Driving to Net Zero Industry Through Long Duration Energy Storage

LDES
LONG DURATION ENERGY STORAGE COUNCIL

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Preface

LONG DURATION ENERGY STORAGE (LDES)

The Long Duration Energy Storage Council commissioned this report to demonstrate the current and potential applications for member technologies to decarbonize industry.

There are multiple long duration energy storage technologies commercially available and under development. In general, these technologies provide more than eight hours of energy using a variety of electrochemical, mechanical, thermal, and chemical storage media.

Many of these technologies have been under development for more than a decade and oftentimes utilize existing motors, pumps and other equipment that has already been utilized in other industries.[1]

The importance of long duration energy storage technologies will increase in line with increasing saturation of intermittent renewable energy supply on electric grids around the world.

This report examines how long duration energy storage technologies can decarbonize fossil fueled industrial processes by utilizing this renewable energy supply to provide reliable baseload electric supply.

The Long Duration Energy Storage Council commissioned global management consulting firm Roland Berger to conduct the analysis and compile the report.

Roland Berger collaborated with the Long Duration Energy Storage Council staff as well as its technology and anchor members on the content, analysis and assumptions in this report.

ABOUT THE LDES COUNCIL

The Long Duration Energy Storage Council (LDES Council) is global non-profit organization committed to decarbonizing global energy systems by 2040 through the development, deployment, and integration of long duration energy storage technologies (LDES).

The LDES Council's mission is to facilitate the transition to a more sustainable and resilient energy future by advocating for policies, fostering innovation, and promoting collaboration among its membership and stakeholders in the energy industry.

As the leading voice in advocating for the widespread adoption of diverse long duration energy storage technologies, the LDES Council provides guidance and reports to enable the integration of renewable energy sources and enhance grid stability using LDES technologies to achieve a flexible, secure, reliable, affordable, and fossil fuel free energy system.

ABOUT ROLAND BERGER

Headquartered in Munich, Germany, Roland Berger is a global management consulting firm of approximately 3,500 consultants. Roland Berger has more than 50 offices in 30 countries, and specializes in supporting its industrials, utility, investor and government clients through the energy transition.

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1 "The idea of hydraulic energy storage by means of pumps and turbines was born at the end of the 19th century in Switzerland and in Germany. The first pumped storage plant was built in Zurich in 1891 at the Limmat river followed by a second installation 1894 at lake Maggiore and a third one 1899 at the Aare river. The principle of pumped storage was first realized in Germany 1891, where a steam machine was driving a centrifugal pump for dewatering the Rosenhof ore mine in the Upper Harz mountain by filling an upper reservoir, which was serving a separate water wheel."
Krueger, K., 2020. Pumped Hydroelectric Storage. In K. Brun, T. Allison, and R. Dennis: Thermal, Mechanical, and Hybrid Chemical Energy Storage. New York, NY: Elsevier, ISBN 978-0-12-819892-6

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Executive summary

Long duration energy storage technologies paired with renewables could reduce global industrial greenhouse gas emissions by 65%.

One of the most attractive current applications for LDES technologies is to support firm renewable electricity for off grid applications based on representative case studies analyzed in this report.

LDES technologies also reduce the cost of abatement for low-to-medium temperature fossil fueled industrial processes (100°C to 500°C) and would be attractive with carbon incentives.

Governments worldwide should prioritize policies that increase industrial users' propensity to deploy LDES technologies such as subsidies, prices on carbon and pilot projects.

LDES technologies paired with renewables are a viable, cost-efficient and readily appliable option for industrial decarbonization, as observers consider these technologies "An embarrassingly simple solution for industrial emissions."[2]

Moreover, long duration energy storage technologies are already being piloted by blue chip industrial firms, as they are impatient to decarbonize now and LDES gives them this opportunity.

Tata Steel, ArcelorMittal, BHP, Rio Tinto, Yara, Avery Dennison, Eni and Microsoft are among the industrial firms embarking on projects to demonstrate the ability of LDES technologies to decarbonize their operations.

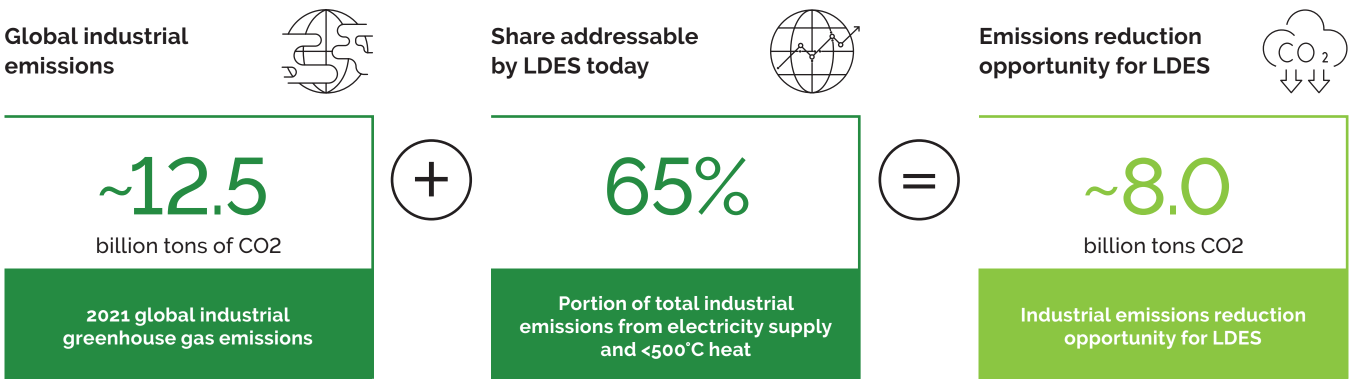
LDES technologies' costs, capabilities, and durability enable them to support a wide range of applications for industrial energy use cases that are unsuited to shorter duration resources. LDES has the ability to provide the equivalent of base load renewable power for industrial customers, in some cases for mulitple days or even on a seasonal basis. Employing LDES technologies on a behind the meter basis will in many instances, enable industrial users to realize their decarbonization targets independent of the status of the decarbonization of the broader regional wholesale electricity system. In many instances, LDES technologies can also address industry's needs for thermal energy that cannot be addressed by electricity alone.

Commercially available LDES electric and heat technologies are technically capable of reducing industrial emissions by 65%. As described in Figure 1, a reduction of 7.7 billion tons of CO_2 are addressable by LDES technologies today. Yet policy and market support is required to ensure that these reductions can be achieved. FIG. 1

2 https://www-ft-com.ezp.lib.cam.ac.uk/content/7c6a0928-a233-4444-b294-297006270141

FIGURE 1

Global industrial emissions addressable by LDES[3]



3 Derived using data from the Emissions Database for Global Atmospheric Research – 2022 Report - https://edgar.jrc.ec.europa.eu/report_2022 and the International Energy Agency

Source: Our World In Data, IEA, Roland Berger

LDES USE CASES

Existing applications for long duration electric and thermal energy storage include firming wind and solar for off-grid use, and using renewable energy to decarbonize fossil-fueled industrial processes at 500°C and below through electrification. LDES technologies are already economically attractive in enabling off-grid facilities to replace high-cost diesel fuel with firmed renewable electricity – even without carbon incentives. FIG.2

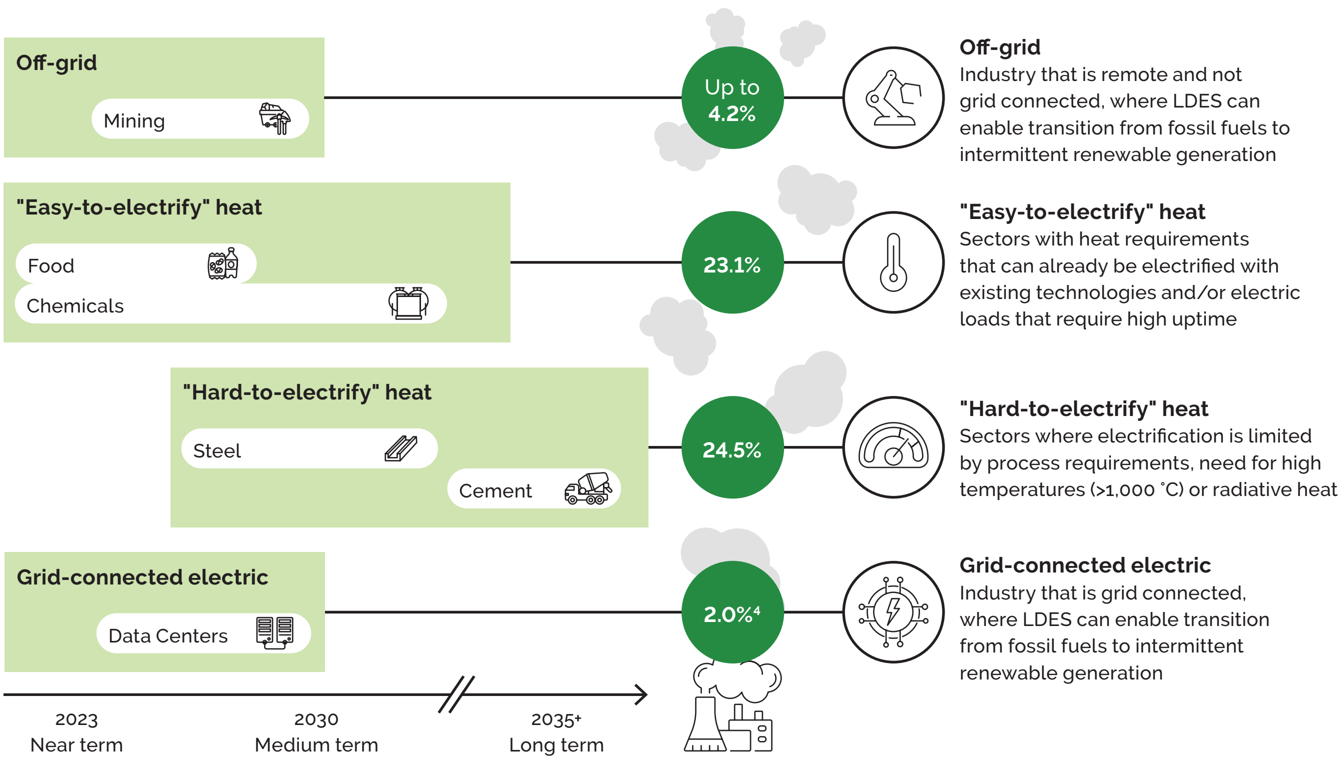
The technologies reduce the cost of abatement by more than 20% for low-to-medium temperature processes used in food manufacturing and chemical processes. They would be more economically attractive with carbon incentives in place.

The level of deployment of LDES in "Hard-to-electrify" industries like steel and cement are currently limited due to integration requirements for electric technologies to support their high temperature, radiative heat needs. However, LDES can already reduce emissions in these sectors by enabling those industrial users to take advantage of intermittent renewable generation for their round-the-clock electricity needs, and accessing CO2-free heat supply and recovery waste heat for lower temperature processes. Additionally, steel producers looking to utilize 100% renewable energy in their operations are looking to 100+ hour LDES technologies to provide reliability in their steelmaking process and solve inherent intermittent renewable power generation.

In the longer term, LDES has the potential to directly replace heat supply for high temperature fossil-fueled processes (e.g., thermal energy storage-powered kilns for cement) or support complementary technologies (e.g., electric LDES with e-kilns for cement or thermal energy storage paired with concentrated solar power).

FIGURE 2

Share of total industrial emissions for industries sectors examined in case studies, 2022



4 2.0% indicates the share of total global emissions that data centers represented in 2022; data centers are not categorized as a component of industrial emissions

Source: IEA, MIT Press, Roland Berger

LDES provides a clear pathway for ensuring reliable, 24/7 carbon-free power for grid-connected electric applications, e.g., data centers.

RECOMMENDATIONS

The pace at which LDES can contribute to industrial decarbonization will depend on the propensity of industrial firms to adopt these new technologies and government support. Pilot programs and technology demonstrations like those already in use today can increase adoption among industrial users.

Government policy support that includes subsidies for early adopters, carbon taxes on firms who delay and pilot projects to demonstrate LDES technology maturity could have a significant impact on driving adoption of these technologies.

Glossary

Capex	Capital expenditure
CO2	Carbon dioxide
°C	Degrees Celsius
DCF	Discounted cash flow
EV	Electric vehicle
GJ	Gigajoules
H_2	Hydrogen
ICE	Internal combustion engine
k	1,000
kg	Kilograms
kW_e MW_e TW_e	Kilowatts, megawatts, terawatts electric
kW_t MW_t TW_t	Kilowatts, megawatts, terawatts thermal
MWh_e TWh_e	Megawatt-hours, terawatt-hours electric
LDES	Long Duration Energy Storage
mmbtu	Million British Thermal Units
NPV	Net present value
Opex	Operating expenditure
p.a.	Per annum
PPA	Power purchase agreement
R&D	Research and development
RE	Renewable energy (solar and wind for report)
REC	Renewable energy credit
SMR	Small modular reactors
Ton(s) or t	Metric tons
TOU	Time-of-use
USD	United States Dollars
VOLL	Value of lost load
WACC	Weighted average cost of capital
Δ	Delta
>/<	Greater than, less than

01 The case for industrial decarbonization

KEY FINDINGS

Industrial emissions account for more than a quarter of total global greenhouse emissions and are expected to increase; therefore, industrial decarbonization is critical to achieve the Paris Climate Accord's 1.5˚C pathway

1. The industrial sector produces a large and rising share of global greenhouse gas emissions, especially in rapidly growing developing nations[5]; this challenge is compounded by growth in demand for heat and commodity price pressures

2. Decarbonization of the sector requires:

   a. Technologies that can firm renewables and address a broad range of temperature requirements

   b. A policy- and market-driven approach that encourages firms to procure renewables matched to electricity consumption and implement new production processes

3. LDES can address 65% of industrial emissions today, equating to an ~8 billion tons CO2 emissions reduction opportunity

Industry is a key driver of the global economy. However, it is also a dirty business.

Industrial emissions account for around a quarter of annual global emissions. In 2016, total industrial greenhouse gas emissions were around 12 billion tons CO2e, a figure that, without interventions, will almost double by 2050.[6] The bulk of incremental emissions is forecasted to be in developing economies.[7]

Around half of industrial emissions are driven by heat requirements for production processes.[8] Emissions are high because the vast majority of industrial heat demand is currently met by burning fossil fuels, jeopardizing the ability to achieve the Paris Climate Accord's 1.5°C pathway.

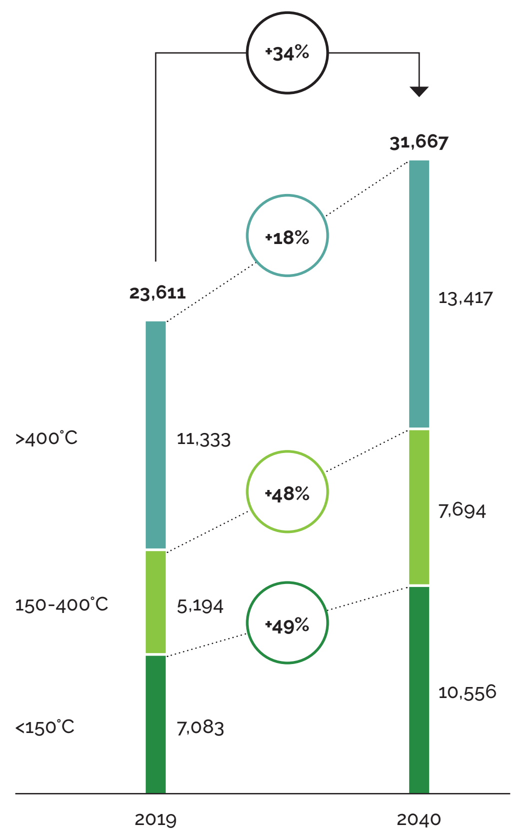
Most industrial processes require heat at specific levels – and lots of it. Demand for industrial heat is expected to grow by 34% between 2019 and 2040, with low and medium temperature heat the fastest growing segments. FIG. 3

This rise in demand coincides with economic and population growth and a push by countries around the world to achieve energy independence, driven by economic forces and national security concerns. This rush towards self-sufficiency has sometimes been pursued at the expense of decarbonization progress, threatening global efforts to reduce emissions.

On a per country basis, industrial emissions have more than doubled in non-OECD countries since 2000, while they have fallen by 16% in OECD countries over the same period.[9] CO2 emissions in non-OECD countries have risen 3% per year on average, while slightly declining in the industrialized world. These trends present both challenges and opportunities.

FIGURE 3

Global industrial energy and heat demand, 2019 [TWh]



Note: Figure based on IEA New Policies scenario from WEO 2017

Source: RC2ES Center for Climate and Energy Solutions, International Energy Agency, Roland Berger

5 'Developing nations' or 'developing economies' are a proxy for non-OECD countries

6 Roland Berger estimate based on a 2016 baseline from the PBL Netherland Environmental Assessment Agency

7 Energy Information Agency – 2021 International Energy Outlook; non-OECD countries are a proxy for 'developing economies'

8 Power Infrastructure Needs for Economywide Decarbonization (c2es.org)

9 Emissions Database for Global Atmospheric Research – 2022 Report https://edgar.jrc.ec.europa.eu/report_2022

DECARBONIZATION CHALLENGES

Successfully decarbonizing industry is expensive and requires technologies that can firm renewables and service a broad range of temperature requirements.

