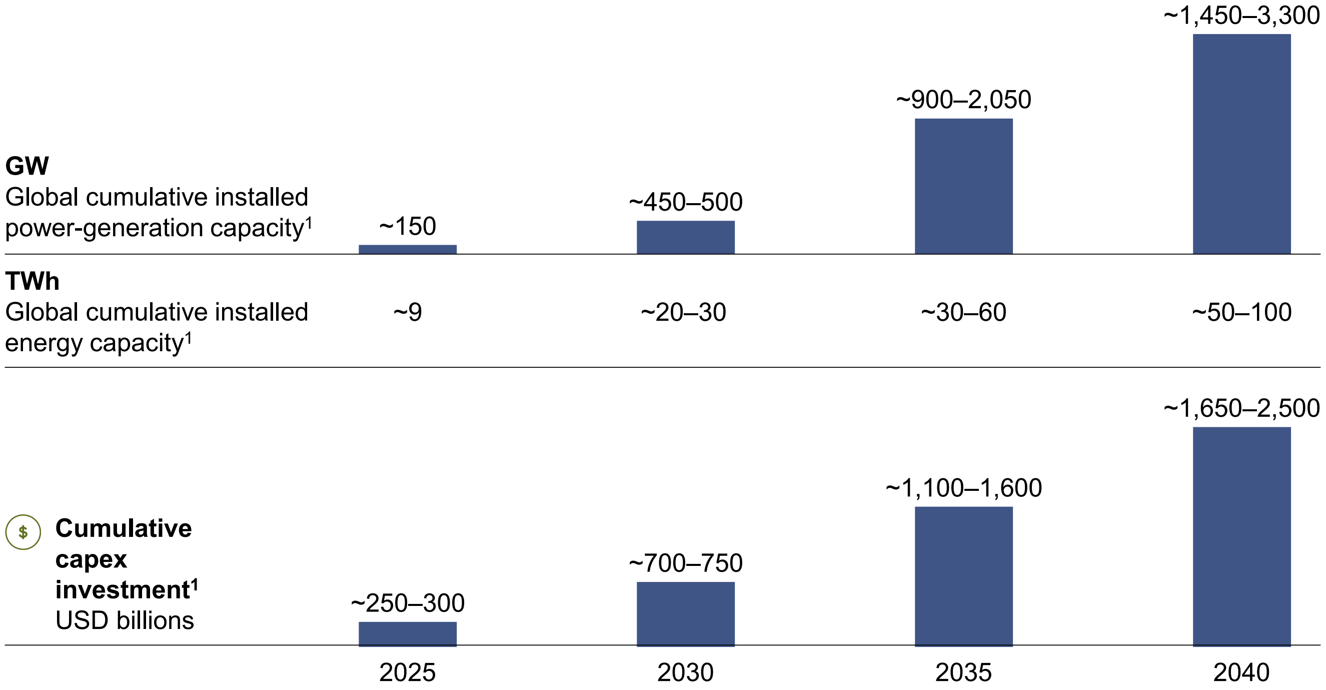
The standalone power LDES scenario requires 1 to 3 TW of LDES capacity by 2040. The model indicates that, in the short term, power LDES is already part of the most cost-efficient pathway, growing to 450 to 500 GW of installed capacity by 2030. This translates into 20 to 30 TWh of energy storage capacity. As the electricity networks fully decarbonize and the share of renewables reaches very high levels, power LDES potential would increase to between 1.5 and 3.3 TW by 2040 (Exhibit 22). This translates into USD 1.6 trillion to USD 2.5 trillion cumulative investment needs by 2040. While modeling indicates total LDES potential based on technology cost benchmarks, it remains agnostic as to which technologies will be deployed. Different location-specific factors might affect the technology choice, ranging from modular, stackable solutions deployed anywhere, to custom-made systems like pumped-hydro, which can have a cost advantage if geographical conditions are favorable.

Adding TES increases overall LDES capacity potential by 1 to 5 TW by 2040. The combined power LDES and TES scenario indicates that in a cost-optimized pathway, the introduction of TES could add 0.8 to 4.8 TW extra LDES capacity (Exhibit 23) and approximately 15 to 80 TWh of installed energy storage capacity by 2040 (assuming the average duration of around 16 hours for intraday shifting). This type of system would likely require global investments between USD 0.250 trillion and USD 1.4 trillion by 2040.

Moreover, each gigawatt of heat generation capacity could reduce about 1 $MtCO_2$/year when replacing natural gas heat sources and roughly 2 $MtCO_2$/year when replacing coal. The combined power LDES and TES configuration allows for more targeted use, focusing power LDES on electricity applications and TES on heat applications. Furthermore, TES provides an additional inexpensive flexibility source. The

Exhibit 22

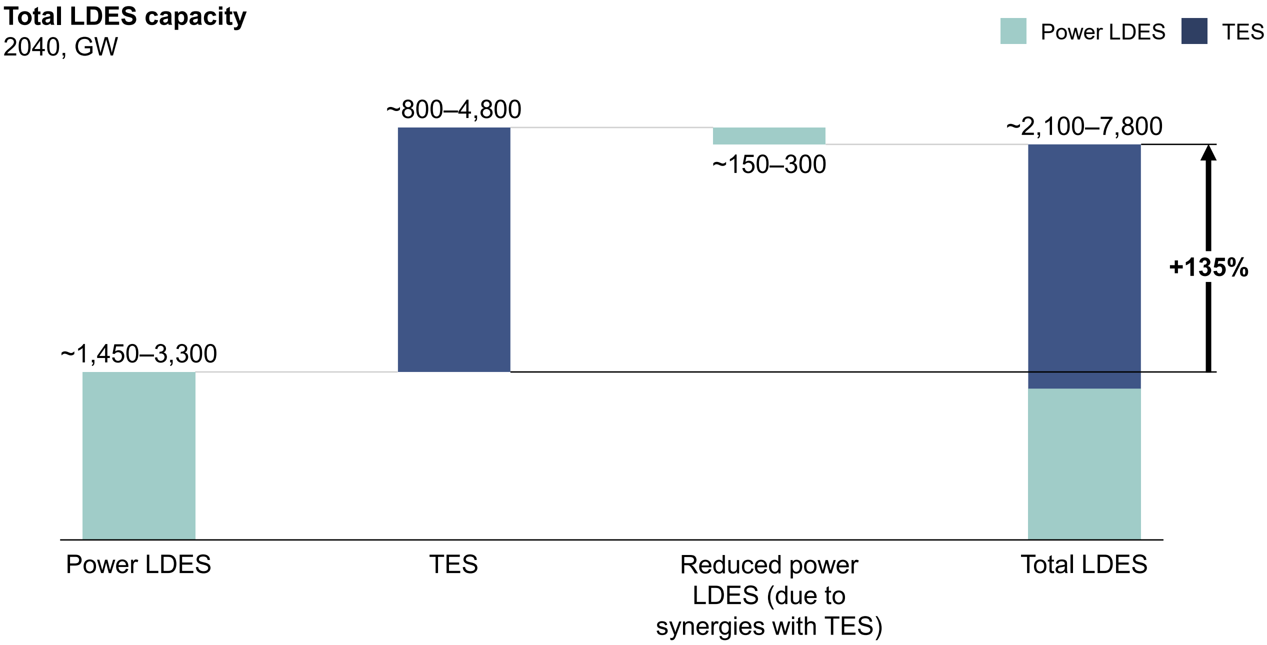
Potential power LDES cumulative capacity and investments by year



1. Ranges refer to LDES central and progressive scenarios.

Exhibit 23

TES more than doubles the potential LDES capacity to 2–8 TW by 2040



introduction of TES can help improve system efficiency and reduces power LDES needs by around 10 percent. The introduction of TES increases the potential of LDES technologies to a total between 2 and 8 TW and the overall market size to USD 1.7 trillion to USD 3.6 trillion by 2040.