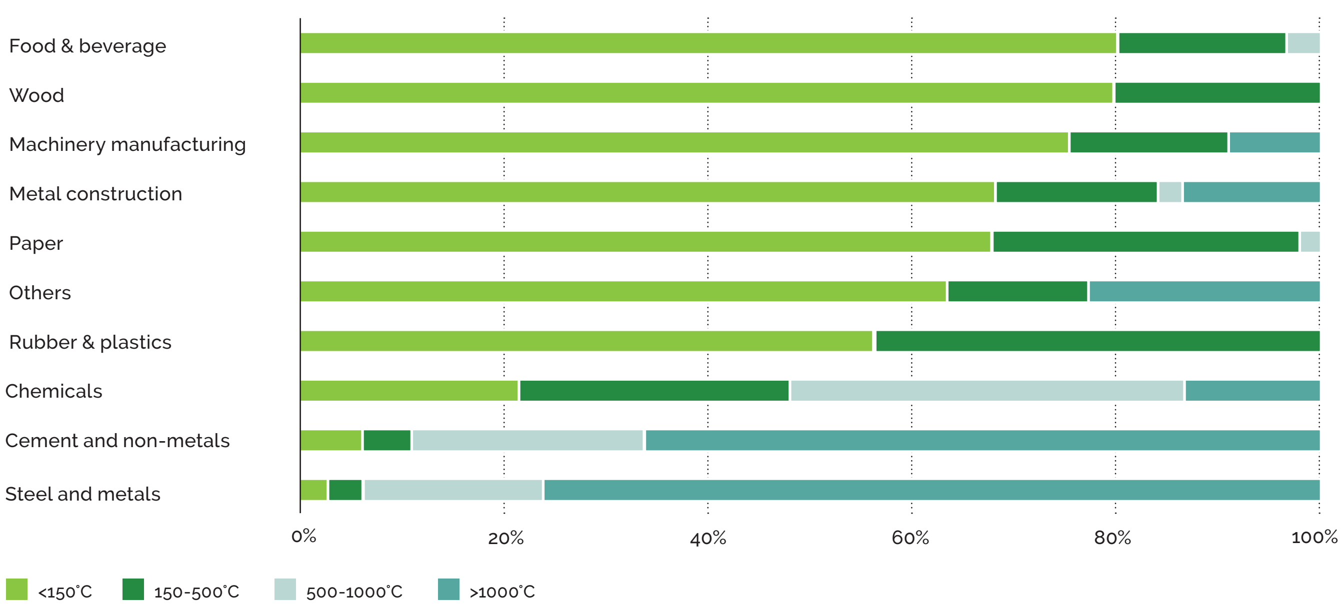
While technologies are constantly advancing, meeting these temperature demands is a key challenge. As shown in Figure 4, temperature requirements vary across and within industrial sectors, even in individual plants. While some lower temperature requirements can already be met by electrification using renewables, meeting the very high temperature needs of, for example, the steel and cement industry through electrification is extremely challenging. FIG. 4

As well as satisfying temperature demands, decarbonization alternatives require often-risk-averse plant managers to embrace new technologies that are only now starting to gain commercial traction. Few proven solutions to electrify industrial processes have emerged and there has been a lack of scale to commercialize them (resulting in cost barriers).

In addition, implementing decarbonized solutions is a CFO-level decision for industrial firms, many of whom are highly sensitive to cost pressures because they operate in commodity-reliant industries. They are also used to operating in a climate of where industrial energy is very cheap, simple and efficient.

FIGURE 4

Industrial temperature requirements, Germany [%]



Source: Bundesverband Geothermie, Roland Berger

INDUSTRIAL DECARBONIZATION APPROACHES

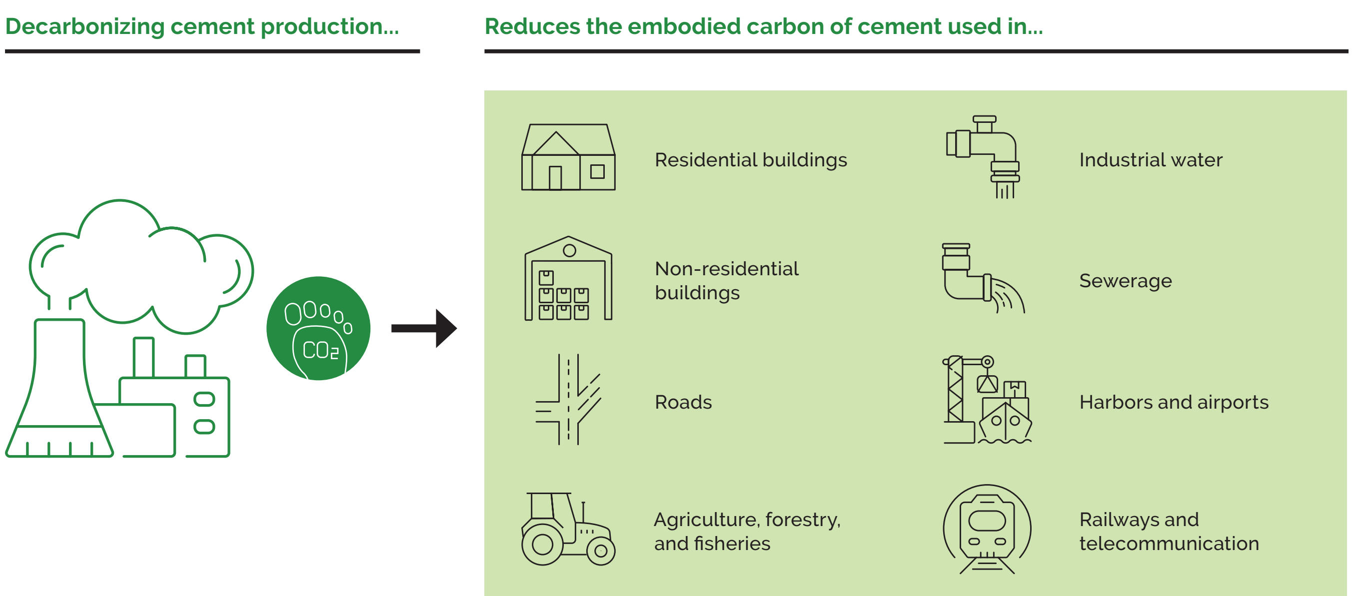
Successfully decarbonizing the energy sources and production processes of industry is not just good for the sector itself, it also has a knock-on effect on the wider economy. It reduces the embodied carbon of industrial products while also cutting the impact of pollutants on nearby communities and ecosystems. For example, as shown in Figure 5, decarbonizing cement reduces the embodied carbon of the downstream products that use it as an input.

This also effects bottom lines. Embodied carbon reductions could enable early decarbonization movers to capitalize on green willingness-to-pay premiums on their products. Such premiums are gaining traction due to both end-consumer pull towards sustainability and government policy on the carbon footprints of produced goods. This downstream interest in the carbon intensity of upstream production is demonstrated by the rise of environmental declarations about goods and services. FIG. 5

Decarbonization also offers social benefits. For example, the reduction of non-GHG emissions from industrial plants, such as particulate matter, ozone and heavy metals that impact local air and water quality, can lead to health improvements for communities living close by to these facilities. In addition, a transition to sustainable operations can extend the useful lives of such facilities, helping to preserve jobs.

FIGURE 5

Example downstream embodied carbon reductions in decarbonized cement production



Source: Roland Berger

However, change will not come about by itself. Achieving these decarbonization goals will require both new policy and market willingness to implement new production processes.

EXAMPLE APPROACHES

A growing number of industrial companies – large and small around the world – are already proactively undertaking decarbonization initiatives, or will soon be mandated to as governments roll out strict decarbonization standards, carbon taxes or equivalent cap-and-trade mechanisms and/or subsidies for clean energy technologies.

One such example is the European Union's Carbon Border Adjustment Mechanism. It aims to protect early industrial decarbonization adopters in the bloc by imposing a carbon tax based on the embodied carbon in imported commodity materials.

Another example is Australia's Safeguard Mechanism, which was implemented in July 2023. It specifically requires industrial facilities to reduce their emissions below a baseline, or acquire carbon credits. The policy targets emissions-intensive operations and organizations[10] that emit over 100,000 tons[11] of CO_2 per year.

In terms of subsidies, the United States and European Union are advancing substantial tax credits and subsidies through the Inflation Reduction Act and the Green Deal Industrial Plan, respectively. The EU's Net Zero Industry Act, which stems from the Green Deal Industrial Plan, identifies goals for net-zero industrial capacity and aims to create a regulatory framework to speed its deployment.

Companies themselves – either as a matter of corporate strategy or due to investor/public pressure – have also taken voluntary action. For example, as of June 2023, more than 1,300 large industrial companies around the world have committed to meaningful emissions reductions by setting a Science Based Target (SBTi).[12] FIG. 6

10 For example, mining, oil and gas production, manufacturing, transport, waste facilities.

11 “Tons” refers to metric tons (1,000 kg); this applies to all further mentions of “tons”

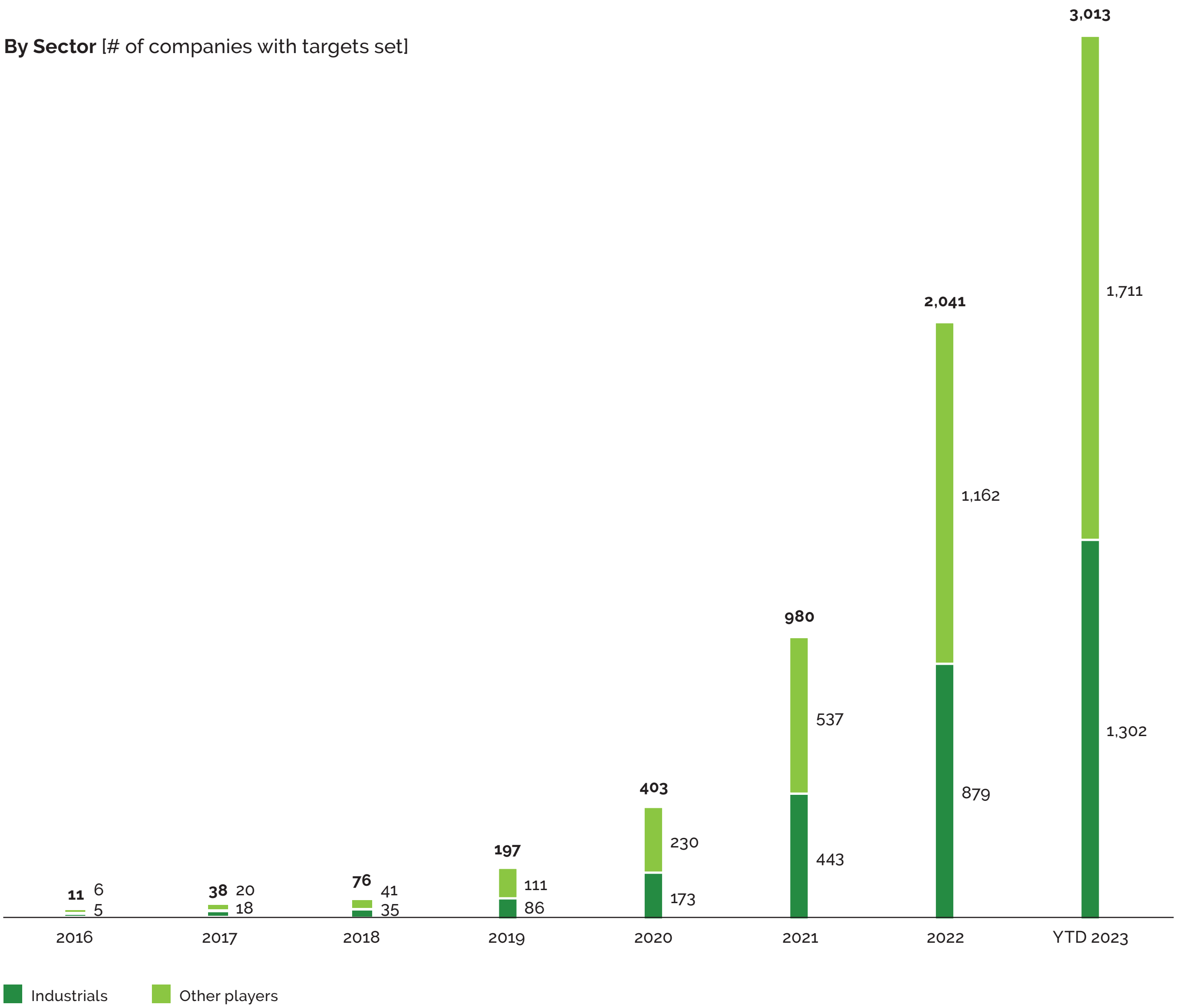
12 Science Based Targets Initiative – global partnership that provides guidance and a pathway for the private sector to set science-based emissions-reduction targets

FIGURE 6

Number of companies with a Science Based Target[12] by type

Cumulative corporate sustainability targets set in line with the 2015 Paris Agreement

By Sector [# of companies with targets set]



Source: SBTI, Roland Berger

FIGURE 7

Announced support for LDES in indicative countries

Countries (Ordered by USD)	USD	Details
Chile	2.0 bn	Energy storage, incl. LDES
Hungary	1.16 bn	Energy storage, incl. LDES
United States	500 m	LDES-specific
Spain	350 m	LDES-specific
Canada	220 m	Energy storage, incl. LDES
United Kingdom	37 m	LDES-specific

Source: LDES Council, Roland Berger

02 Net Zero Industry: Methodology overview

INTRODUCTION

LDES uses specialized technologies to store and discharge electric and thermal energy over durations ranging from eight to 100 hours or more.

These technologies can be grouped into four principal LDES technology families: electrochemical, chemical, thermal and mechanical. Each one has its own application sweet spot, in terms of duration, power and cycling requirements. See Figure 8 for a detailed description.

We have created case studies specific to each family to demonstrate their value for real-world applications. We assessed how LDES could complement other technologies in decarbonizing and the economic attractiveness of doing so.

FIGURE 8

Long Duration Energy Storage categories

	Electrochemical	Thermal	Chemical	Mechanical
Description	Energy storage systems generating electrical energy from chemical reactions	Solutions stocking thermal energy by heating or cooling a storage medium	Chemical energy storage systems store electricity through the creation of chemical bonds	Solutions that store energy as a kinetic, gravitational potential or compression/pressure medium
Types	• Flow • Metal anode • Non-metal Chemical Storage	• Sensible heat • Latent heat • Thermochemical	• Green hydrogen • Methane • Ammonia • Methanol	• Compressed air energy storage • Liquid air energy storage • Pumped hydro storage • Gravity based storage • Liquid CO2
Advantages	• Flexibility • Declining long-term costs • Wide operating range	• **No degradation** • Cycling throughout the day • Modular options available	• Potential range of footprint and RTE with relative higher C-rates • Technology options either have **inexpensive** materials or require less expensive materials than LiB	• **No degradation** • **Proven** via established technologies (pumped hydro) • Considered **safe** • Attractive economics

Source: LDES Council, Roland Berger

OBJECTIVES

The objectives of this study were to understand: 1) how LDES can be applied to decarbonize different industrial applications around the world; 2) the economic attractiveness of doing so; 3) how LDES could complement other technologies addressing the same task; and 4) to identify if there are policy/regulatory actions which could accelerate the application of LDES-based decarbonization.

The study uses case studies and assumptions to provide an assessment of the benefits that LDES technologies offer industrial users. It also provides information on the requirements of LDES and its current and expected capabilities.

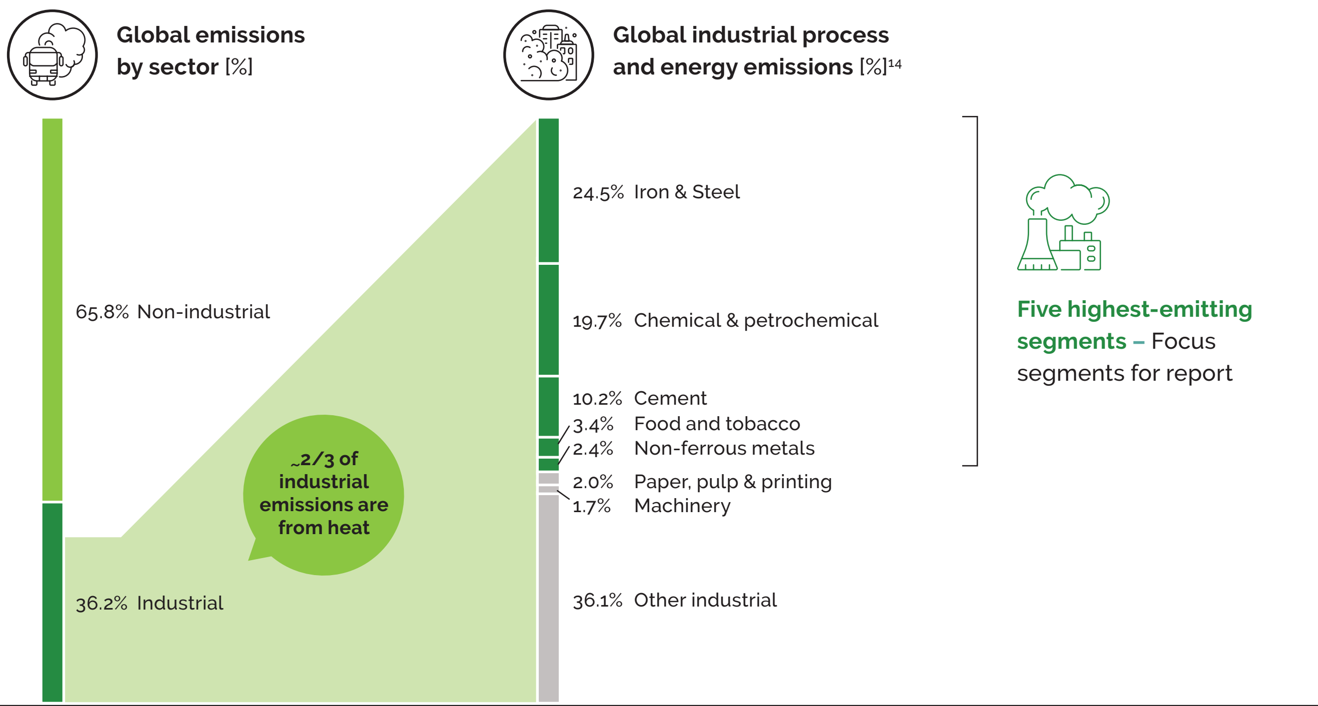
FOCUS AREAS

The study focuses on LDES opportunities across a representative sample of industries and geographies that characterize global industrial heat, electric, and process energy needs. The sample prioritizes the five highest-emitting segments in traditional industry, as shown in FIG. 9.[13]

13 While typically not categorized as belonging to industrial emissions, Appendix 1 also highlights data centers as an example of how LDES can support decarbonization of electric loads that require uninterrupted 24/7 baseload electricity

FIGURE 9

Global greenhouse gas emissions by sector and industrial segment, 2016



14 Data center emissions are not included in global industrial process emissions

Source: Our World In Data, IEA, Roland Berger

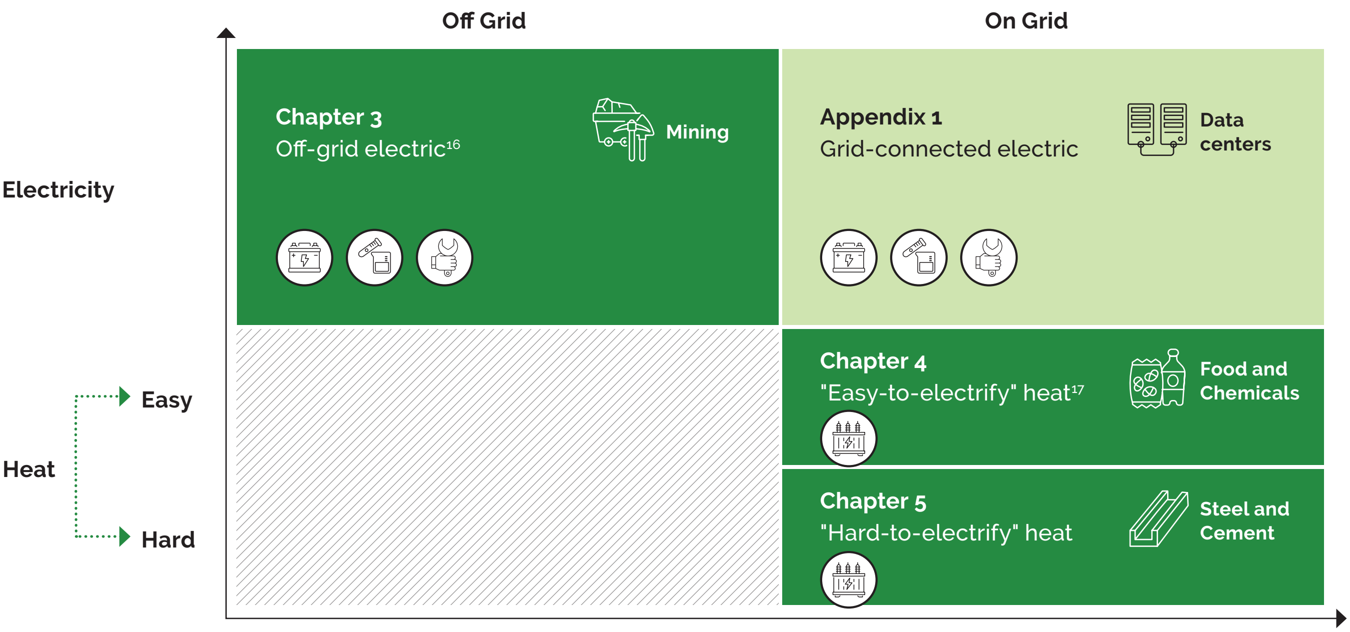
Current LDES technologies can be applied to both on- and off-grid industry; and electric and heat applications. The opportunities offered by LDES can be grouped into three categories described in Figure 10, which are used to structure the subsequent chapters of this report (FIG. 10).

- **Off-grid electric:** Remote industrial applications that are not connected to the grid, where LDES can enable the transition from fossil fuels to intermittent renewable generation. (Case study: Mining)
- **"Easy-to-electrify" heat:** Industrial sectors with heat requirements that can be electrified using existing technologies. (Case studies: Chemicals, Food)
- **"Hard-to-electrify" heat:** Sectors where electrification is currently limited by process requirements, such as, the need for high temperatures (>1,000°C) or radiative heat. (Case studies: Steel, Cement)

FIGURE 10

Categorization of industrial sectors by dimension as examined in this report[15]

Industry segments highlighted below were selected to be representative of each category for case studies; in the real world, industry segments may have energy demands that do not match this categorization



15 Off Grid heat is a viable application; however, it is not examined in this report

16 Focus in Chapter 3 is primary extraction, not mineral processing

17 Heat required by Alumina industry sector relates to Chapter 4 "Easy-to-electrify" heat

LDES technologies evaluated by case: Electrochemical, Thermal, Chemical, Mechanical

Source: Roland Berger

METHODOLOGY

The first step of the analysis involved characterizing the prioritized industrial segments. This included establishing electricity and heat needs, operating constraints and considerations, energy market and regulatory conditions, and sustainability goals for each industry using published research and expert interviews.

To account for geographic variations, selected segments were examined across eight countries – Germany, the United Kingdom, South Africa, the United Arab Emirates, India, Australia, Chile, and the United States. These were selected based on their respective industrial footprint, current and future energy mix, and commercial strategies of LDES technology providers. The findings are laid out in the 'Global Relevance' sections of the applicable chapters. FIG. 11

FIGURE 11

Focus countries

Source: Roland Berger

For each industry segment, one country was then selected for a case study. The choice was based on the prominence of the industry in the country, the country's global share of that industry, and the country's decarbonization targets.

From this, more detailed information on specific LDES applications across each of the three focus sectors was gathered. Publicly available LDES technology costs (and cost declines through 2040) and performance parameters were then validated based on LDES Council member review and input. Leading decarbonization alternatives were also identified and their costs and performance parameters collected. FIG. 12

Next, a technoeconomic analysis was conducted to determine each decarbonization solution's economic attractiveness from the standpoint of project economics and carbon reductions. This

FIGURE 12

LDES can be part of a larger portfolio of industrial decarbonization technologies, including boilers, heat pumps and SMRs

Electric Boiler	Hydrogen Boiler	Electric Heat Pump	Li-Ion Battery	Small Modular Reactor
• Low capital costs • Limited applicability due to operational temperature range of 100°C - 500°C	• Economic feasibility dependent on access to large supply of green hydrogen at low cost	• Higher capital costs than LDES • Limited applicability due to operational temperature range of 100°C - 150°C	• Weaker cost position compared to LDES due to augmentation and oversizing costs stemming from degradation • Supply chain risks and environmental impacts from mining relating to rare earth mineral components	• Commercialization expected in the 2030s • Feasibility challenges due to regulatory, siting, and potential customer acceptance complaints

The diversity and adaptability of LDES technologies allow them to complement the options in the table above

Source: Roland Berger

was done by comparing each segment's status quo costs and emissions. All case studies in this report represent a 99+% reduction of status quo emissions (scope of emissions specified by case).[18] Each solution's current and future economic attractiveness over a 20-year period was then analyzed for all the representative geographies, using project start years of 2023, 2030, and 2040.

The technoeconomic analysis yielded a cost of abatement by solution for each of the three time periods, representative segments, and geographies. FIG. 13

Variations in the findings for the eight countries reflect differences in: input retail and wholesale electric prices; PPA prices; REC prices; grid emissions factors; solar and wind generation profiles and costs (capital and operating); fuel prices (diesel, natural gas, green hydrogen, nuclear); outage frequency and durations: subsidies; and carbon prices.

All of these inputs were forecasted to 2060[19]. The results of the analysis underlined the critical role of a number of variables, including the evolution of electricity markets and policy regimes

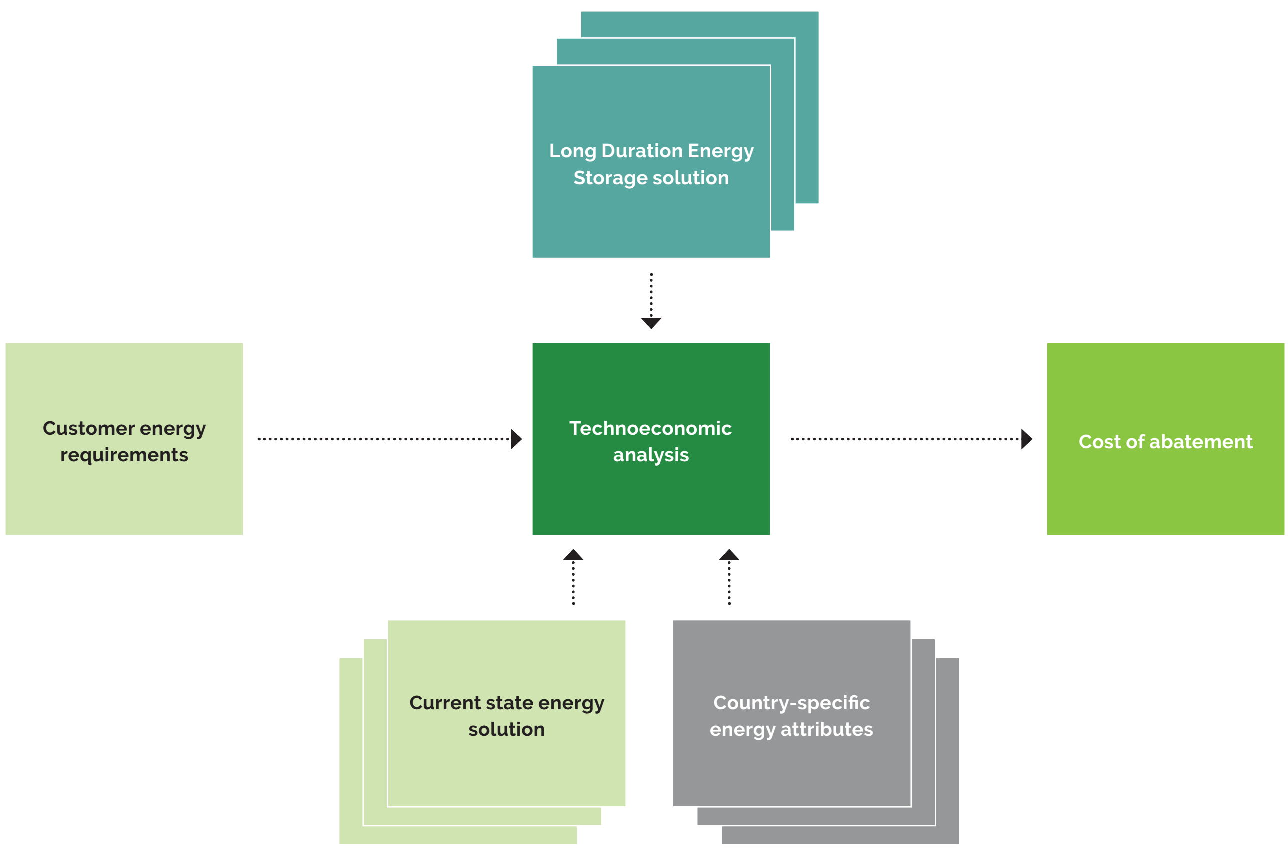
18 It is important to note that the marginal cost of abating e.g., the first 5% of emissions is significantly lower than the marginal cost of abating the last 5% of emissions

19 Reflecting 20-year period analyzed from a project start in 2040 could alter the cost of abatement in the future. We also performed sensitivities on a selected set of these variables for each case to reflect how potential scenarios could alter analysis results.

See Appendix 2 for further detail on the techno-economic analysis methodology and inputs.

FIGURE 13

Simplified schematic of model



Note: See Appendix 2 for details on variables considered in analysis and for detailed model schematic

Source: Roland Berger

03 Off-grid electric

KEY FINDINGS

The off-grid industrial segment presents an immediately attractive application for LDES due to the cost advantage of renewables over fossil fuels

1. LDES technologies support electrification and decarbonization of off-grid sites, such as mines, by enabling them to shift from fossil fuels to renewables, while maintaining reliable supply
2. There are few current alternatives to LDES for decarbonizing and maintaining reliability off-grid; LDES is cheaper than lithium-ion storage, depending on site conditions and performance needs
3. The business case for switching to off-grid LDES is already very attractive in several mining regions, especially where fuel prices are high and where solar and wind resources are abundant

OVERVIEW AND APPLICATIONS

Off-grid refers to facilities that are not connected to a central power grid, and instead rely on power generated locally. Industrial off-grid applications are most common in the mining sector. They are also found in oil and gas exploration and extraction, and remote agricultural facilities such as dairy farms.

LDES technologies support electrification and decarbonization of off-grid facilities by enabling them to switch from fossil fuels to a reliable, renewables-powered supply. When paired with renewables, LDES enables full decarbonization of electricity supply, an important goal of many companies. Decarbonization of electricity supply also allows off-grid facilities to decarbonize vehicles through electrification.

The mining industry is the biggest potential user of off-grid LDES, with many attractive applications. For example, renewables-based LDES is capable of powering equipment and vehicles involved in processes such as comminution, digging, drilling, blasting, and ventilation, replacing diesel fuel and power generated from natural gas. Specific applications vary according to the quality of renewable resources. FIG. 14

While electric mining vehicles and equipment are nascent, they are already available and are near parity with diesel counterparts. The rapid scaling of electric mining vehicles' production, as well as cost declines, are expected over time.

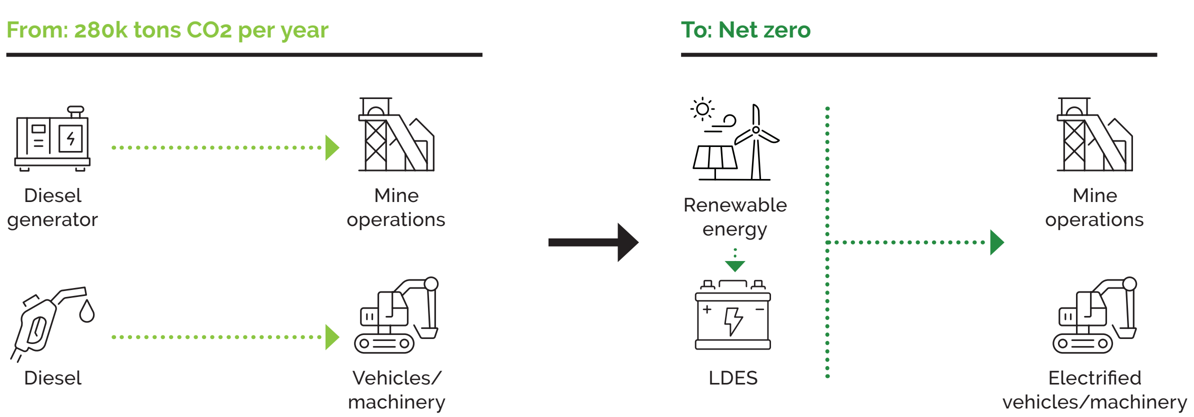
VALUE PROPOSITION AND FEASIBILITY

The economics of fully decarbonizing an off-grid site with LDES plus renewables are already very attractive due to the relative cost of renewables compared to diesel.

The use of liquid fuel is not only expensive but also highly carbon intensive. For example, diesel has an emissions rate of approximately 75 kg CO_2 per mmbtu, about 150% the emissions rate of natural gas and 80% the emissions rate of coal.

FIGURE 14

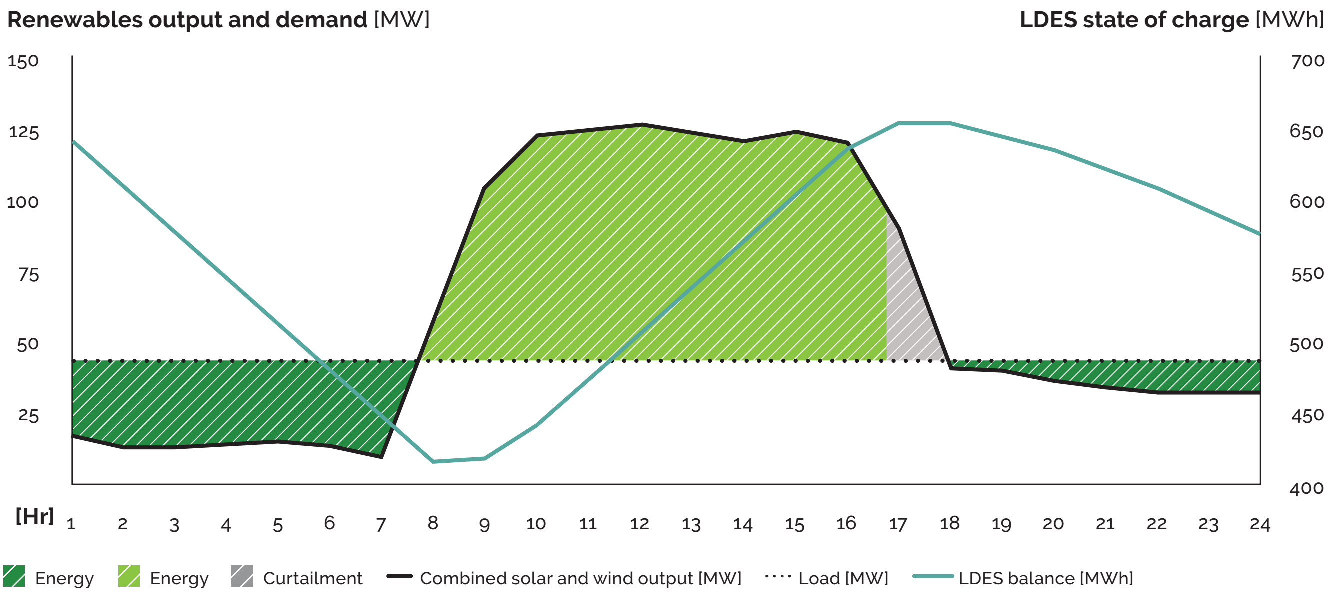
LDES solution for off grid electric (mining)



Source: Roland Berger

FIGURE 15

Indicative daily (July) energy production and LDES dispatch for off-grid mining, Australia



Source: Roland Berger

This does not include the additional emissions resulting from fuel deliveries, which can be on a daily or weekly basis. The case for LDES should become even more financially attractive into the future, given the expected increases in diesel prices and anticipated improvements in LDES costs and performance.