Introducing LDES could reduce energy system costs

LDES could enable energy system savings of up to USD 540 billion annually. The introduction of LDES provides a longer duration firming capacity and thereby obviates the need for energy curtailment or redispatch.[25] This generates estimated cost savings of up to USD 70 million per GW of LDES capacity installed, including fuel savings, and better utilization of variable generation resources. This translates into potential annual savings of USD 145 billion in a 2 TW case and USD 540 billion in an 8 TW case by 2040 (Exhibit 24).

LDES could provide a broad range of energy system benefits. Incorporating various types of storage technologies creates an opportunity to optimize the current utilization and future development of fixed infrastructure assets. For example, grid upgrades or expansions will be required to accommodate a large share of renewables. LDES can enable more efficient grid utilization through supply-and-demand management and storage as a transmission asset, thereby reducing costs related to such expansions. This could prove especially beneficial over the next five to ten years, when the bulk of grids will need to be re-designed, given the typical ten-year development timeline of major grid expansions. Better grid utilization may in turn allow the integration of more renewable generation capacity into the system. Additionally, the option to shift a significant amount of load over time creates possible opportunities to integrate variable renewable sources without affecting the heat demand of the final industrial process, allowing for a faster and more economical uptake of renewable energy sources.

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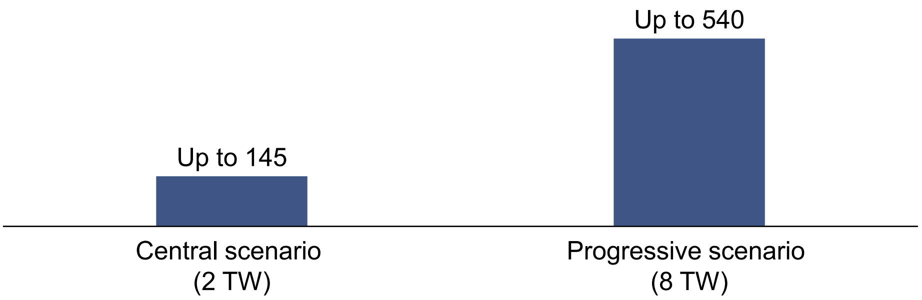
[25] Savings estimated based on the assumption of a 16-hour system working over 365 cycles per year and discharging a total of 5,840 GWh. The emission range is estimated based on emission factors of coal (around 360 kg/MWh) and gas (about 180 kg/MWh).

Exhibit 24

LDES energy system savings by scenario

Potential global savings generated by LDES in 2040
USD billions/year



KEY TAKEAWAYS

- TES could increase total LDES market up to 2 to 8 TW by 2040.
- Overall market size of LDES technologies is expected to reach a cumulative USD 1.7 trillion to USD 3.6 trillion by 2040.
- LDES could enable energy system savings of up to USD 540 billion annually.

6

Unlocking the TES opportunity

Critical support elements could help drive more TES adoption. A supportive ecosystem that rewards flexibility and promotes a technology-level playing field for flexibility solutions, like LDES, could be critical to accelerating the scale-up of TES. Additionally, increasing awareness and providing support to derisk initial investments could be pivotal.

Business leaders, policymakers, and investors could each contribute to unlocking the TES potential by reducing long-term uncertainty and thereby shaping the cost-optimized pathway toward the net-zero energy system of the future.

TES adoption faces potential challenges

This report shows that some TES technologies can already be commercially attractive. Yet several challenges exist that, if addressed, would help achieve fast rollout and wide adoption:

- **Need for increased awareness of potential TES applications.** Historically, there has been less focus on LDES solutions, including TES, as the relatively small share of renewables could be accommodated without long-duration flexibility solutions.

- **Need for acknowledgment of TES's decarbonization potential.** This report shows that TES could enable a cost-optimized pathway to net zero for the energy system—a role that has yet to gain broad recognition.

- **Potential commercial risks as a result of the industry's nascency.** Technical maturity varies among TES technologies. The lack of a track record for emerging technologies can affect risk perception for investors and users, especially as heat applications in industry and electricity infrastructure are long-term assets, and hence risk averse.

- **Limited supporting market mechanisms that could enhance TES business models.** As highlighted in Chapter 4, the commercial feasibility of TES is currently subject to specific conditions—namely, access to captive energy or surplus renewables—and supportive market mechanisms (for example, carbon pricing, reduction of grid fees, or flexibility payments). Market designs and policy frameworks that value flexibility have emerged but still remain limited.

Key stakeholders could help unlock the potential of TES

Multiple measures could support wider TES adoption. There are different ways to address the challenges, and various stakeholders could play a role in supporting flexibility, creating a level playing field, and derisking initial investments. Raising awareness could be a critical enabler and can be addressed by all stakeholders. Positioning TES correctly is key to creating a clean, affordable, and reliable energy system. More specific options that could support the TES rollout could also be considered by several TES stakeholders, as mentioned below.

Business leaders could help scale up TES solutions and supply chains by considering the following:

- **Deploying TES technology and identifying critical enablers.** Business leaders could ensure TES technologies are deployed. Early on, pilots and demonstration plants could be essential enablers showcasing TES business cases, identifying critical enablers, and initiating relevant stakeholder discussions.

- **Supporting supply chain developments and diversification.** Early movers could support the deployment of commercially ready TES technologies, thereby derisking supply chain investments, accelerating learning curves, and scaling up capabilities to kick-start the market. Such deployments may benefit from collaborating with key parties in the supply chain—from industry and governments to academia—to create a joint effort to scale up TES and help materialize broader (societal) value.

Policymakers could support TES adoption, potentially through long-term policy frameworks that reduce uncertainty, by considering the following:

- **Developing market mechanisms that pay for flexibility.** Energy markets that reward flexibility—such as ancillary or balancing markets in the Netherlands and the United States, or the reduced demand-side grid fees for power storage in Germany—are limited. Policymakers help implement such markets around the world, which could improve TES business case returns. Rewarding decarbonization may also be important; many countries have carbon pricing or taxation, and policymakers could support their expansion and effectiveness.

- **Supporting the scale-up of the TES industry to derisk initial investments.** During the initial scale-up, support mechanisms could help significantly derisk investments in TES business cases, with the long-term benefits of creating sustainable TES supply chains. Examples of such mechanisms include supporting transition costs (for example, contracts for difference) and providing one-off support (for example, investment guarantees and subsidies).

- **Incorporating TES into relevant regulatory frameworks.** As nascent technologies are often excluded from relevant regulation (for example, technical standards), policymakers could incorporate TES and thereby help remove barriers to operation. This inclusion also applies to policies, such as heat-efficiency requirements or decarbonization targets (for example, storage, renewable energy adoption, or carbon intensity). Inclusion in regulations and policies could provide long-term market signals and reduce investors' uncertainty.
- **Coordinating the move to cost-optimized system designs.** In the transition to net-zero energy, infrastructure will likely be disrupted significantly across the entire value chain. In this process, it will likely be important to consider the role of different clean LDES and TES flexibility assets and the broader infrastructure to move toward cost-optimized system designs. It could also be important to reflect these cost-optimized energy system designs in decarbonization roadmaps.
- **Creating a technology-level playing field for flexibility solutions.** As a newer set of technologies, LDES and TES have an opportunity to be treated equally to alternative technologies (for example, hydrogen production and electricity storage). This treatment could address the aspects mentioned before. For example, policymakers could include TES in existing policy frameworks or assess whether flexibility solutions, like TES, require changes in current instruments or market mechanisms to support their role as part of the energy system.