An off-grid mine in Australia, for example, might expect to incur USD 3 billion in opex over 20 years, use 28 million gallons of diesel per year, and emit ~300 k tons CO2 per year. However, given a diesel price of USD 6 per gallon, attractive renewable resources, and a mining operation that can be adapted to electrified transport and processing equipment, the mine could save 76% on its opex with a switch to renewable generation and LDES. Averaging across all electric LDES technologies, it could achieve full decarbonization at a savings - not a cost - of USD 609 per ton of CO2 abated.

Electric LDES technologies therefore support a strong case for use as electrification and decarbonization tools, and are the most economic option today. They are better suited to long-duration applications (8+ hours) than, for example, lithium-ion cells, and are more economically attractive than lithium-ion by avoiding additional costs associated with oversizing and augmentation.

A typical LDES resource duty cycle for the off grid mine is illustrated in the figure below. The resource is able to charge during the day and support night time mine operations with LDES and wind energy. FIG. 15

Small modular reactors (SMR) have a role to play in electrification and decarbonization, but are not yet available (expected in the 2030s). In addition, SMRs may not be feasible at all locations due to regulatory, siting, and customer acceptance constraints.

GLOBAL RELEVANCE

Countries with sizable off-grid mining industries present the best off-grid opportunities for LDES. These include Australia, Canada, and countries in South America and Africa, like Chile and South Africa.

The economics of LDES for off-grid power applications are globally favorable, with the case varying according to local fossil fuel costs, renewable costs and resources, and carbon taxes or policy support. For example, for every dollar of carbon tax, the cost of abatement reduces by a dollar per ton of CO_2.

ENABLERS

LDES is already an economically attractive decarbonization solution for off-grid industry. However, subsidies can complicate the case for or against it. In some countries, there may be countervailing price signals – such as subsidies – or other support for fossil-fuel-driven equipment. As the case for LDES is strongly tied to fossil fuel prices, fossil fuel subsidies weaken the case; conversely, carbon taxes or subsidies for decarbonization bolster the case.

CASE STUDY: MINING

Electrifying power from diesel generators and diesel vehicles/machinery (off grid)

The case: Off-grid mine in Western Australia. Brownfield development of renewables plus LDES for decarbonization of all energy consumption.

Status quo: The mine uses 28 million gallons of diesel p.a. to fuel vehicles (40%) and generate power (60%, or 33 MWe). Diesel price starts at USD 6/gallon and escalates over time. The mine is expected to incur USD 3 billion in opex and emit 5.6 million tons of CO_2 over 20 years. See Appendix 4 for details.

LDES solution: Vehicles are electrified and power decarbonized through 210-230 MWe renewables and 27-54 MWe of 24-hour LDES (dependent on the LDES technology). LDES enables 10% additional fuel switching compared to renewables only as LDES allows time-shifting of renewables to periods when solar and wind generation drops off.

Emissions abatement: The mine is able to abate >99% of emissions, equaling 5.6 million tons of CO_2 over 20 years (or 279k tons CO_2 p.a.).

Economics: LDES supports electrification and decarbonization of the mine, resulting in a 76% reduction in opex. The saving from mechanical-only LDES technologies is USD 594/ton CO_2.

- The highest value comes from switching from expensive diesel to renewables
- LDES-only contribution is USD 54/ton CO_2

Outlook: Net savings improve by ~40% through 2040, driven by rising diesel price and declining LDES costs

Geographies: Renewables + LDES helps to decarbonize off-grid mining profitably in each of the analyzed countries, with economics varying based on:

- Fuel cost differences (primary driver)
- Carbon taxes
- Renewables costs and resources

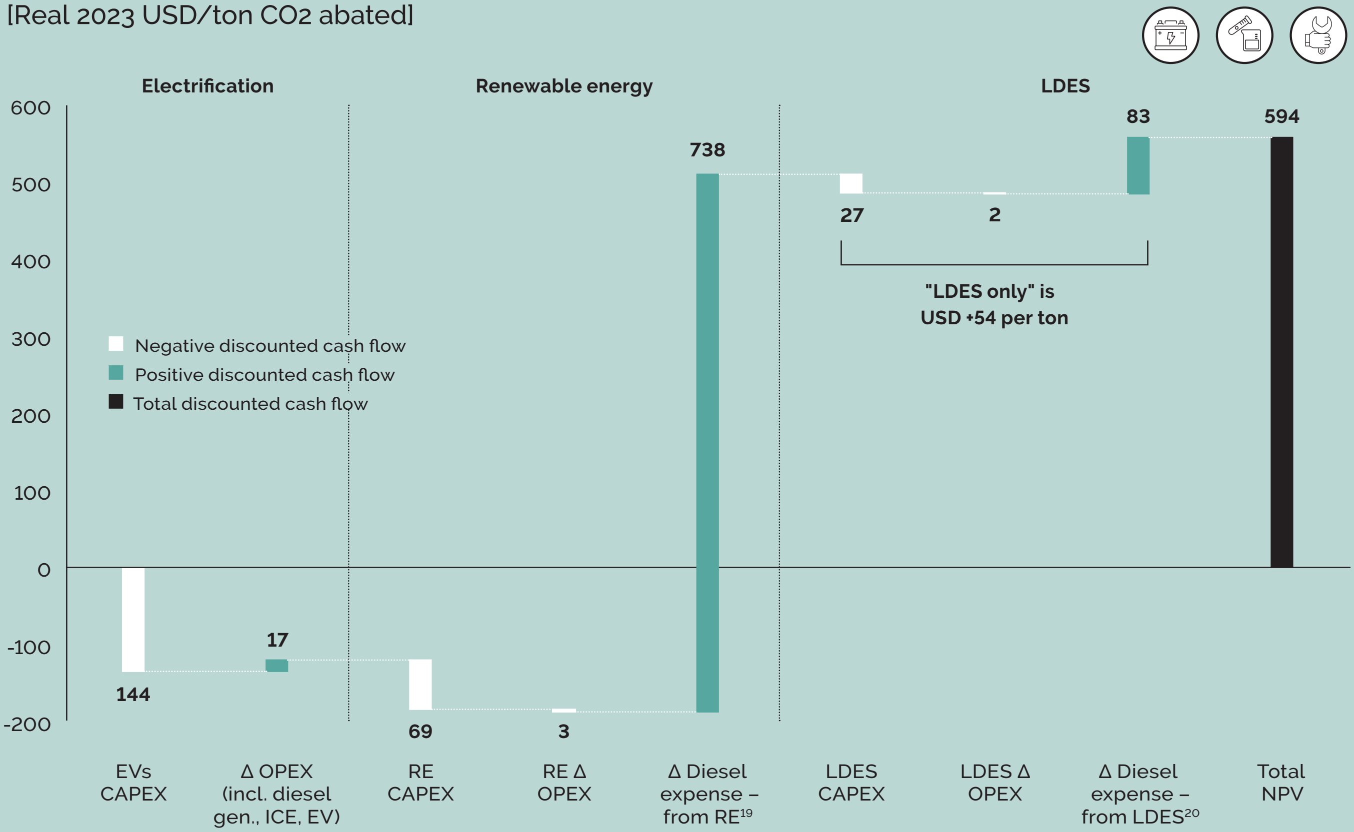
Alternatives: Electric LDES technologies support a strong electrification and decarbonization case and are the most economic options explored that are currently available.

- In 2023, lithium-ion is less economically attractive than all LDES technologies, with a 6% higher cost of decarbonization

FIGURE 16

Case study: Off-grid mining, Australia – renewable energy and electric LDES solution, 2030

[Real 2023 USD/ton CO2 abated]



20 Diesel fuel used for both ICE vehicles and diesel generator; diesel savings attributed to each technology based on % of load met directly by each technology

Source: Roland Berger

04 "Easy-to-electrify" heat

KEY FINDINGS

LDES is an economically attractive solution for industrial firms seeking to decarbonize heat or improve the reliability of their electric supply

1. In heat applications, LDES makes the most sense where temperatures between 150˚C and 500˚C are required
2. The business case for LDES is most attractive in places where customers are exposed to high and volatile electricity prices (such as Germany), and where reliability of supply is a challenge (such as South Africa)
3. The case for LDES is expected to improve through 2040 due to the falling cost of LDES solutions, increasing price volatility and deterioration in grid reliability
4. Key enablers are long-term contracts which enable the amortization of investments over 15-30 years and market/regulatory encouragement of industry to procure 24/7 renewables

OVERVIEW AND APPLICATIONS

"Easy-to-electrify" heat includes a wide range of sectors with heat requirements that can be electrified using existing technologies (for example, electric boilers and heat pumps). Processes in these sectors typically utilize heat in the form of steam or hot air, with temperature requirements between 100°C and 500°C. Half of global industrial heat production falls within the Easy-to-electrify segment. Higher-temperature sectors such as steel and cement make up the remaining 50% (see Chapter 6).

Facilities that fall within the this segment need not only fossil fuels to supply heat (for example, natural gas boilers), but also electricity from the grid to supply adjacent manufacturing processes, control systems, HVAC,[21] and lighting. This means that heat demand usually goes hand-in-hand with electricity demand, which also needs to be decarbonized.

In many sectors requiring process heat, reliability is vital. However, costs relating to both lost inventory and lost production, but also damaged equipment[22] yield a very high value of lost load (VOLL) in these sectors. This increases significantly at longer durations.

Thermal LDES, in conjunction with complementary technologies such as e-boilers, enables electrification of low-to-medium temperature heat (100˚C to 500˚C), facilitates decarbonization of electricity supply, and ensures reliability of supply.

For this analysis, thermal LDES was coupled with an e-boiler, though in some cases LDES technologies are capable of providing heat without one.[23] FIG. 17

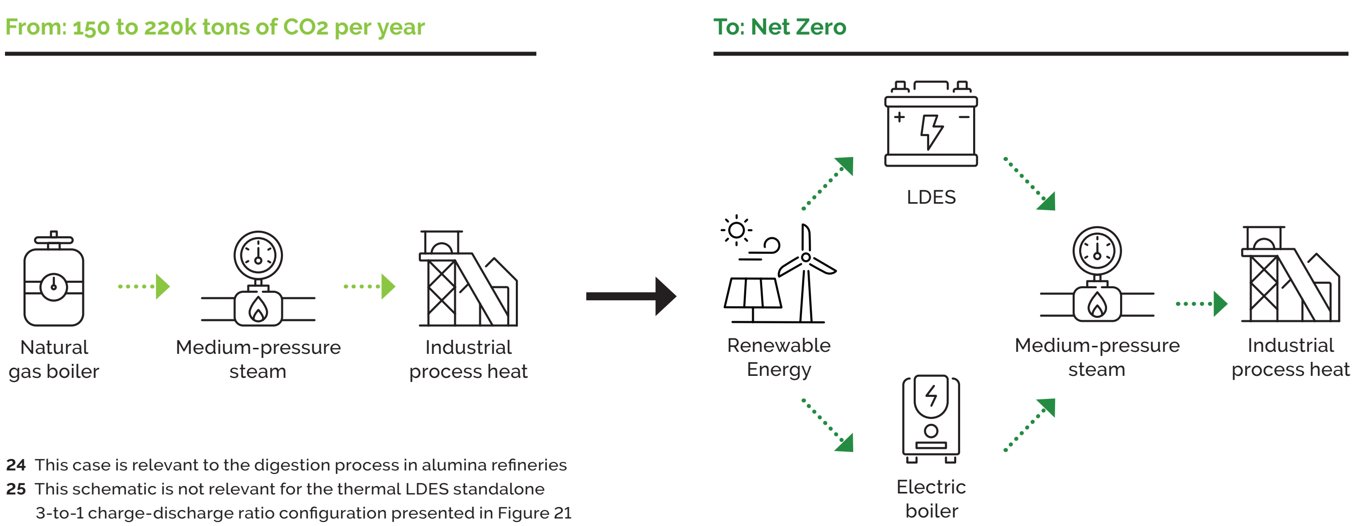
21 Heating, Ventilation, and Air Conditioning systems

22 For example, if an outage were to cause a chemical to cool and solidify inside piping and cause permanent damage

23 Meaning, in this analysis, thermal LDES has a 1-to-1 charge-discharge ratio; in some cases, thermal LDES technologies can be configured with higher charge-discharge ratios, e.g., 2-to-1 or 3-to-1 ; see Figure 21 for a thermal LDES standalone 3-to-1 charge-discharge ratio configuration that incurs a 15% higher capex

FIGURE 17

LDES solution for easy to electrify heat (food/chemicals)[24, 25]



24 This case is relevant to the digestion process in alumina refineries

25 This schematic is not relevant for the thermal LDES standalone 3-to-1 charge-discharge ratio configuration presented in Figure 21

This is especially the case when temperatures outside the operational range of high-temperature heat pumps (>100-150°C) are required. Both e-boilers and electric heat pumps are readily available.

Due to the high lost load costs, there is potential for a complementary relationship between on-site thermal energy storage technologies and front-of-the-meter, 100+ hour electric LDES technologies in a scenario where grid outages become more frequent and longer in duration due to climate change and aging infrastructure.

VALUE PROPOSITION AND FEASIBILITY

The economics of solutions leveraging LDES to electrify processes are primarily contingent on electricity costs – price volatility and availability of dynamic price signals – and avoided lost load costs.

In many applications, LDES can enable electrification of low-to-medium temperature steam and hot air at lower cost than other alternatives. Additionally, in many applications, LDES solutions are ready to be implemented sooner than other technologies.

LDES improves electrification economics by decreasing the cost of abatement by 10% to 20% compared to a scenario where LDES is not utilized.

Project economics are most sensitive to four key variables: lost load cost savings (related to outage count and duration); natural gas prices; carbon taxes; and bill savings (tied to grid volatility). Increasing any of these variables would enhance LDES feasibility in the future, reducing cost of abatement by ~10-65%.

SMRs could be a feasible alternative for this segment in the future, assuming the technology achieves anticipated cost reductions and commercialization timelines.

Nearer term, however, thermal energy storage technologies appear to be the most feasible and cost-effective solution for decarbonized heat in the "Easy-to-electrify" heat segment with their capability to both provide heat and firm intermittent renewables supply.

GLOBAL RELEVANCE

LDES presents economically attractive opportunities in countries with industry that requires low-to-medium temperature heat, albeit still with a cost of abatement to overcome.

This includes low-to-medium temperature heat demand in, for example, chemical, food, paper, and several 'other industrial' segments highlighted in Figure 9. These segments' total energy demand (including electricity and heat) account for up to 41% of global industrial emissions.

In particular, LDES improves the economics – through avoided lost load costs in regions with very long outages (for example, countries with unreliable grids like South Africa) – of storing electricity/heat for up to 100 hours.

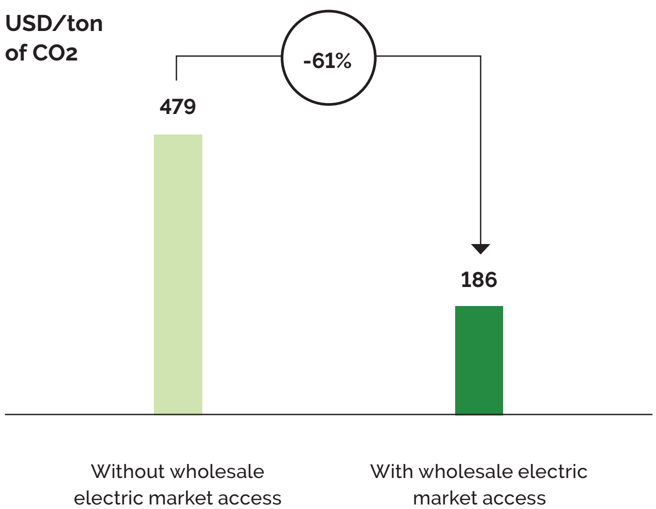
LDES economics are also strong in regions where the technology can mitigate high carbon taxes and high natural gas prices, and where LDES maximizes bill savings due to high and volatile power prices.

High natural gas prices and carbon taxes along with comparatively low electricity prices in the UK make electrification there particularly economically attractive, for example. The country's high electricity price volatility and the potential for high bill savings add to LDES's economic attractiveness.

Access to wholesale instead of retail electric prices lowers the final cost of abatement by 60% to 186 dollars per ton of carbon abated, see Figure 18. This is because higher volatility for wholesale versus retail prices enables the LDES resource to provide greater value through taking advantage of time-based arbitrage of wholesale power prices.