Investors could consider allocating capital efficiently by assessing the following:

- **Deploying capital into TES investments.** Investors focused on energy-related technology and infrastructure could include TES—and broader LDES—in their investment scope. This will likely enable portfolio diversification into a growing industry.
- **Assessing TES-related opportunities across the current portfolio.** Investors with portfolios where energy, especially heat, plays a significant role could (re)assess the value potential of TES and broader LDES. This could enable optimized energy usage and asset decarbonization with their investees.
- **Informing investment strategy with knowledge of TES opportunities.** Investors could deepen their understanding of TES applications and use cases to identify investment opportunities. In addition, accounting for climate externalities could improve risk-return ratios and thereby help decrease the costs for decarbonization solutions, including TES.

KEY TAKEAWAYS:

- Business leaders, policymakers, and investors could play a key role in helping to scale up TES.
- Raising awareness about TES applications and their potential, rewarding flexibility, creating a technology-level playing field, and derisking initial investments could be important in decarbonizing the energy sector.
- Addressing these opportunities could reduce long-term uncertainty and help shape the optimal pathway toward the net-zero energy system of the future.

Conclusion

This report highlights TES's role in bringing down heat emissions and decarbonization costs. The transition to a net-zero energy system with increasing variable renewable energy generation requires new forms of flexibility to ensure a reliable energy system. TES technologies can play a central role in realizing net-zero heat and power in a cost-optimized manner, integrating variable renewable sources into more constant heat loads and optimizing heat processing by enabling the cost-efficient use of waste heat. This could enable the accelerated build-out of renewables providing stability and resiliency, the optimized use of generation capacity and energy shifting, and the improved utilization of grid infrastructure as the energy system decarbonizes.

With initial TES technologies already available, there is an opportunity to consider action to achieve wider adoption. Economic analyses suggest that TES could be among the most cost-effective options for decarbonizing steam, even in a non-net-zero scenario.
A series of four TES business case assessments show it can generate profitable investments with IRRs of up to 28 percent. However, the commercial viability of TES depends heavily on local market conditions in terms of physical configurations (such as access to behind-the-meter renewables) and market designs (such as variable electricity pricing and carbon pricing). In addition, specific enablers would help support profitable business cases, such as reducing grid connection fees for flexibility solutions.

All stakeholders have the opportunity to help unlock TES's potential. This report shows that TES helps realize a clean, low-cost, and reliable energy system. As such, raising awareness of TES's potential is in the best interest of many stakeholders as it could help them execute their decarbonization strategies. Various other relevant options could scale up TES, particularly rewarding flexibility and leveling the playing field. Stakeholders could take steps to reduce uncertainty in the long term and thereby guide action in the short term to shape the net-zero energy system of the future.

Appendix A: Methodology and assumptions

A1. Benchmarking

Data collection

The data used in the analysis of this report was collected from the LDES Council members, who submitted more than 18,000 data points (21 Council members contributed 12,000 data points to the power benchmark, and 11 provided 6,000 to the TES benchmark) outlining the cost and performance of their technologies. The data was aggregated and processed by an independent data analytics team.

LDES Council members provided cost and performance data for two projected trajectories for how these metrics would change from a progressive to a central scenario:

- Progressive scenario: Council data reflecting ambitious cost-reduction trajectories and learning rates
- Central scenario: Council data reflecting conservative cost-reduction trajectories and learning rates

Data processing

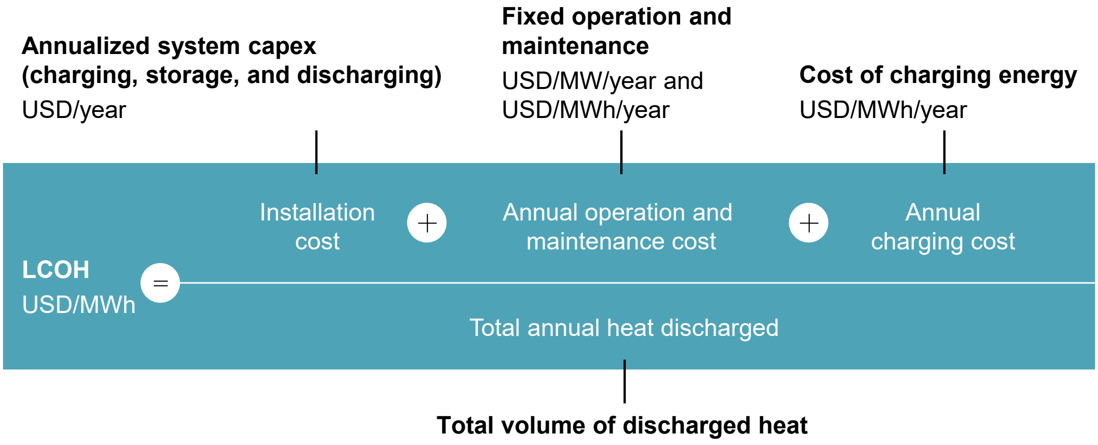
For power LDES technologies, the data was grouped into two archetypes that are expected to be most prevalent in the energy system based on their nominal duration: 8 to 24 hours and 24 hours or more, with some members offering products in both ranges. For TES technologies, the data was grouped into four archetypes based on end use: saturated steam at 1, 10, and 25 barg of pressure and hot air at 450°C. For every archetype, aggregated data points for each cost, design, or performance metric created representative numbers while preserving the data confidentiality of each individual technology. Top-quartile parameters were calculated and used as input for the models.

A2. Levelized cost of heat

The cost-competitiveness benchmark of heat decarbonization options was based on the LCOH metric, which is analogous to the LCOE metric commonly used to benchmark electricity generation. LCOH is defined as the net-present cost of heat over the project's lifetime. This metric accounts for all technical and economic parameters impacting the lifetime cost of generating heat and facilitates a like-for-like comparison between different decarbonization technologies. Exhibit 25 shows the LCOH formula and its components.

Exhibit 25

LCOH



The main assumptions used in the LCOH benchmark were:

- Utilization of technologies: the LCOH benchmark is sensitive to the operating conditions of the installed technology. Key assumptions on operating conditions, mainly efficiency and availability, are shown below.

Technology	Efficiency of input fuel to output heat	Availability of heat technology	Other parameters
Gas boiler	95 percent	98 percent	
Gas boiler with CCS	95 percent	98 percent	Carbon capture rate: 85 percent
Hydrogen boiler	98 percent	98 percent	Electrolyzer efficiency: 75 percent
Biomass boiler	95 percent	98 percent	
Electric boiler	98 percent	98 percent	
Heat pump	300 percent	98 percent	

- Fuel costs: to show a variety of possible scenarios, a range of input fuel costs was considered: gas (USD 6 to USD 12 per mmBTU); wood pellet costs (USD 200 to USD 350 per ton); and renewable electricity (USD 25 to USD 50 per MWh)
- WACC: 5 percent
- Storage lifetime: 15 years for batteries and 25 years for TES

A3. Business cases

Each of the business cases presented in Chapter 4 were designed with LDES Council industry experts and technology providers. A breakdown of invested capital and annual production costs for each business case are highlighted in Exhibit 26.

The business cases are sensitive to fossil-fuel and renewable electricity costs. The archetypes presented in Chapter 4 were selected based on the assumption of a regional archetype in which such technology might be tested first. Nevertheless, it is acknowledged that each individual business will operate in different market conditions and would be exposed to other fossil-fuel and electricity price combinations. Therefore, IRR sensitivities for different price compositions are shown in Exhibits 27 to 33 to illustrate the range of possible returns for the various business cases.

Exhibit 26

Invested capital and annual production cost change of base and upside business cases

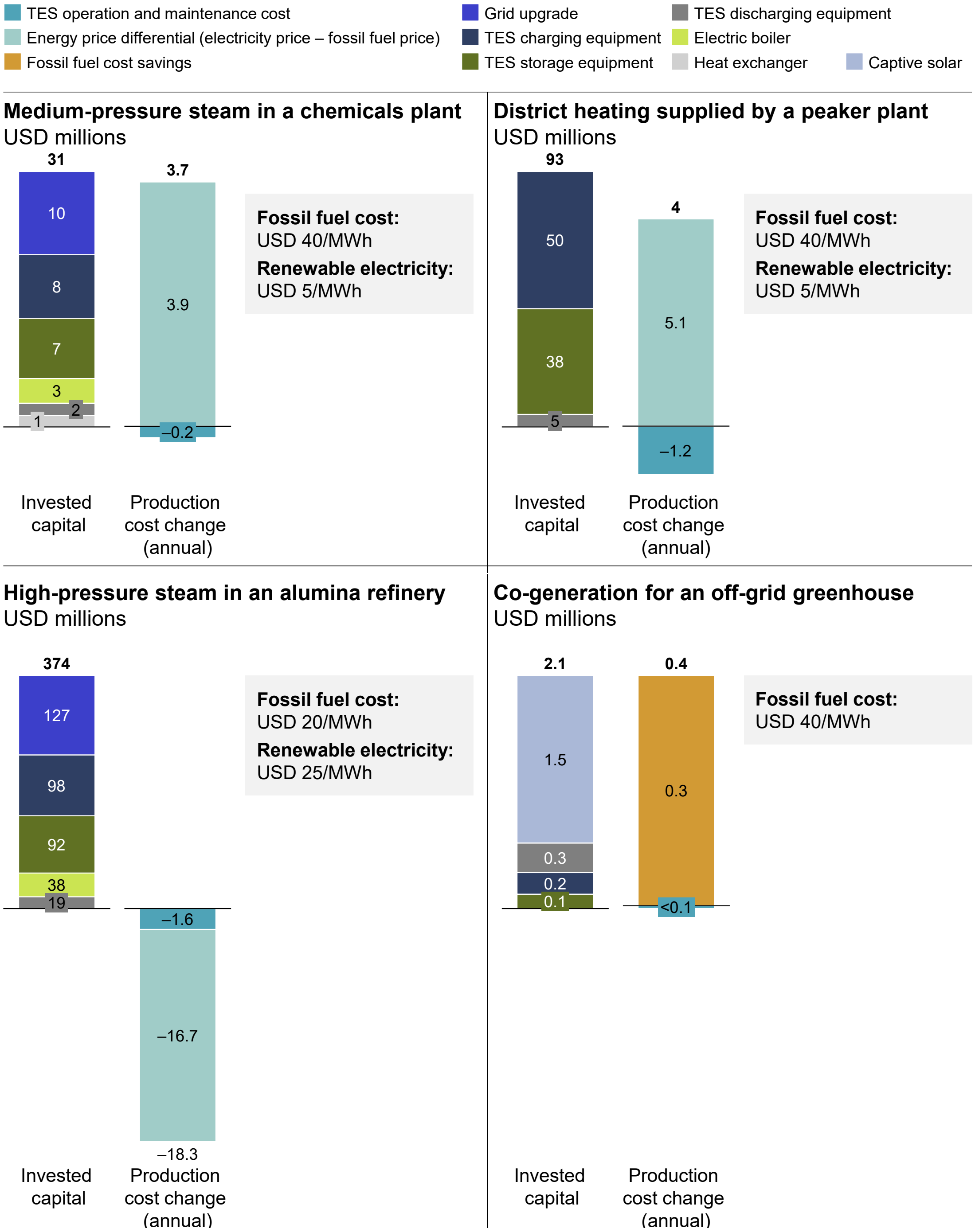
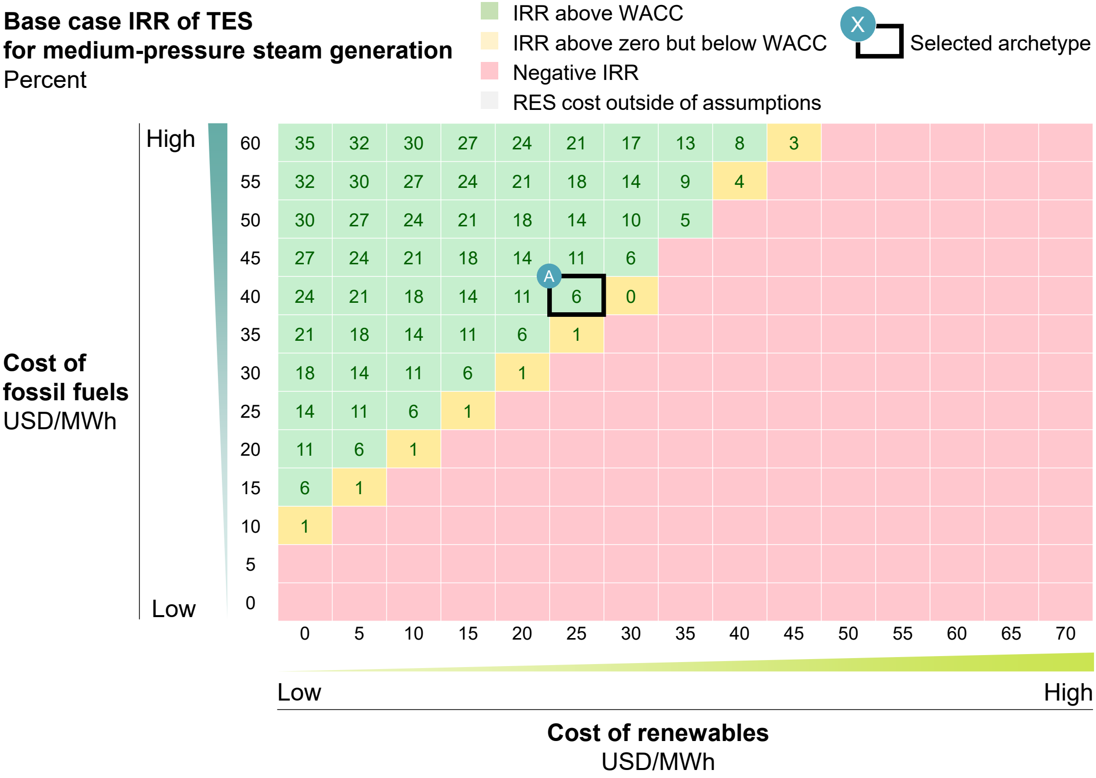