FIGURE 18

Cost of abatement sensitivity on wholesale electricity market access – Food, United States[26]

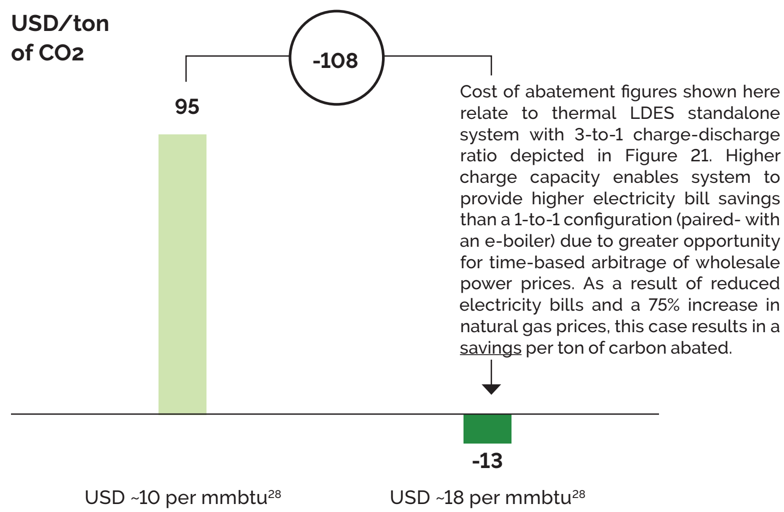


26 Overall cost of abatement figures shown here relate to Figure 22 and Figure 23

Source: Roland Berger

FIGURE 19

Cost of abatement sensitivity on natural gas price – Chemicals, Germany[27]



27 Overall cost of abatement figures shown here relate to Figure 21
28 USD per mmbtu natural gas prices are 2023 starting points, escalated over time

Source: Roland Berger

Economics of electrification with LDES are sensitive to natural gas prices due to avoided natural gas expenses. At a natural gas price of ~10 dollars per mmbtu, final cost of abatement for a thermal LDES standalone configuration is 95 dollars per ton of carbon abated. However, at a 75% higher natural gas price of ~18 dollars per mmbtu, the result is instead a savings of 13 dollars per ton of carbon abated. For details, see Figure 19.

ENABLERS

Costs of switching energy and aversion to change will prove key barriers to LDES. This is especially the case in regions where electrification will prove expensive due to the relatively high cost of electricity compared to conventional fuels, and where infrastructure upgrade costs are elevated.

In some industries, industrial producers may be able to pass on the increased cost of decarbonizing via electrification to their customers who are willing to pay a "green premium." Obviously, establishing the equivalent of a carbon tax would also provide a similar incentive for decarbonization. Additionally, policy that establishes dynamic price signals is a key enabler to improve LDES economics (critical to bill savings).

CASE STUDY: CHEMICALS

Electrifying thermal energy for medium-temperature steam from a natural gas boiler (grid connected)

The case: Brownfield development of an e-boiler paired with thermal LDES[29] to serve the heat needs of a chemicals plant in Germany with 400°C, 200 bar steam demand.

Status quo: The plant produces steam using a natural gas boiler (100 MWt demand). See Appendix 4 for details.

LDES solution: Steam production is electrified with an 100 MWt e-boiler, with a 100 MWt, 24-hour thermal LDES to provide reliability and electricity load shifting. Storage of heat yields the highest savings for facilities electrifying heat via electric boilers, as opposed to storage of power only (prior to producing heat).

Emissions abatement: The plant is able to abate 100% of scope 1 emissions related to heat demand, equal to 3 million tons of CO_2 over 20 years (or 154k tons CO_2 p.a.).

Economics: LDES supports electrification and decarbonization of the chemical plant. The result is a 30% increase in opex. The cost of abatement using only an e-boiler is USD 240/ton CO_2 abated, but LDES reduces that cost by USD 31/ton CO_2.

- The largest cost contributor is the higher cost of electricity relative to natural gas
- USD 144/ton CO_2 carbon tax savings mitigate some of the costs associated with electrification
- By shifting electric load, LDES helps reduce the electricity bill by USD 141/ton CO_2 (28% savings). It also allows the plant to avoid USD 13/ton CO_2 lost load costs associated with grid outages (VOLL: USD 5/kWh). Higher charge capacity of 3-to-1 system depicted in Figure 21[29] enables system to provide higher electricity bill savings than a 1-to-1 configuration (paired with an e-boiler), incurring a capex that is only 15% higher. Due to greater opportunity for time-based arbitrage of wholesale power prices using higher charge capacity, bill savings rise to USD 261/ton CO_2 (51% savings).

Outlook: The costs of electrification with LDES improve by 13% through 2040, as fuel prices and carbon taxes escalate and as LDES costs decline. The benefit from thermal LDES load-shifting also improves as LDES technology costs decline, the technology scales and electricity prices become more volatile.

Geographies: The highest LDES-related savings occur in countries with unreliable grids, volatile electricity prices (wholesale or large differentials in TOU utility rates), high natural gas prices, and high carbon prices.

- Of the countries assessed for this report, LDES leads to the highest bill savings in Germany and the United States, where customers are exposed to wholesale price volatility and time-of-use rates respectively
- In the United Arab Emirates, by contrast, there are no bills savings due to very little arbitrage opportunity in electric rates

29 Figure 20 shows thermal LDES paired with an e-boiler and Figure 21 shows thermal LDES standalone, relating to sensitivity shown in Figure 19. Thermal LDES system shown in Figure 20 has a 1-to-1 charge-discharge ratio while system shown in Figure 21 has a 3-to-1 charge-discharge ratio

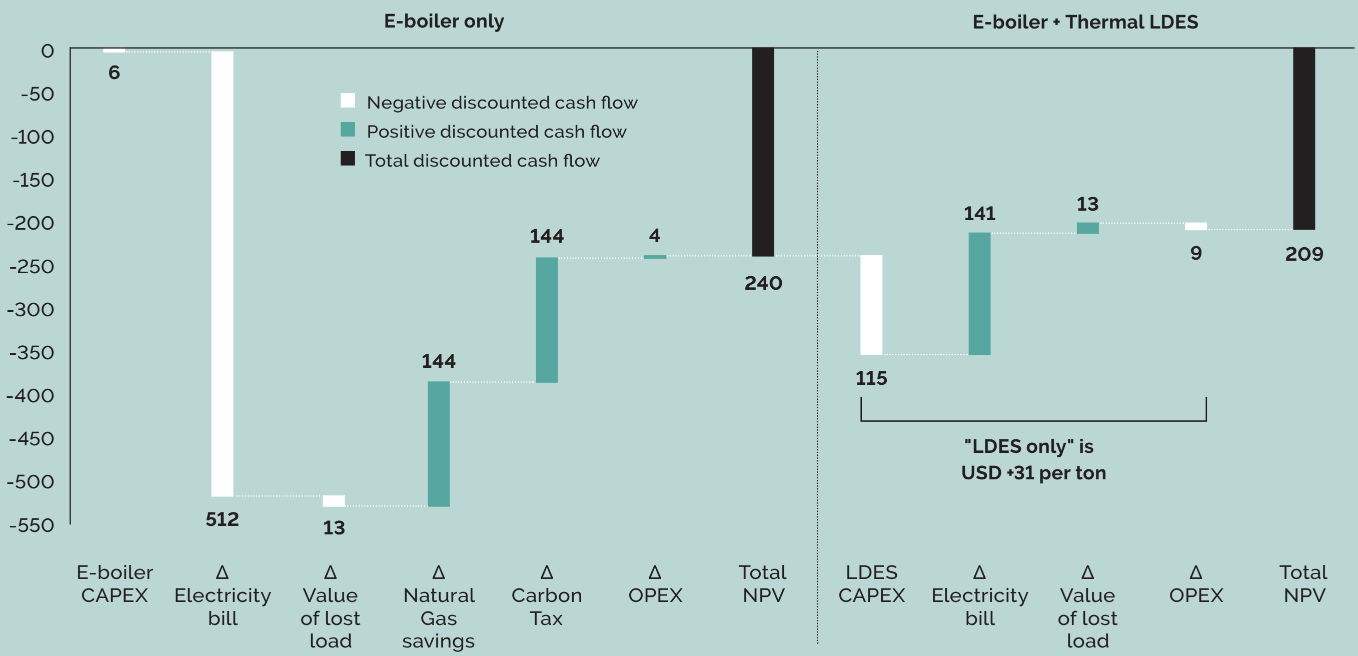
- Electricity price volatility is often found in countries with higher renewables penetration, evidenced by higher price volatility in Germany and the United States compared to the United Arab Emirates and South Africa

Alternatives: Thermal LDES supporting an e-boiler is currently one of the most economic options for decarbonizing medium-temperature steam. Depending on gas and electricity prices, a TES (without an e-boiler) could even be a better economic option than staying on gas, even without a carbon tax.

FIGURE 20

Case study: Chemicals, Germany – e-boiler vs. e-boiler and thermal LDES, 2030

[Real 2023 USD/ton CO2 abated]



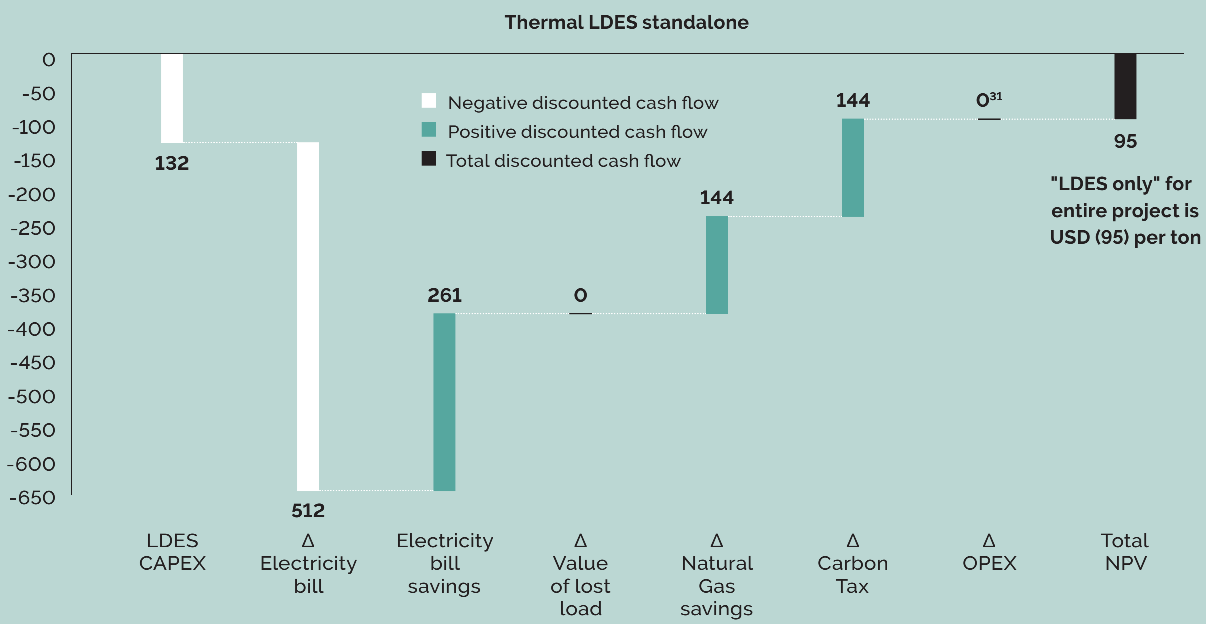
Source: Roland Berger

- Green hydrogen boilers are not currently economically feasible due to high green hydrogen prices in Germany (~7 USD/kg). However, these are expected to improve dramatically
- SMRs are economically competitive but not yet commercially available, and subject to regulatory, siting and customer acceptance constraints
- Other alternatives, including CCUS and lithium-ion batteries, can contribute to decarbonization but face feasibility and supply chain challenges

FIGURE 21

Case study: Chemicals, Germany – thermal LDES standalone, 2030[30]

[Real 2023 USD/ton CO2 abated]



30 Relates to sensitivity shown in Figure 19

31 Delta OPEX value rounded from USD (0.084) per ton to 0, meaning there was a small net spend on OPEX relative to status quo

Source: Roland Berger

CASE STUDY: FOOD

Electrifying thermal energy for low-temperature steam from a natural gas boiler (grid connected)

The case: The electricity and heat demand (and scope 1, 2 emissions) at a food plant in California[32], United States, with low-temperature, low-pressure steam demand. Brownfield development of an e-boiler with thermal LDES.

Status quo: The plant sources electricity from the grid (38 MWe) and produces steam using a natural gas boiler (68 MWt). See Appendix 4 for details.

LDES solution: Steam production is electrified with a 68 MWt e-boiler and a 68 MWt, 24-hour thermal LDES to provide reliability and electricity load shifting. For facilities electrifying heat via e-boilers, storage of heat yields the highest savings, as opposed to storage of power only (prior to producing heat).

Emissions abatement: The plant is able to abate 100% of scope 1 and 2 emissions related to heat and electricity demand, equaling 4.4 million tons of CO_2 over 20 years (or 220k tons CO_2 p.a.).

Economics: LDES supports electrification and decarbonization of the food plant. The result is a 110% increase in opex. The cost of abatement is USD 582/ton CO_2 abated, but LDES reduces that cost by USD 103/ton CO_2.

- The largest cost contributor is the higher cost of electricity relative to natural gas
- USD 33/ ton CO_2 carbon tax savings do not cover the additional costs
- By shifting electricity load, LDES helps reduce the electricity bill by USD 115/ton CO_2 (19% savings) and allows the plant to avoid USD 26/ ton CO_2 lost load costs associated with grid outages

Outlook: The costs of electrification improve by 11% through 2040, as fuel prices and carbon taxes rise. The benefit from thermal LDES load-shifting also improves as LDES technology costs decline, the technology scales and electricity prices become more volatile.

Geographies: The highest LDES-related savings occur in countries with unreliable grids, volatile electricity prices (wholesale or large deltas in TOU utility rates), high natural gas prices, and high carbon prices.

- LDES offers the highest bill savings in Germany and the United States, where customers are exposed to wholesale price volatility and time-of-use rates
- In the United Arab Emirates, by contrast, there are no bill savings due to very little arbitrage opportunity in electricity rates

Alternatives: Thermal LDES supporting an e-boiler is currently one of the most economic options for decarbonizing low-temperature steam where electric heat pumps are not feasible.

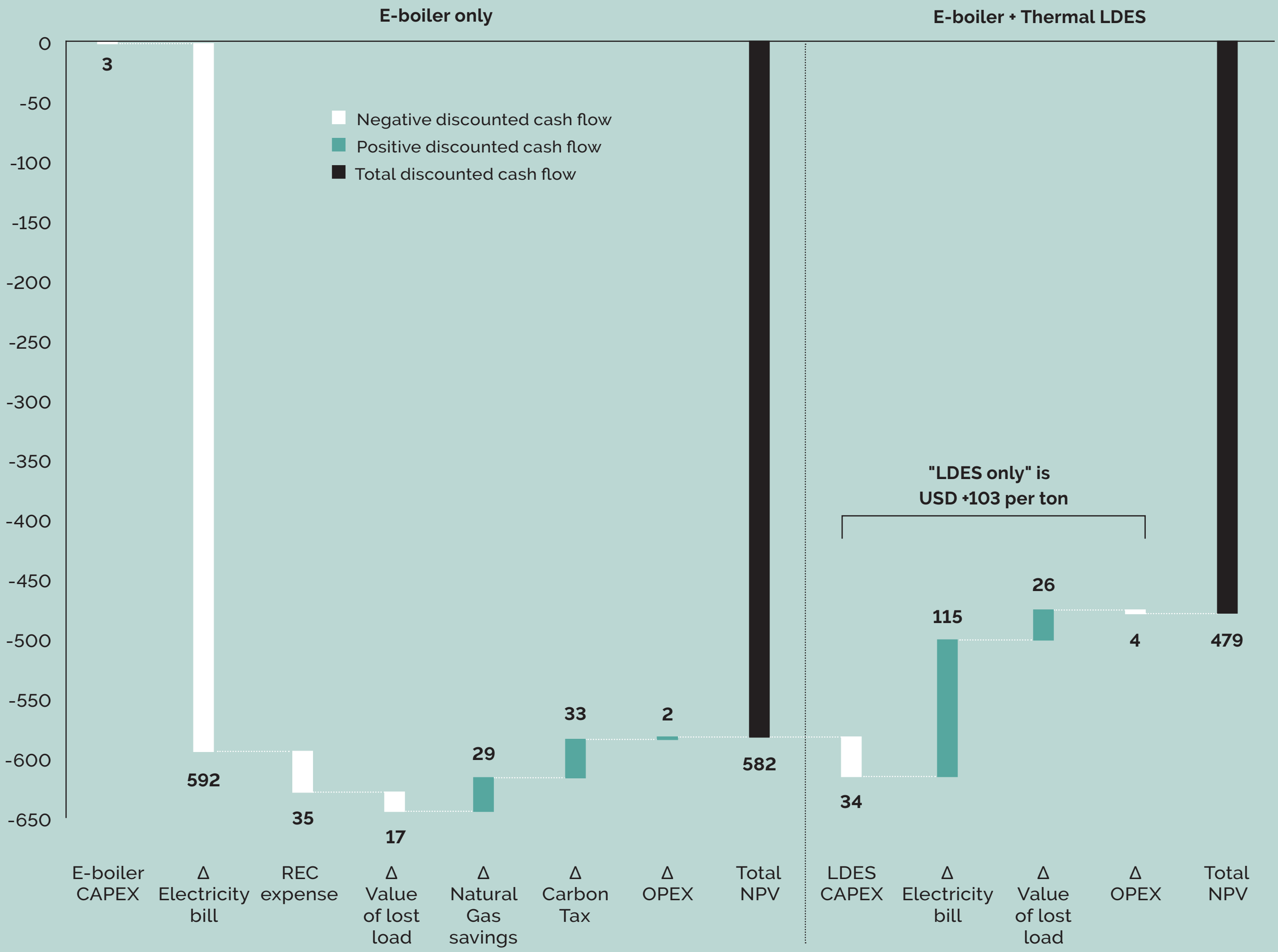
- Standalone e-heat pumps have the strongest economics in geographies with climates that impair the performance of heat pumps (for example, cold weather climates); electric boilers paired with LDES represent the next best alternative
- Other alternatives, as described in the chemicals case study, also exist but face cost, feasibility or commercialization challenges