Exhibit 27

Medium-pressure steam in a chemicals plant: base case IRR sensitivity

Base case IRR of TES for medium-pressure steam generation
Percent

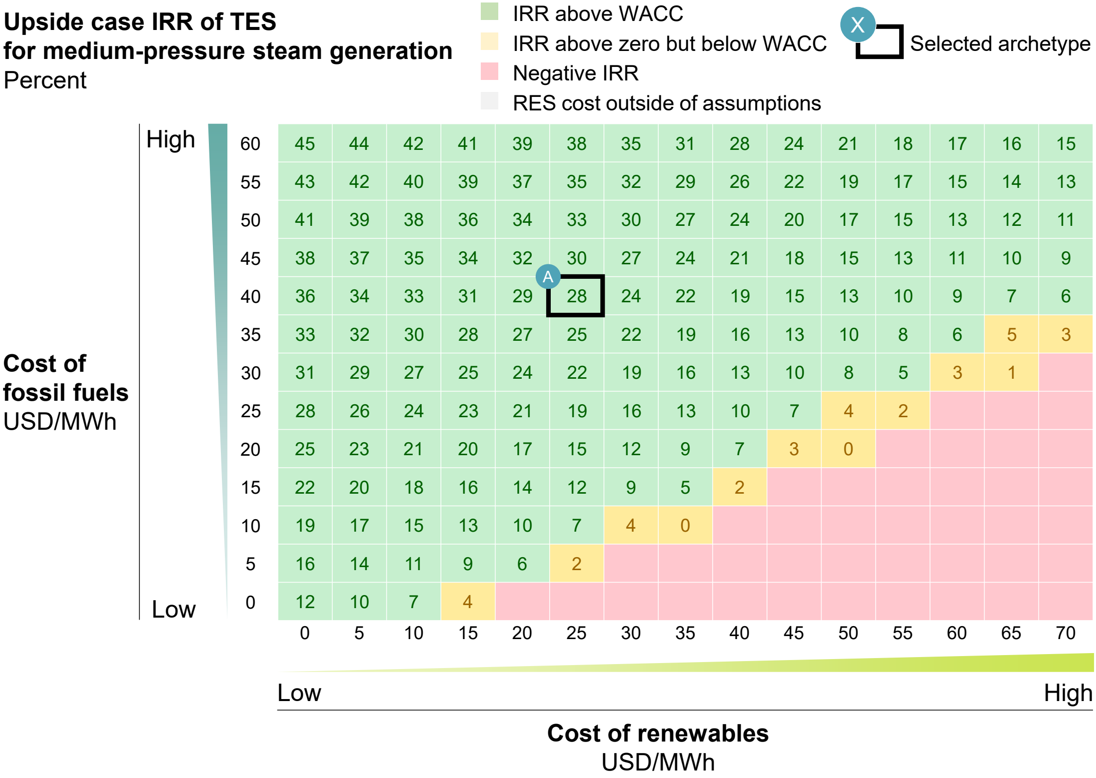


	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
60	35	32	30	27	24	21	17	13	8	3					
55	32	30	27	24	21	18	14	9	4						
50	30	27	24	21	18	14	10	5							
45	27	24	21	18	14	11	6								
40	24	21	18	14	11	6	0								
35	21	18	14	11	6	1									
30	18	14	11	6	1										
25	14	11	6	1											
20	11	6	1												
15	6	1													
10	1														
5															
0															

Exhibit 28

Medium-pressure steam in a chemicals plant: upside case IRR sensitivity

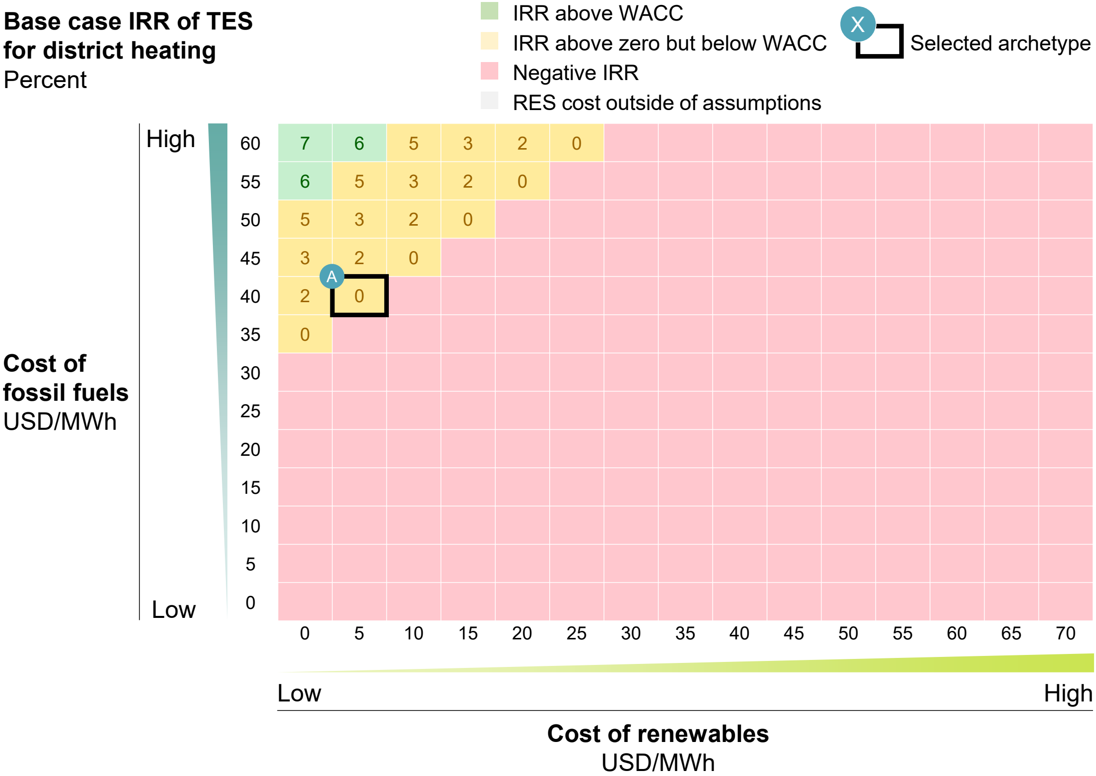
Upside case IRR of TES for medium-pressure steam generation
Percent



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
60	45	44	42	41	39	38	35	31	28	24	21	18	17	16	15
55	43	42	40	39	37	35	32	29	26	22	19	17	15	14	13
50	41	39	38	36	34	33	30	27	24	20	17	15	13	12	11
45	38	37	35	34	32	30	27	24	21	18	15	13	11	10	9
40	36	34	33	31	29	28	24	22	19	15	13	10	9	7	6
35	33	32	30	28	27	25	22	19	16	13	10	8	6	5	3
30	31	29	27	25	24	22	19	16	13	10	8	5	3	1	
25	28	26	24	23	21	19	16	13	10	7	4	2			
20	25	23	21	20	17	15	12	9	7	3	0				
15	22	20	18	16	14	12	9	5	2						
10	19	17	15	13	10	7	4	0							
5	16	14	11	9	6	2									
0	12	10	7	4											

Exhibit 29

District heating supplied by a peaker plant: base case IRR sensitivity



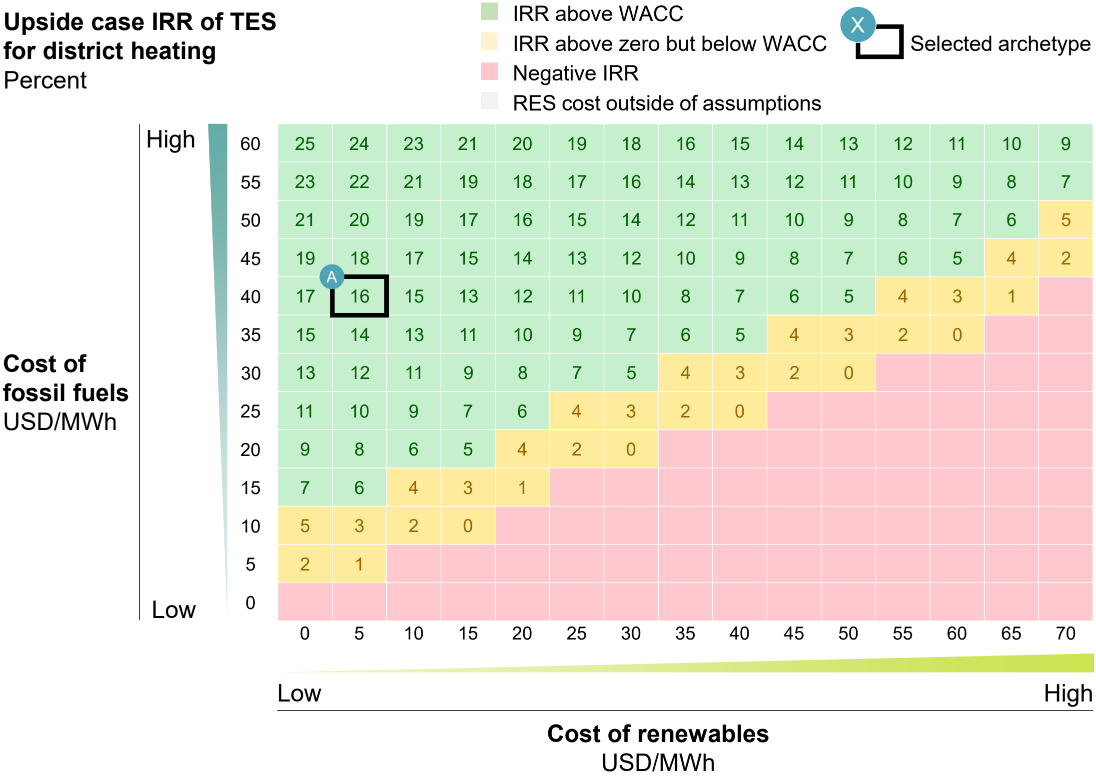
Base case IRR of TES for district heating
Percent

🟩 IRR above WACC
🟨 IRR above zero but below WACC
🟥 Negative IRR
⬜ RES cost outside of assumptions

	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
60	7	6	5	3	2	0									
55	6	5	3	2	0										
50	5	3	2	0											
45	3	2	0												
40	2	0													
35	0														
30															
25															
20															
15															
10															
5															
0															

Exhibit 30

District heating supplied by a peaker plant: upside case IRR sensitivity



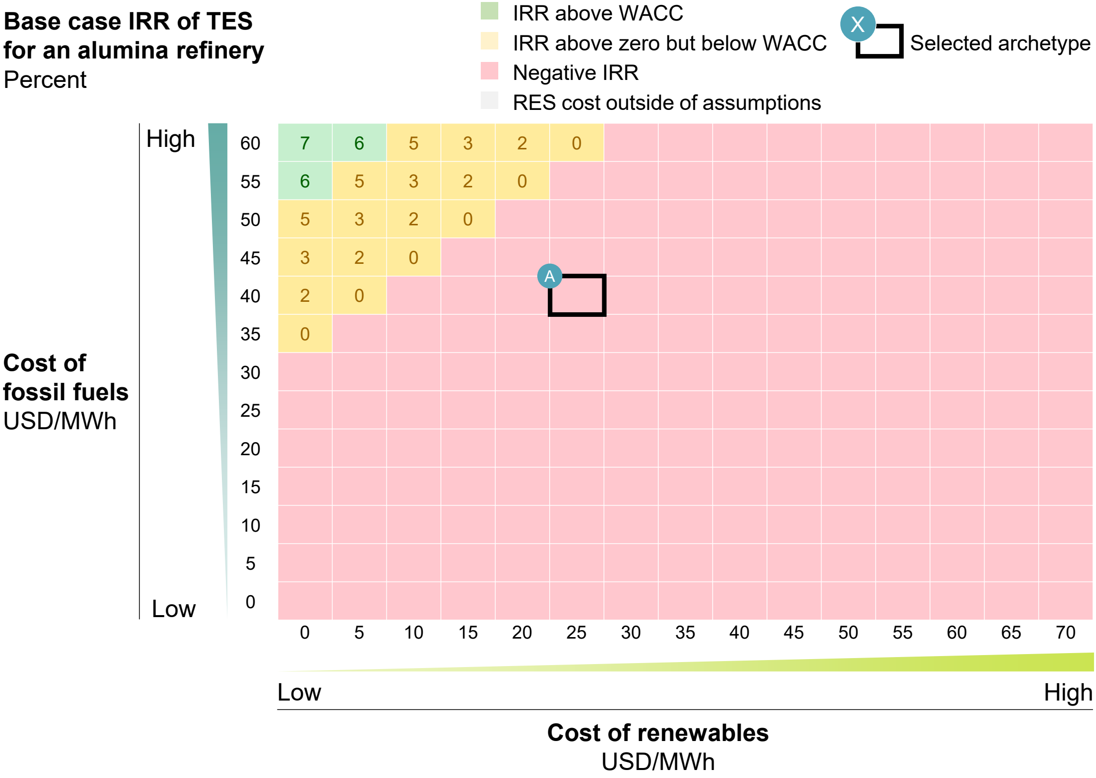
Upside case IRR of TES for district heating
Percent

🟩 IRR above WACC
🟨 IRR above zero but below WACC
🟥 Negative IRR
⬜ RES cost outside of assumptions

	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
60	25	24	23	21	20	19	18	16	15	14	13	12	11	10	9
55	23	22	21	19	18	17	16	14	13	12	11	10	9	8	7
50	21	20	19	17	16	15	14	12	11	10	9	8	7	6	5
45	19	18	17	15	14	13	12	10	9	8	7	6	5	4	2
40	17	16	15	13	12	11	10	8	7	6	5	4	3	1	
35	15	14	13	11	10	9	7	6	5	4	3	2	0		
30	13	12	11	9	8	7	5	4	3	2	0				
25	11	10	9	7	6	4	3	2	0						
20	9	8	6	5	4	2	0								
15	7	6	4	3	1										
10	5	3	2	0											
5	2	1													
0															

Exhibit 31

High-pressure steam in an alumina refinery: base case IRR sensitivity

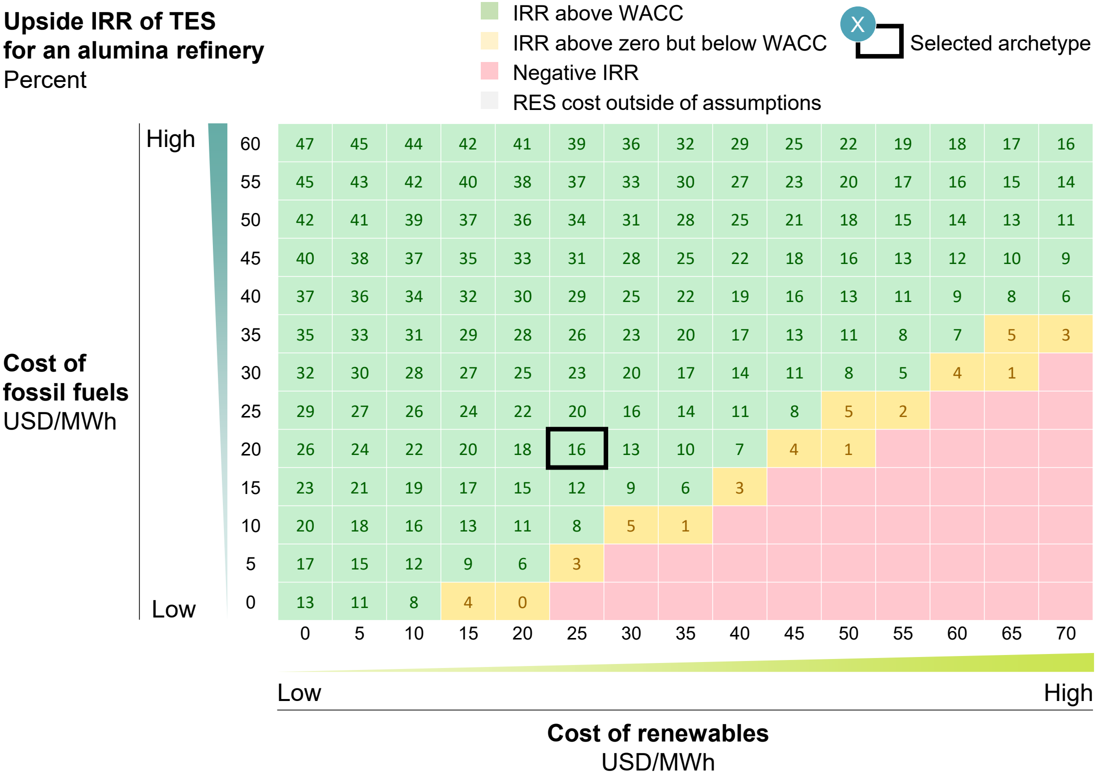


Base case IRR of TES for an alumina refinery
Percent

60	7	6	5	3	2	0									
55	6	5	3	2	0										
50	5	3	2	0											
45	3	2	0												
40	2	0													
35	0														
30															
25															
20															
15															
10															
5															
0															
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70