32 As a result of this case being in California, cost of abatement is higher than in other locations (California has among the highest electricity costs in the United States)

FIGURE 22

Case study: Food, United States – e-boiler vs. e-boiler and thermal LDES, utility tariff, 2030

[Real 2023 USD/ton CO2 abated]

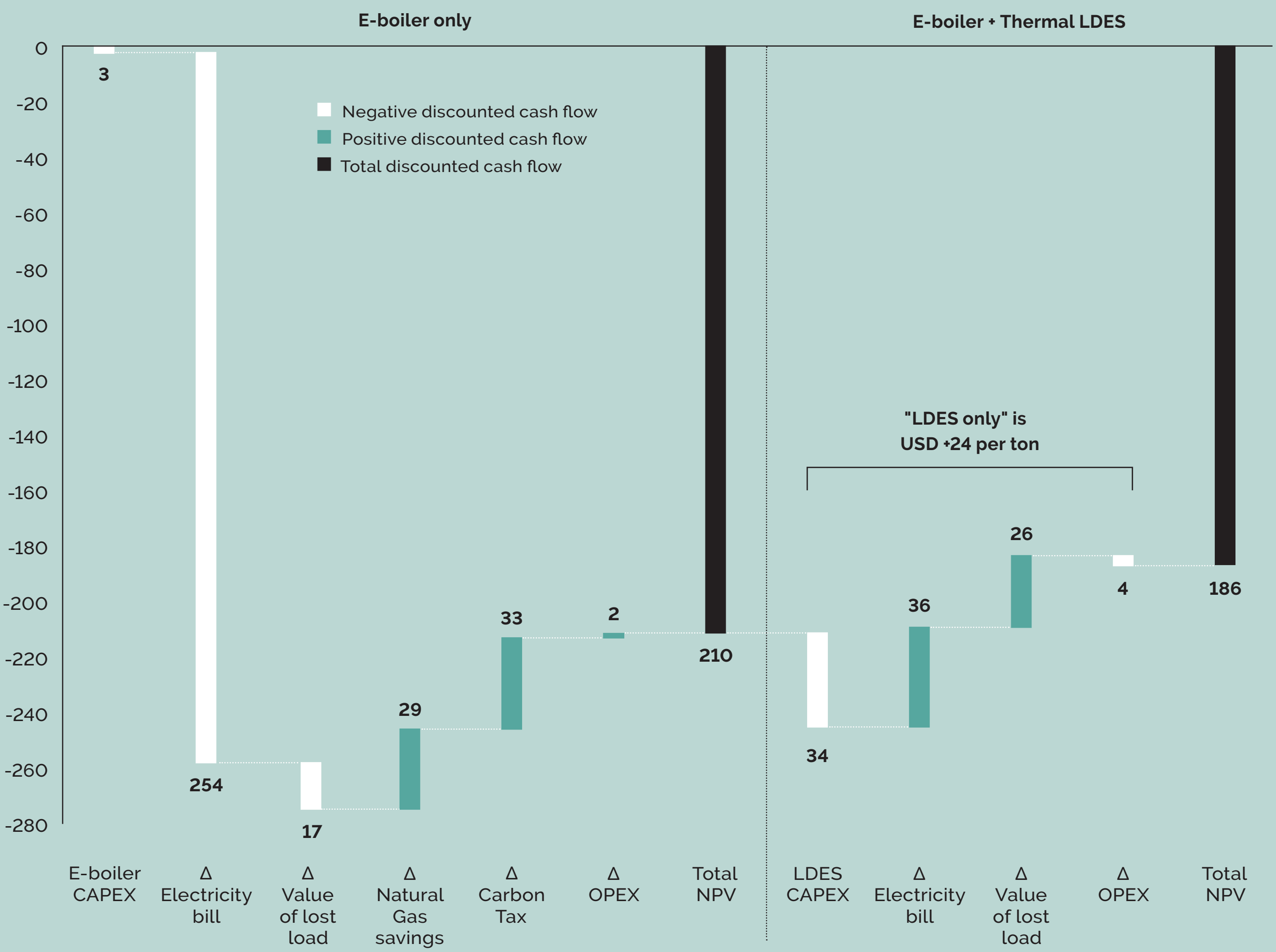


Source: Roland Berger

FIGURE 23

Food, United States – e-boiler vs. e-boiler and thermal LDES, wholesale 2030[33]

[Real 2023 USD/ton CO2 abated]



33 Relates to sensitivity shown in Figure 18

Source: Roland Berger

05 "Hard-to-electrify" heat

LDES offers game-changing longer-term opportunities in steel and cement

KEY FINDINGS

LDES can already support partial abatement in high-emitting and hard-to-abate industrial sectors such as steel and cement, and has the potential to support net-zero energy

1. The large, high-emitting steel and cement sectors are considered "hard-to-electrify" due to their high temperature requirements (>1,000°C), the need for radiative heat and integration requirements

2. While cost barriers exist, medium-term opportunities for thermal LDES technologies could result in a significant reduction of global emissions

3. Longer-term opportunities for LDES applications require technical improvements and greater scalability but could support complete fuel switching as they focus on the most energy- and emissions-intensive processes

OVERVIEW AND APPLICATIONS

Together, the steel and cement sectors account for 7% of global emissions (25% and 10% of global industrial emissions, respectively), making them a policymaker focus.

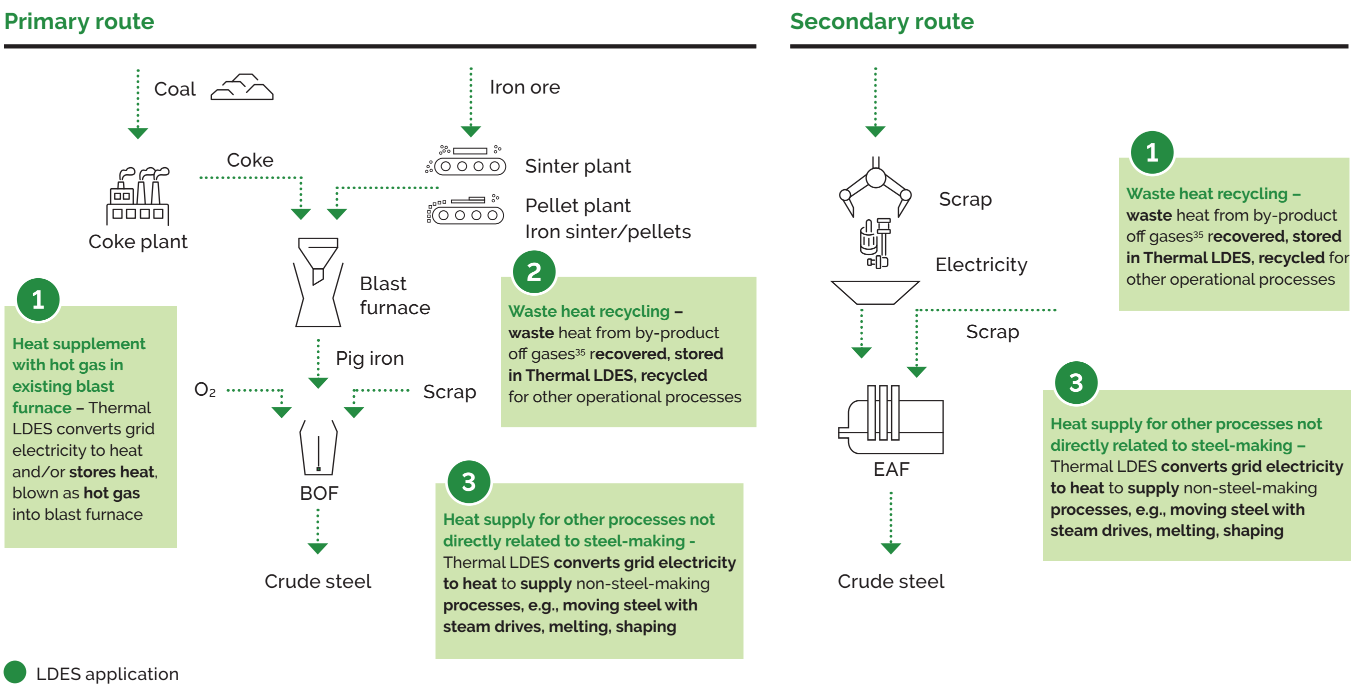
The sectors are "hard-to-electrify", meaning they cannot readily be electrified due to high temperature requirements (>1,000°C), the need for radiative heat and process integration requirements. High costs and a potential lack of scalability across steel and cement plants are another barrier.

Current LDES technologies can contribute to limited decarbonization of steel and cement in the medium term (the next five years) through waste heat recovery and preheating[34]. However, they have far greater decarbonization potential in the long run (10 years+) as costs decline and integration barriers are reduced. LDES could ultimately support full energy decarbonization of cement through the electrification of kilns.

34 For example, inlet material for steel

FIGURE 24

Overview of potential LDES applications in existing steel-making routes (simplified)



35 By-product off gases (coke oven gas, blast furnace gas, basic oxygen furnace gas) are released as part of the chemical process in steel manufacturing and contribute a large portion of steel-making CO2 emissions

Source: Roland Berger

STEEL: VALUE PROPOSITION AND FEASIBILITY

Thermal LDES could support incremental abatement in both major steel-making routes – the primary route using blast furnaces (BOF), which accounts for ~75% of total steel production, and the secondary route using electric arc furnaces (EAF).

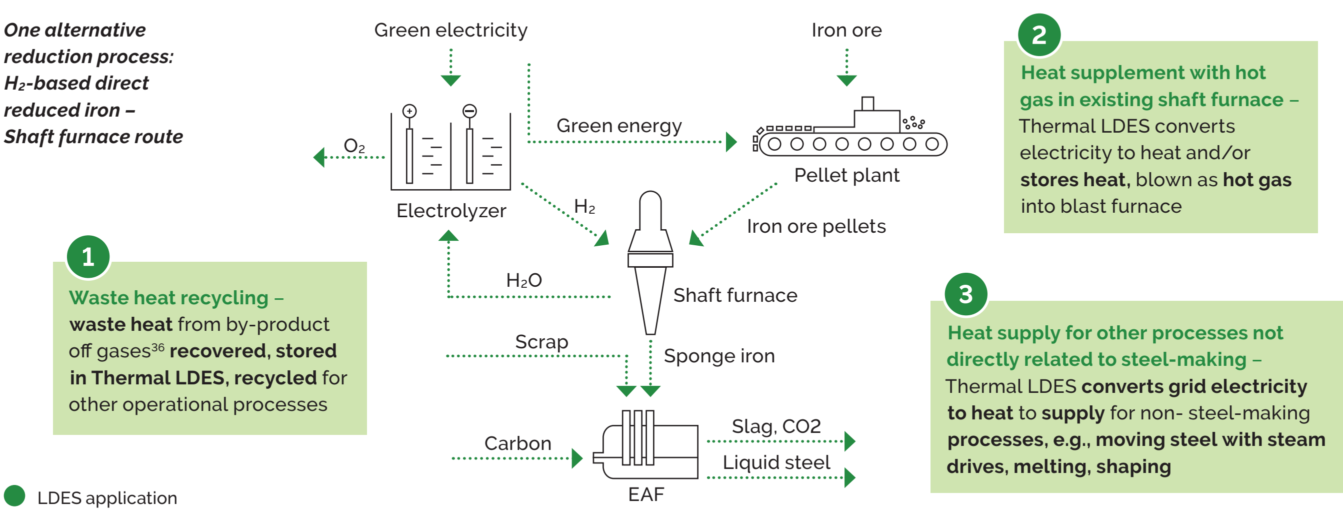
Applications in the "hard-to-electrify" steel-making process are in early pilot or conceptual phase, with commercialization expected in the 2030s. They include waste heat recovery and supplementing heat supply with hot gas. Thermal LDES can also support electrification of lower-temperature heat applications (as discussed in Chapter 4) outside of core steel-making. FIG. 24

LDES technologies also offer attractive solutions in driving partial decarbonization of the steel-making processes beyond the two routes. Depending on the decarbonization pathway, they can continue to provide supplemental heat in furnaces, recycle waste heat and supply heat for other processes.

Several other decarbonization technologies exist in this segment. The two main alternative pathways to decarbonize steel production are CCUS for BOF or direct reduced iron (DRI). The DRI process uses natural gas or hydrogen to reduce iron ore pellets to direct reduced iron (or sponge iron) which is then fed into an electric arc furnace. Most technologies in these areas, including the use of hydrogen, are not well developed but have considerable potential. For example, CCUS systems can capture steel plant emissions and inject CO_2 into the ground. However, they cannot achieve full decarbonization as the CCUS process captures most (90%) but not all CO_2 emissions.

FIGURE 25

Overview of potential LDES applications in a decarbonized steel-making route (simplified)



36 By-product off gases (coke oven gas, blast furnace gas, basic oxygen furnace gas) are released as part of the chemical process in steel manufacturing and contribute a large portion of steel-making CO2 emissions

Source: Subject-matter experts: industry and LDES; academic studies; Roland Berger

STEEL: OUTLOOK FOR LDES TECHNOLOGIES

As well as standalone use, LDES can improve the economic performance of complementary decarbonization technologies if integrated into steel plant design. For example, LDES can play a significant, complementary role in the green hydrogen-based DRI process. Here, thermal LDES has the potential to recover waste heat for other operations, supplement heat with hot gas in the shaft furnace and supply heat for non-core steel-making processes. FIG. 25

37 Annual CO2 emissions at the facility are approximately 12.6 million tons per year.

38 https://www.process-worldwide.com/tata-steel-implements-thermal-energy-storage-demo-project-a-595990/

STEEL APPLICATIONS

Waste heat recovery:

LDES solution: Waste heat is recovered, stored in thermal LDES and recycled for other lower-temperature applications such as preheating scrap (reduces the level of heat required for scrap melting in the electric arc furnace). Waste heat recovery eliminates some emissions and can generate electricity for the plant.

Emission and economic impact: Thermal LDES offers an attractive opportunity as the steel-making process is extremely demanding regarding the amount and temperature of required heat, and that up to 50% of input energy could be lost during the process. An early-stage project by Tata Steel demonstrates that "a 500 MWht thermal LDES can yield annual savings of 2.3 million GJ of natural gas… and 130,000 tons[37] of emitted CO2."[38]

Outlook: Steel-makers are already working with thermal LDES providers on early stage pilots and demonstrations through 2030 for waste heat recovery; scaling of waste heat recovery technology likely to occur post 2030.

Preheating processes using thermal LDES:

LDES solution: Thermal LDES converts electricity to heat and then stores this heat before blowing it directly into the blast furnace.

Emission and economic impact: The blast furnace operation accounts for 60-75% of emissions in the overall steel-making process. Heat from thermal LDES can reduce use of fuel and emissions incrementally (total achievable reduction of less than 5%), limited by minimum required levels of coke and coal reductant for chemical reactions.

Outlook: As LDES technologies will need to be capable of reaching extremely high temperatures, demonstrations and pilots will likely only be ready in the medium term, with commercialization in the next 10 years.

CEMENT: VALUE PROPOSITION AND FEASIBILITY

Like steel, cement decarbonization is challenging due to the need for extremely high production temperatures, and the energy-intensive calcination process (which contributes more than 50% of cement emissions).[39] For example, limestone, clay, iron ore and fly ash need to be heated to more than 1,400°C in a kiln to produce clinker, which is mixed with limestone and gypsum to produce ground cement.

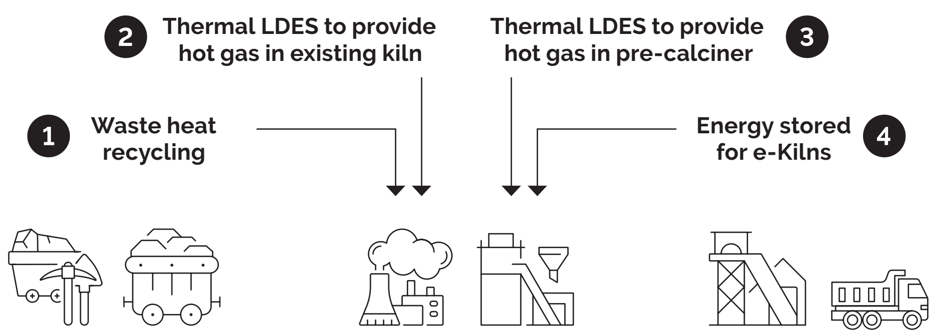
LDES applications in the sector require technical improvement to meet these challenges. However, they have enormous potential as they focus on the most energy- and emission-intensive parts of the process – the preheater/pre-calciner and kiln (FIG. 24). LDES technologies can also support decarbonization of process heat by providing supplemental heat or electrification of cement kilns.

Beyond cement, LDES providers are also exploring other rapidly growing, high-temperature materials-processing segments such as lithium and bauxite ore processing.

39 Calcination process discussed in this section is relevant to alumina refining sector

FIGURE 26

Overview of potential LDES applications in cement



	Raw material preparation into raw mill	Preheater/pre-calciner and kiln produce clinker	Cement production from clinker and final logistics	Total
Energy [MJ/t]	5%	80%	15%	100% 3,751
CO2 [kg/t]	3%	53% Calcination process 34% Fossil fuels	10%	100% 956

Source: Desk research, Roland Berger

CEMENT APPLICATIONS

Waste heat recovery:

LDES solution: Waste heat is recovered, stored in thermal LDES and recycled for other, lower temperature applications or electricity generation. Similar to steel, this application could reduce incremental emissions in the process.

Emission and economic impact: Cement production is also a heat- and emission-intensive process, hence waste heat recovery is a promising opportunity for thermal LDES. The impact of this application will vary by plant and by country, as waste heat recovery infrastructure advances and mandates are different across cement-producing countries.

Outlook: LDES providers are conducting early pilots and demonstrations through 2030.

Hot gas supply in existing kiln and pre-calciner:

LDES solution: Thermal LDES converts electricity to heat, stores heat and then blows it as hot gas into a kiln or pre-calciner.

Emission and economic impact: If commercialized, this application could be extremely impactful as the kiln and pre-calciner consume ~80% of total cement process energy requirements, and account for ~87% of total process emissions.

Outlook: This application has a medium-term potential for use in pre-calciners and long-term for use in kilns.

- For kilns: Considerable technological improvement is required to meet the extremely high heat requirements in the kiln. With most LDES players still discussing and examining the application with cement producers, commercial implementation will most likely occur beyond the current decade.
- For pre-calciners: The lower temperature of required heat (~900°C) in this application is achievable in the medium term, with a commercial timeline of post 2030. Pilots can be done in with necessary technology and plant integration.

Energy storage for e-kiln:

LDES solution: LDES technologies store grid electricity to operate electric kilns.

Emission and economic impact: This technology can provide zero-emission process heat for kilns and other applications in the materials processing industry up to 1,400-1,500°C.

Outlook: This application is still largely in the conceptual phase. Significant development will be required to make this technology viable in the long term due to the extremely high energy requirement of electric kilns.

GLOBAL RELEVANCE

Global steel and cement production is geographically widespread. The top 5 steel producers by production volume are China, India, Japan, the United States, and Russia. The top 5 cement producers are China, India, Vietnam, the United States, and Turkey. Propensity to decarbonize, as well as baseline emissions, vary across countries. Steel and cement emissions impact embodied carbon across the global economy.

ENABLERS

Key enablers in the segment are mainly policy based. Policies such as carbon pricing and greenhouse gas targets can incentivize or otherwise require cement and steel makers to decarbonize. The commoditized nature of products from these sectors therefore make it important to financially support decarbonization and/or implement carbon border adjustment mechanisms.

In addition, as electrification in these sectors increases, it will be important to highlight the need to shift electricity loads and ensure electricity grids can handle the dramatically increased electrical loads through dynamic pricing and network planning.

Players in the sectors will look to a suite of technologies, including LDES, to achieve these goals, and will likely require policy-based support to implement them. Specific policy for LDES technologies for high-temperature cement and steel will therefore also need to be developed. Sandboxes and R&D support can enable early demonstrations of both LDES and complementary technologies such as e-kilns.

In addition to policy, there is a need to communicate and demonstrate the LDES value proposition to industry, through early engagement and partnerships. Shared learnings within industry can help to accelerate decarbonization and the role of LDES.

06 Supporting policy mechanisms

Policy solutions for LDES need to encourage adoption and competitiveness

KEY FINDINGS

Long duration energy storage technologies require policy support to ensure that industrial users capture the full value of these resources

1. The appropriate policy solution for LDES technologies to decarbonize industry varies by industry sector. Solutions fall into three categories: long-term market signals; revenue mechanisms; and technology support and enabling measures

2. Off-grid applications are already cost effective and require the least support relative to other applications

3. On-grid heat applications that can be electrified today and hard-to-electrify sectors require policies that incentivize industrial customers to electrify their fossil-fueled heat processes and ensure that electric grids can support larger electricity loads

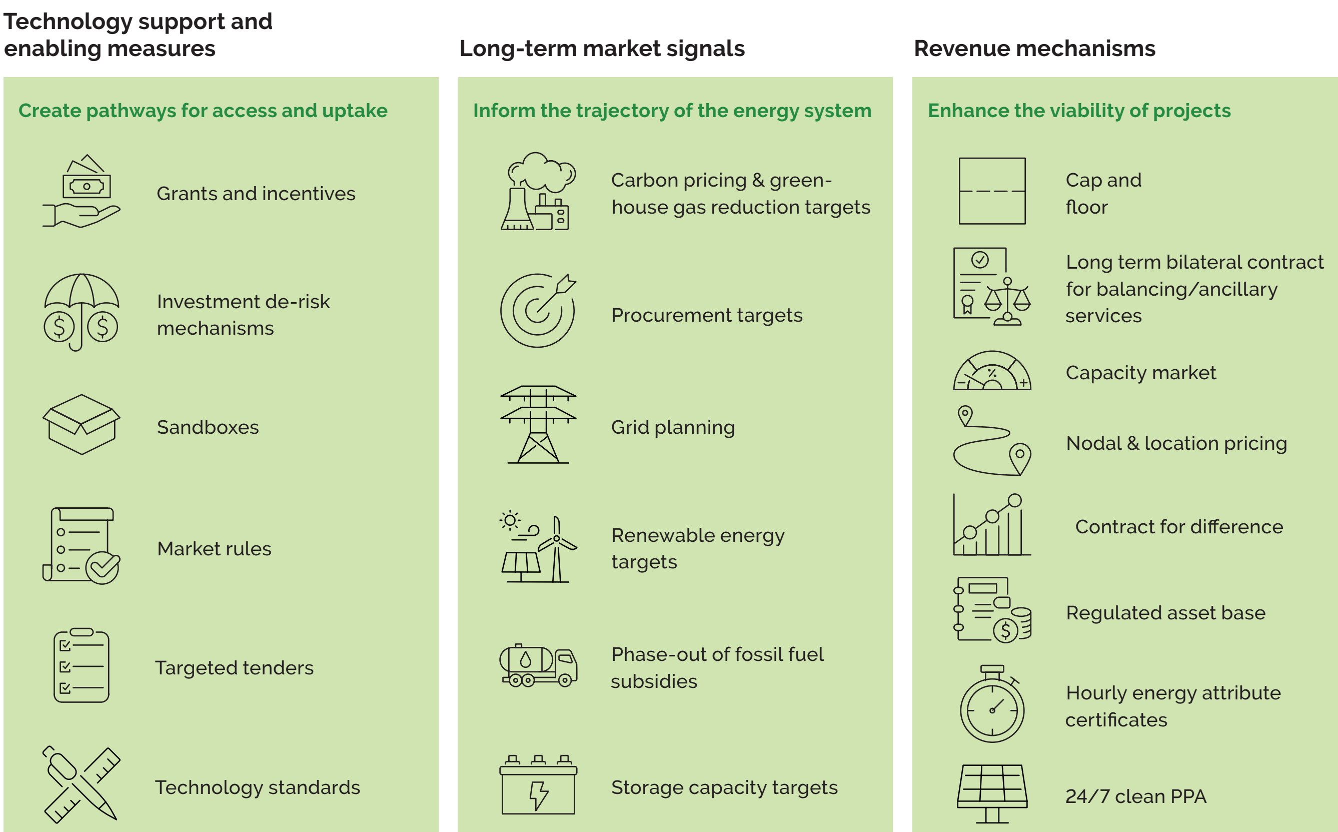
POLICY SOLUTIONS

Accelerating the adoption of LDES technologies for industrial decarbonization requires a broad range of policy solutions. To reflect this, the Long Duration Energy Storage Council has developed a policy framework. It consists of three policy enabling tiers covering long-term market signals, revenue mechanisms and direct technology support and enabling measures. FIG. 27

Each of the three policy enablers contains a subset of levers that will support industrial decarbonization applications. Their relative importance to individual sectors and regions depends on decarbonization ambitions, market conditions, barriers to adoption and technology readiness. FIG. 28

FIGURE 27

Overview of LDES policy framework[40]



40 For further detail, see LDES Council's "Journey to Net Zero" report: https://ldescouncil.com/assets/pdf/journey-to-net-zero-june2022.pdf

Source: LDES Council

FIGURE 28

Relative importance of LDES policy enablers by sector

	LDES policy enablers			
	Long-term market signals	Revenue mechanisms	Technology support	Detail
Off-grid electric	■□□□	□□□□	□□□□	• Elimination of government support for fossil fuels • Fossil fuel support undermines decarbonization and LDES economics
Grid-connected electric	■■□□	■■■■	□□□□	• Wholesale market access with nodal & locational pricing • Contract for differences renewable PPAs • Market revenue streams to improve LDES economics
"Easy-to-electrify" heat	■■■■	■■■□	□□□□	• Transparent electricity price signals for load shifting • Contract for differences renewable PPAs • Emissions reduction mandates and carbon prices • Market revenue streams to improve LDES economics • Grid planning to support large, newly-electrified loads
"Hard-to-electrify" heat	■■■■	■■■□	■■■■	• Support enabling development and demonstration of LDES technologies for high-temperature processes

Relative importance ■■■■ High □□□□ Low

Source: Roland Berger

OFF-GRID ELECTRIC

LDES is already an economically attractive decarbonization solution for off-grid industry that faces few barriers. Savings are achieved by substituting renewables and LDES technologies for diesel fuel.

Policy support in this sector should therefore be related to long-term market signals, specifically to eliminate government support for fossil fuels. Fossil fuel subsidies undermine the case for LDES because the cost-benefit analysis is highly sensitive to the price of diesel.

GRID-CONNECTED ELECTRIC

The most important levers for on-grid electricity applications are revenue mechanisms, as well as technology support and enabling mechanisms. Grid-connected electricity customers already respond to long-term price signals for the lowest cost electricity they can find. However, policy support is still needed to ensure access to cheap, decarbonized electricity, which is where nodal and locational pricing can be helpful.

'EASY-TO-ELECTRIFY HEAT' AND 'HARD-TO-ELECTRIFY HEAT'

Policy support could be most impactful in enabling LDES to support heat decarbonization. Policies can address industrial customers' propensity to electrify process heat and ensure that electric grids can handle the dramatically increased electrical loads from these processes.

First, industrial customers need to be motivated to decarbonize, they need transparent electricity price signals to demonstrate the value of load shifting to customers, and they need proof that LDES solutions are a feasible replacement to their incumbent (and trusted) fossil-fueled processes.

Policies to support the above include carbon pricing and greenhouse gas targets, nodal and locational pricing and sandboxes, or pilots and demonstrations. Given the price pressure due to the commodity nature of their products, they will also need contracts for differences, to ensure they are made whole for differences between renewable PPA and wholesale energy prices.

Policies will also need to encourage electric utilities and transmission operators to prepare for electrification of large industrial loads. They will need better grid planning – to ensure adequate network capacity and to integrate the required amount of carbon-free electricity – so that industrial customers are assured of reliable supply.[41]

Hard-to-electrify heat will also require technology support in the form of sandboxes and standards, given that LDES technologies for high-temperature cement and steel will need to be developed, demonstrated and implemented.

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41 LDES technologies can also support transmission network planning by reducing peak demand from large industrial load on the electric grid

Appendix

Appendix A:
Data centers

KEY MESSAGE AND SUMMARY

LDES enables data centers to optimize their use of renewable energy and enhance reliability

1. LDES technologies enable high load factor, grid-connected electric industrial facilities, specifically data centers, to decarbonize their electricity supply
2. When LDES is deployed in this manner, such facilities also benefit from improved reliability, whose value would otherwise not be enough to justify LDES capital costs
3. In geographies with very low cost renewable electricity, LDES is the lowest-cost option for firm, decarbonized electricity at data centers

OVERVIEW AND APPLICATIONS

LDES technologies support decarbonization of already electrified grid-connected facilities in two ways. First, by providing reliability, and second, by time-shifting renewable generation to enable a decarbonized electricity supply (and even a true 24/7 decarbonized electricity supply)[42], potentially also creating bill savings by capturing differences in hourly electricity prices (time-based arbitrage). This includes support for grid-connected facilities that are "islanded," which means they can turn their grid connection on or off, functioning as microgrids.

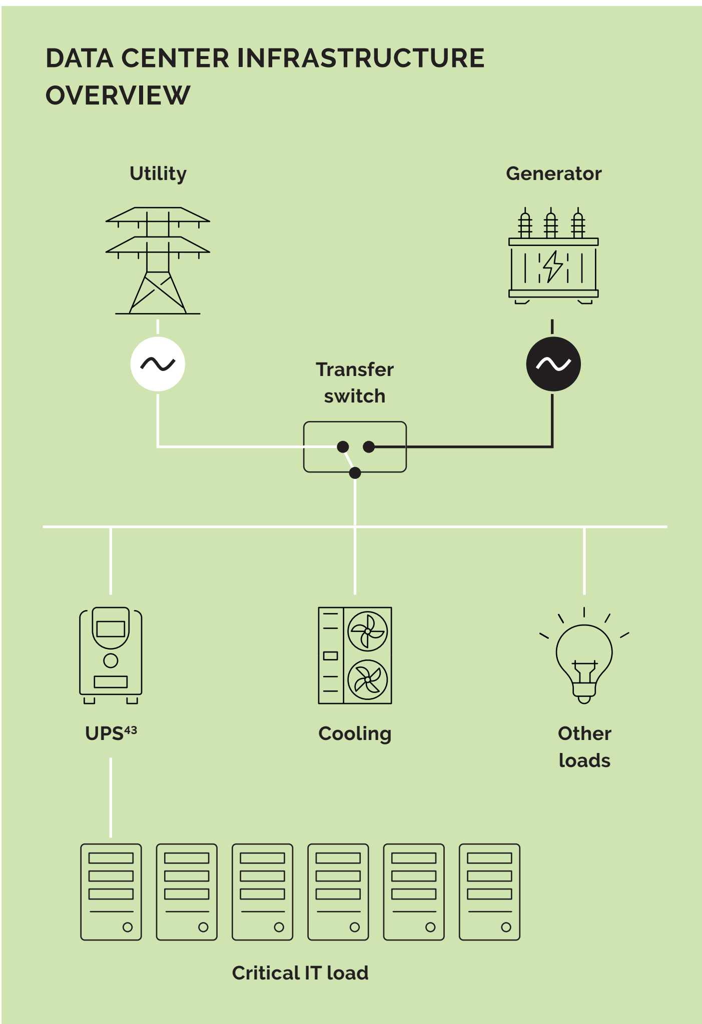
Data centers are a prime example of such electrified grid-connected facilities. They range in size from localized "edge" data centers with small electricity demands (100s of kWe) to hyperscale data centers with massive electricity demands (100s of MWe). Due to corporate commitments, data center providers will increasingly aim to not only satisfy decarbonized electricity demand but also meet true 24/7 time-matched decarbonized electricity demand.

Data center deployments and their corresponding electricity load are expected to drastically rise to support increasing data traffic from cloud computing, 5G communications, and artificial intelligence. Overall, data centers are expected to consume nearly 1,000 TWhe by 2025, a figure which is expected to triple by 2030. This trend will be especially pronounced in developing economies as they have been slower to adopt computing relative to industrialized economies. FIG. 29

42 The heat demand sectors highlighted in Chapter 4 that have already electrified operations fall into this category. Data centers are also included in it and present large, high load factor electricity demands along as well as having extremely high uptime requirements. This means they place a very high value on reliability of supply.

FIGURE 29

Overview of data center infrastructure



	Component	Description
Architecture	**Servers**	Engines of the data center – includes the processing and memory used to run the applications
Architecture	**Media storage**	Software designed storage technologies
Architecture	**Networks**	Includes the cabling, switches, routers and firewalls that connect the servers to each other and to the outside world
Support	**Security systems**	Includes environmental control systems like fire suppression, ventilation and cooling systems
Support	**UPS[1] transition systems**	UPS systems are short-term energy storage devices that are used to ensure uninterrupted data center operation
Support	**Backup power generators**	Provide an emergency or alternative power source when the main power source is interrupted

Potential LDES applications: UPS[1] transition systems; Backup power generators

43 Uninterruptible Power Supply

Source: Roland Berger

Today, data centers ensure reliability using diesel generators, presenting an opportunity for LDES to store cheap renewables power and discharge when required.

VALUE PROPOSITION AND FEASIBILITY

The ability of LDES to support decarbonization of grid-connected facilities depends on the availability of cheap renewables and required transmission infrastructure. In the case of reliability, the economics are not yet attractive. Generation for reliability has a very low capacity factor (for example, <1% capacity factor for a facility facing eight 10-hour outages per year). Given this, the volume of avoided diesel expense (purely for reliability) is lower than LDES capital costs and the costs associated with charging the LDES system with green power.

Renewable diesel and green H2 (fuel cell) are technically lower-cost decarbonization alternatives for reliability only. However, both currently face feasibility roadblocks: they are scarce (due to competition with higher value transportation applications) and come at a significant price premium.

LDES is economic for decarbonization of electricity supply, provided renewable electricity prices result in savings high enough to offset LDES capital costs.

In summary, LDES is the lowest cost decarbonized solution today. However, LDES paired with renewable power faces a future threat from SMRs given their ability to provide reliable carbon-free on-site power (although SMRs face feasibility challenges, as mentioned earlier in this report). If already installed, then the reliability benefits of LDES are a bonus and enable full decarbonization (assuming grid outages occur).

GLOBAL RELEVANCE

In places where renewables costs are low, LDES is the lowest cost of abatement option overall.

Data center providers already site facilities in locations with lower power prices, meaning the attractiveness of LDES to support decarbonization of electricity supply and reliability is particularly relevant.

ENABLERS

LDES adoption will be in large part driven by market influences, with many data center providers having made aggressive decarbonization commitments that necessitate LDES. Additionally, increased regulation for high data center reliability in light of growing risks to grid reliability would drive LDES deployment at data centers.

Policy restricting data center deployment could pose a potential risk by limiting data centers from being established in areas with low-cost renewables.

Appendix B:
Analytical approach

Roland Berger developed an analytical model that estimated the impact LDES technologies can have on off-grid and process heating applications. At a high level, the tool estimates customers' status quo energy costs and emissions levels and compares them against energy costs and emissions levels after integrating LDES.

For Chapter 3, the comparison is between the cost and emissions from using diesel for plant operations and equipment, and renewable generation firmed by LDES.

For Chapter 4, the comparison is between the cost and emissions of natural gas-fueled process heating, and an electrified solution supported by LDES.