Exhibit 32

High-pressure steam in an alumina refinery: upside case IRR sensitivity

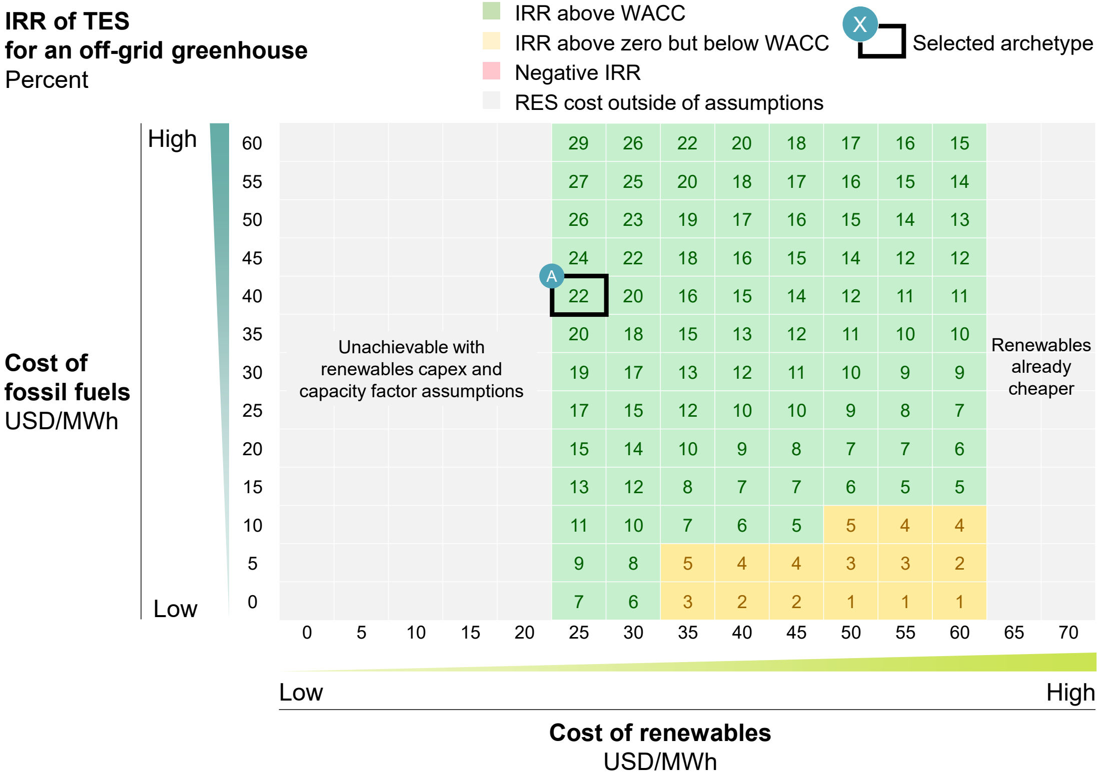


Upside IRR of TES for an alumina refinery
Percent

60	47	45	44	42	41	39	36	32	29	25	22	19	18	17	16
55	45	43	42	40	38	37	33	30	27	23	20	17	16	15	14
50	42	41	39	37	36	34	31	28	25	21	18	15	14	13	11
45	40	38	37	35	33	31	28	25	22	18	16	13	12	10	9
40	37	36	34	32	30	29	25	22	19	16	13	11	9	8	6
35	35	33	31	29	28	26	23	20	17	13	11	8	7	5	3
30	32	30	28	27	25	23	20	17	14	11	8	5	4	1	
25	29	27	26	24	22	20	16	14	11	8	5	2			
20	26	24	22	20	18	16	13	10	7	4	1				
15	23	21	19	17	15	12	9	6	3						
10	20	18	16	13	11	8	5	1							
5	17	15	12	9	6	3									
0	13	11	8	4	0										
	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70

Exhibit 33

Co-generation for an off-grid greenhouse: base and upside case IRR sensitivity



	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70
60						29	26	22	20	18	17	16	15		
55						27	25	20	18	17	16	15	14		
50						26	23	19	17	16	15	14	13		
45						24	22	18	16	15	14	12	12		
40						22	20	16	15	14	12	11	11		
35						20	18	15	13	12	11	10	10		
30						19	17	13	12	11	10	9	9		
25						17	15	12	10	10	9	8	7		
20						15	14	10	9	8	7	7	6		
15						13	12	8	7	7	6	5	5		
10						11	10	7	6	5	5	4	4		
5						9	8	5	4	4	3	3	2		
0						7	6	3	2	2	1	1	1		

A4. Pathway modeling—archetype modeling

Pathway modeling intends to provide a perspective on a cost-optimized way to net-zero emissions. Modeling results foster an understanding of how the road to net-zero emissions could look and what potential benefits could arise from sector pairing and integration that includes interactions between power and heat and cold supplies. Traditionally, heat and power supplies were optimized separately given the high share of fossil fuels in heat production and high power costs. This approach often resulted in increased electricity demand due to extensive electrification and subsequent requirements to match that demand from the power sector, without considering the possible interactions of those sectors.

High renewable penetration and ample availability of low-cost electricity have the potential to change this. By combining the optimization for both commodities, the model can inform how heat storage can affect the overall system.

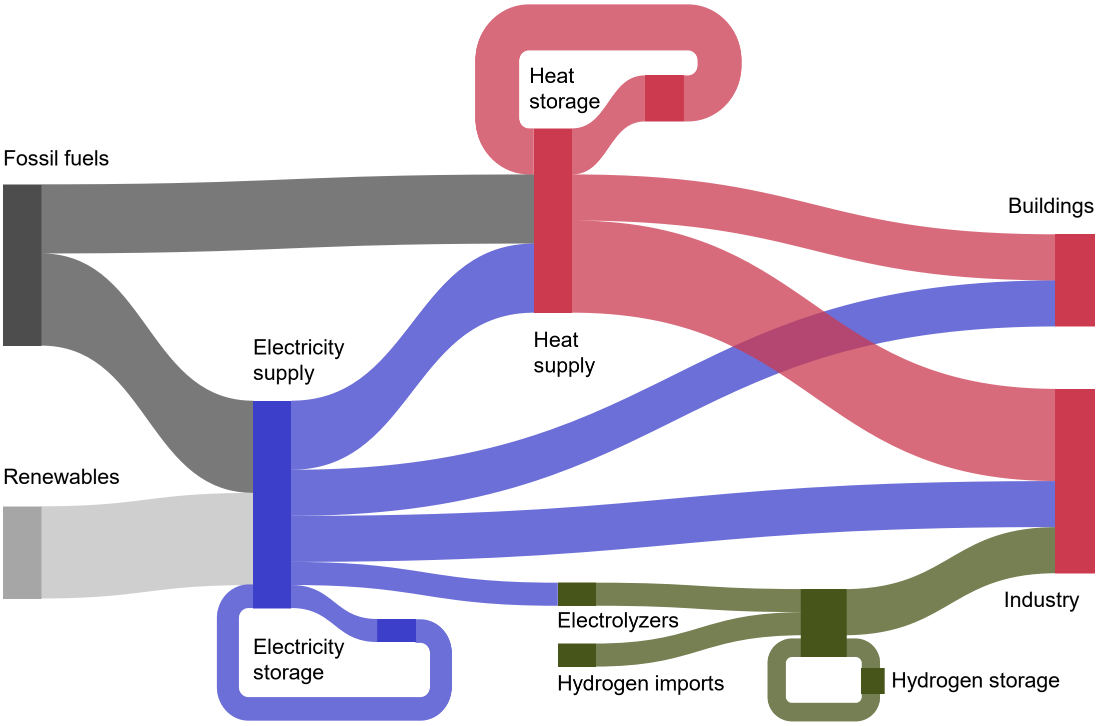
The illustrative energy flow in the pathway modeling optimization is shown in a Sankey diagram in Exhibit 34. A Sankey diagram is a graphic illustration of energy flows, indicating where they can be combined, split, and traced through a series of events or stages (such as conversion of fuel into electricity or putting electricity into storage). The width of each stream represents the amount of energy in the flow.

While such co-optimization of power and heat demand across sectors can yield additional insights, it also makes the model inherently more complex. In order to manage the complexity, several simplifications have been introduced:

1. Only two grades of heat are considered as separate demand categories: low-to-medium temperature and high temperature.

Exhibit 34

Integrated net-zero pathway modeling



2. Three types of regions (solar-heavy, wind-heavy, and balanced wind and solar) are modeled separately; while this approach allows us to understand the behavior of each individual stream type, conclusions can't be drawn on the relative pathway development of a fully integrated system of multiple archetypes.
3. Commodity pricing is static for anything other than electricity; retail margins on electricity are not included.
4. The power system for pathway modeling includes only the main technologies (for example, for fossil fuel generation, coal and gas are modeled, while oil is excluded for simplification purposes).

A5. McKinsey Power Model

The MPM is a techno-economic optimization that simulates large-scale power systems concurrently on hourly and multi-decadal time resolutions. It was used to determine the cost-optimized pathway to net-zero emissions across a set of real-world systems. The result is a portfolio of technologies and fuel consumption that minimizes the societal cost of the transition in the modeling horizon.

A wide set of technologies was included in the model, ranging from traditional thermal generators, such as gas turbines and nuclear power plants, to technologies with increasing potential in the energy transition, such as renewables, CCS, energy storage, and power-to-fuel. The modeling effort specifically focused on the role of LDES in the transition to net-zero emissions. The result provides an outlook for the LDES market size and a possible operational profile. The LDES market size is a result of cost optimization and therefore does not indicate any specific type of technology that would be deployed, other than two duration archetypes: 8 to 24 hours and 24 hours or more.

The capital cost reductions of LDES technologies were defined based on the learning rate and technology's commercial readiness gathered from the data submissions of LDES Council members. Different technology build decisions and market size restrictions, such as biomethane blending, nuclear new build restrictions, and transmission expansion restrictions were also modeled.

The model contains bulk-transmission-level grid connections (meaning no mid-voltage transmission or distribution grids are included). It also does not represent transmission within the smallest modeling region, which means that intraregional transmission effects are not included. This modeling limitation will necessarily underestimate the market size of LDES, since transmission constraints, which LDES can provide a strong value proposition to mitigate, are not fully considered.

A6. Currency

All financial figures are in 2022 US dollars (USD) and refer to global averages unless otherwise indicated.

Appendix B: State of the TES industry

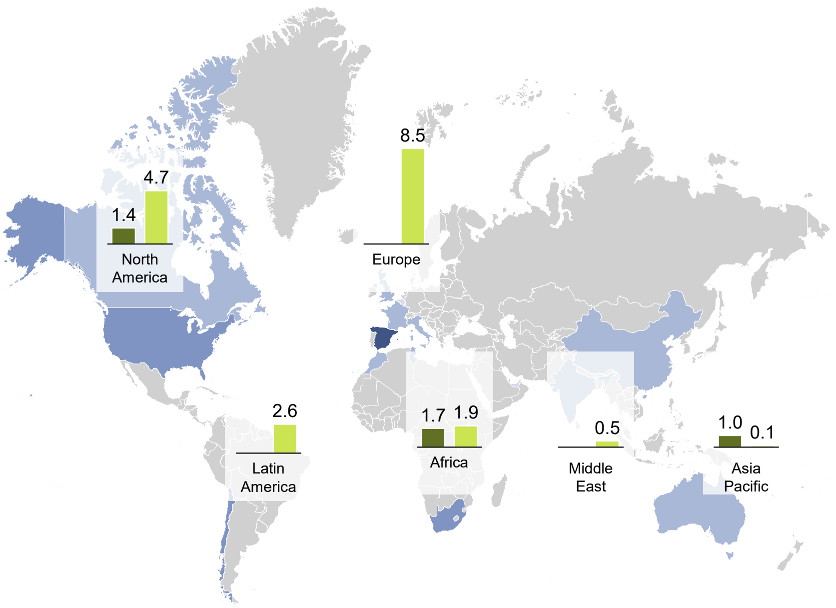
B1. TES projects announced or installed

Some TES technologies have already been commercially deployed. Globally, there are more than 200 projects already announced or installed, comprising more than 20 GWh of storage capacity. The largest TES capacity is concentrated in Europe and North America, where Spain stands out with more than 5 GWh installed, mainly for concentrated solar power (Exhibit 35).

Exhibit 35

Global announced and installed TES projects

TES projects cumulative capacity
GWh



>200

TES projects installed

>20 GWh

TES storage capacity operational or announced

Source: DOE Global Energy Storage Database, September 2022

B2. LDES Council TES companies

More information about the LDES Council's TES technology providers can be found on the LDES Council website www.ldescouncil.com or by contacting the LDES Council directly at info@ldescouncil.com.

LDES Council TES technology providers by technology type (membership overview as of November 2022)[26]

Sensible heat		Latent heat	Thermochemical heat
BRENMILLER ENERGY	KYOTO	1414° CLEAN SCALABLE ENERGY STORAGE	SaltX Technology
ECHOGEN power systems	MAGALDI	AZELIO	
Electrified Thermal Solutions	MALTA	MGA THERMAL	
ENERGYNEST	SIEMENS energy	TORC	
HEATRIX DECARBONIZING INDUSTRY	Stiesdal		
KRAFT BLOCK	STORWORKS POWER		

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[26] Besides the TES technology providers, the LDES Council also consists of member companies who are involved with TES as energy system integrators and developers, equipment manufacturers, capital providers, and wastewater energy treatment (WET) developers. To find out more about these companies, please visit the LDES Council website at www.ldescouncil.com.

Acknowledgements

The LDES Council would like to thank all its members who contributed to this report. In particular, we are appreciative of the Net-zero heat report working group who generously offered their time, expertise, and guidance.

1414° CLEAN SCALABLE ENERGY STORAGE
ALFA LAVAL
AZELIO
Baker Hughes
bp
Breakthrough Energy
BRENMILLER ENERGY
ECHOGEN power systems
EGA الإمارات العالمية للألمنيوم EMIRATES GLOBAL ALUMINIUM
Electrified Thermal Solutions
ENERGYNEST
HEATRIX DECARBONIZING INDUSTRY
KRAFT BLOCK
KYOTO
MAGALDI
MALTA
MGA THERMAL
NEOM نيوم
Ørsted
RioTinto
SaltX Technology
SENS
SIEMENS energy
SOUTH32
STORWORKS POWER
Sumitomo SHI FW
THERMOWATT
TORC
TotalEnergies