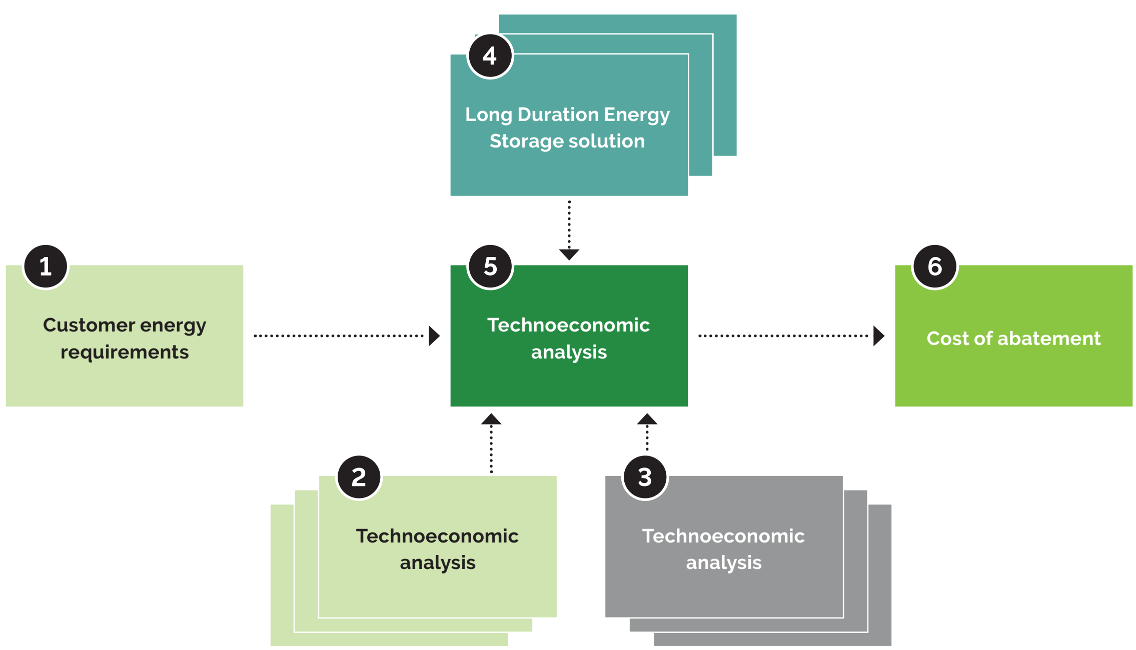
Roland Berger ascribed a positive cost of abatement when the cost to decarbonize is greater than the status quo, and a negative cost of abatement when the opposite is true.

ANALYTICAL OVERVIEW

The analytical model used for this report evaluated customer energy needs, customer energy costs and billing factors, and the potential financial and emissions impact of utilizing LDES technologies by simulating the operation of these resources based on their unique operating parameters. FIG. 30

FIGURE 30

Detailed schematic of analytical model



Source: Roland Berger

1. Customer energy requirements

The tool incorporates inputs and assumptions related to customer energy needs including the following:

- Load shape
- Baseline demand in MW
- Annual energy consumption (in gallons of diesel fuel, MCF of natural gas or MWH)
- Required service level/load factor

2. Current state energy solution:

- Chapter 3 – Generator type and heat rate
- Chapter 4 – Boiler type and efficiency
- Other fossil-fueled processes or equipment, for example, ICE trucks that can be electrified

3. Country-specific energy attributes:

- Retail/wholesale electricity rates (including transmission fees)
- PPA prices, REC prices
- Grid emissions factors
- Solar and wind generation profiles and costs (capital and operating)
- Fuel prices (diesel, natural gas, green hydrogen, nuclear)
- Outage frequency and durations
- Carbon prices

4. Long Duration Energy Storage solution:

- Financial metrics
  - Capital cost
  - Operating costs
- Operating parameters
  - Depth of discharge
  - MWH duration
  - MW power
  - Charge-discharge ratio
  - Round Trip Efficiency
  - Degradation
  - Useful life

5. Technoeconomic analysis – Compared the status quo customer energy demand, emissions and cost to the decarbonized solution supported by LDES

6. Cost of abatement – Calculated in USD/ton of CO_2

- All facilities seek to fully decarbonize (99+% reduction of scope 1 and 2 emissions)
  - The analysis assumes carbon accounting on a total annual basis as opposed to being time-matched
- Alternatives analyzed relate to the decarbonization of electric and heat demand for specific processes
- All projects are assumed to be brownfield, meaning the costs for existing status quo technologies are sunk

As described in Chapter 2, variations across countries depicted in this report reflect differences in country-specific:

- Retail and wholesale electric prices
- PPA prices
- REC prices
- Grid emissions factors
- Solar and wind generation profiles and costs (capital and operating)
- Fuel prices (diesel, natural gas, green hydrogen, nuclear)
- Outage frequency and durations
- Subsidies
- Carbon prices.

METHODOLOGICAL DETAIL

The main assumption for this report is that facilities fully decarbonize their Scope 1 and 2 emissions. The analysis also assumes that carbon is accounted for on an annual basis, which means it is not time-matched.

An assumption underlying this entire analysis is that facilities are fully – 100% – decarbonizing scope 1 and 2 emissions. Decarbonization analysis assumes carbon accounting on a total annual basis as opposed to being time-matched. This is key as there is a significant cost difference between fully decarbonizing and partially decarbonizing, e.g., 90%.

The incremental cost of decarbonizing the last, e.g., 10% of emissions is significantly higher than the e.g., first 10%. The analysis highlights decarbonization via one primary pathway for each solution, meaning accomplishing e.g., 90% decarbonization via procurement of renewables and decarbonizing the remaining 10% with hydrogen or other zero carbon fuels was not modeled.

Thus, decarbonization via electrification and procurement of zero carbon electricity was the pathway modeled for LDES solutions.

Electrification of mining operations is highlighted in the case in Chapter 3 and decarbonization of heat (and power) is highlighted in the case in Chapter 4.

All projects are assumed to be brownfield, meaning the costs for existing status quo technologies are sunk. Moreover the alternative technologies modeled relate to the specific electricity and heat requirements of the existing brownfield processes and costs relating to retrofitting these existing processes – and not operations as a whole – are accounted for.

Technologies were sized with respect to each facility's electric and heat demand. LDES in particular was sized based on relative economics of LDES capex and opex with respect to reliability needs and cost of renewables (either procured via PPAs or RECs or via onsite renewables incurring capex and opex).

For the off-grid case study in Chapter 3, LDES (and onsite renewables) were sized to yield the lowest combined capital and operating costs while meeting the facility's electric demand. As highlighted in the previous paragraphs

For on-grid (Chapter 4), LDES was sized to yield the highest possible electricity bill savings relative to its capital and operating costs. In the aforementioned Chapter 4, a sensitivity on thermal LDES configuration with respect to charge-discharge ratio was conducted by evaluating the economics of a 3-to-1 standalone thermal LDES system, see Figure 21. Electricity expenses in this chapter stemmed from either utility rates and REC prices collected for each geography or historical wholesale power prices and PPA prices.

PPA were assumed to be renewable PPAs with a 'contract for differences,' 'pay-as-produced' structure. This PPA structure was selected as it allows the offtaker to take on the most price risk and, thus, have the greatest opportunity to generate savings via price arbitrage enabled by LDES.

Once technologies are appropriately sized and all variables above including costs are accounted for, the decarbonized solutions were compared to the status quo via discounted cash flows (DCF). This approach accounts for all technical and economic parameters impacting the 20-year cost of energy supply for each facility and enables a like-for-like comparison between different decarbonization technologies.

These DCFs were unlevered and pre-tax and were calculated on a 2023 real USD basis using a weighted average cost of capital (WACC) of 7.5%.[44] As mentioned in Chapter 2, each solution's current and future economic viability was analyzed by

44 10% WACC assumed; functionally, this WACC represents the cost of debt given DCFs were unlevered; 2.5% subtracted from 10% to remove the effect of inflation (DCFs calculated on a 2023 real USD basis) looking across a 20-year period with project start years in 2023, 2030, and 2040 across all geographies.

Three DCFs were calculated for each combination of solution, year, and country: one for the facility's status quo, one for the decarbonized solution at that facility, and one for the delta between the status quo and solution (status quo subtracted from solution). The delta between the two respective DCFs yielded a cost of decarbonization in absolute real USD terms. This cost of decarbonization was then divided by the NPV of CO_2 emissions, yielding a cost of abatement in real USD/ton CO_2.

DCF line items included both annualized expenses – fuel expense, electricity expense, lost load expense, emissions, carbon tax expense (calculated based on scope 1 emissions only), and technology opex – and a capex for new technologies in 'year 0'.

As highlighted in Chapter 2, variations across countries depicted in this report reflect differences in country-specific input retail and wholesale electric prices, PPA prices, REC prices, grid emissions factors, solar and wind generation profiles and costs (capital and operating), fuel prices (diesel, natural gas, green hydrogen, nuclear), outage frequency and durations, subsidies, and carbon prices.

CALCULATION OF ADDRESSABLE EMISSIONS

The addressable emissions for LDES were calculated using data from the European Union's Emissions Database for Atmospheric Research, International Energy Agency, Germany's Federal Geothermal Association (Bundesverband Geothermie), and Energy Innovation and Policy, the San Francisco climate research firm, and Roland Berger.

The Emissions Database for Atmospheric Research provided estimates of total global industrial emissions. The International Energy Agency provided estimates on the share of emissions by industrial sector. Data detailing process heat requirements for these sectors were provided by Germany's Federal Geothermal Association and Energy Innovation and Policy.

The specific calculation started with total global industrial emissions which were then allocated to specific sectors. Emissions were allocate further based on process heat temperature requirements provided by the Federal Geothermal Association and Energy Innovation and Policy.

Addressable emissions include all electric consumption as well as processes requiring temperatures of 500 °C and below.

Appendix C: **Technologies – Technical and cost assumptions**

Technical assumptions for LDES technologies were sourced from publicly available databases and Roland Berger proprietary data, and were validated by LDES Council members who provided their own benchmarks.

Roland Berger modeled the performance of LDES technologies within the families outlined below, whose specific values for capacity, round trip efficiency and cost have been aggregated to ensure confidentiality and non-attribution.

Price assumptions for other technologies evaluated in this report are listed in Figure 31:

FIGURE 31

Technology input assumptions

Technical assumptions		Cost assumptions[45]					
Technology	Efficiency [RTE%]	Capital cost			Operating cost [USD/kW[46]-year]		
		2030	2040	Unit	2023	2030	2040
LDES – Thermal	90%-96%	50-100	30-48	USD/kWh_t	13	13	11
LDES – Mechanical	50%-80%	50-61	50-61	USD/kWh_e	16	16	16
LDES – Electrochemical	60%-85%	206-252	165-201	USD/kWh_e	22	20	18
LDES – Chemical	30%-50%	57-69	38-46	USD/kWh_e	20	17	13

45 Cost assumptions shown here correspond to a 24-hour duration

46 'Capital cost - Unit' for corresponding technology indicates whether Fixed OPEX is in USD/kWe or USD/kWt

Source: PNNL, NREL, Expert interviews, Roland Berger

Appendix D: **Case study approach and status quo assumptions**

Case studies are intended to reflect the predominant industries in the selected countries.

CHAPTER 3: OFF-GRID ELECTRIC

The mining example was selected for Australia because – at more than 700 mt of production in 2021 – Australia is the top global producer of non-fuel minerals. Australia produces approximately 25% of all non-fuel minerals and is expected to see its production increase almost 10% per year over the next five years.[39]

Non-fuel minerals include iron ore, lithium, gold, zinc, copper and aluminum, but exclude coal, gas and oil. Details of the mining example in Australia are outlined in Figure 32:

39 World Mining Data, S&P Global Market Intelligence, Statista, Website of Prime Minister of Australia, Australian government - Office of the Chief Economist

FIGURE 32

Mining application in Australia – Status quo

Description

Cast study type: Off-grid electric decarbonization

Off-grid mine in Australia

Diesel generator for electricity production

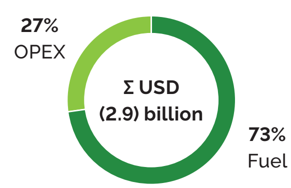
ICE[47] vehicles/ machinery

Energy consumption:[48] **28 m** gal diesel p.a. **60%** diesel gen. **40%** vehicles/ machinery

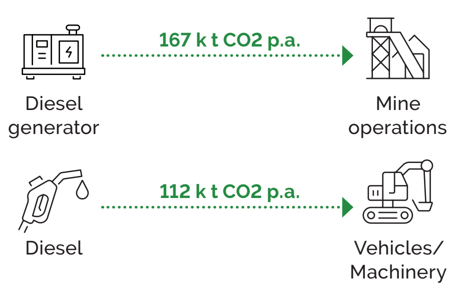
Project type: Brownfield

Present value of energy-related costs

For 20 years, starting in 2023



Current sources of energy emissions



Total emissions (scope 1) = **279 k t CO2 p.a.**

Process assumptions

Description	Value
Exemplary plants/ use-cases	Off-grid minerals extraction, e.g., copper, aluminium
Production	6.1 m t p.a
Load factor	80%
Baseline demand	33 MWe
Required temperature & pressure	N/A
Existing technology	Diesel gen., ICE[47] vehicles/ machinery
Fuel type	Diesel
Efficiency	35% (diesel gen.)

Cost assumptions

Description	Value
2023 fuel price[49]	6 USD/gal
Fixed OPEX	2,218 USD/kWe-yr
Variable OPEX	0.009 USD/kWhe
CO2 2023 price[49]	0 USD/t CO2

47 Internal combustion engine (uses fossil fuel); **48** Mine is consuming diesel for vehicles/machinery but also for diesel generator which generates 231 k MWhe p.a.; **49** 2023 starting point, escalated over time

Source: Roland Berger

CHAPTER 4: "EASY-TO-ELECTRIFY" HEAT

Chemicals

The study examined a hypothetical chemicals processing plant in Germany. After China, the European Union's 27 countries have the highest sales of chemicals, at approximately USD 650 billion in annual sales. Germany comprises 30% of the EU's total annual chemical sales. Within Germany, the chemical industry accounted for between 20% and 25% of total industrial emissions.[50]

Details of the chemicals processing example in Germany are described in Figure 33:

[50] World's Top Exports, Cefic, the European Chemical Industry Council, Statista, Our World in Data, Germany Federal Ministry of Finance

FIGURE 33

Chemicals application in Germany – Status quo

Description

Case study type: Steam decarbonization

On-grid chemical plant in Germany

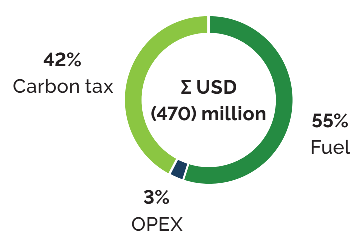
Gas boiler for medium-pressure, medium temperature steam

Energy consumption: **3.1 m** mmbtu NG[51] p.a.

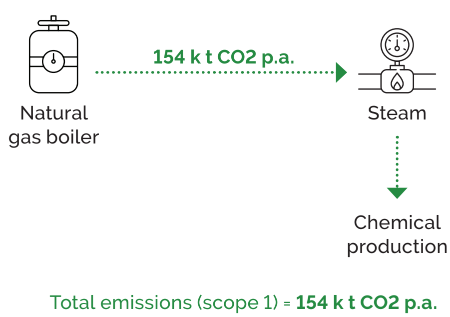
Project type: Brownfield

Present value of energy-related costs

For 20 years, starting in 2023



Current sources of energy emissions



Process assumptions

Description	Value
Exemplary plants/ use-cases	Ammonia/Industrial gases/ Ethanol/Petrochemicals
Production	219 k t p.a.
Load factor	95%
Baseline demand	100 MWt
Required temperature & pressure	400°C at 200 bar
Existing technology	Natural gas boiler
Fuel type	Natural gas
Efficiency	92%

Cost assumptions

Description	Value
2023 fuel price[52]	10 USD/mmbtu
Fixed OPEX	2.4 USD/kWt-yr
Variable OPEX	0.001 USD/kWht
CO_2 2023 price[52]	96 USD/t CO_2
Electricity prices	Historical wholesale

51 Natural gas **52** 2023 starting point, escalated over time

Source: Roland Berger

Food

The United States was selected as the example for food processing because it has the second-highest global emissions from food processing, after China. The food processing market in the United States is estimated to reach more than USD 800 billion, second only to China, which will reach over USD 1.2 trillion.[53]

53 Statista

FIGURE 34

Food application in United States – Status quo

Description

Case study type:
Steam + power decarbonization

On-grid food processing plant in California, US

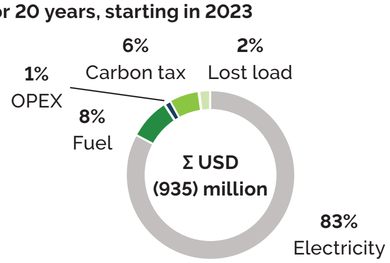
Gas boiler for low-pressure, low-temperature steam

Energy consumption:
312 k MWhe p.a. (36%)
562 k MWht p.a. (64%)

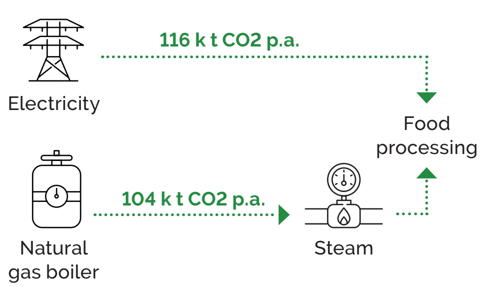
Project type:
Brownfield

Present value of energy-related costs

For 20 years, starting in 2023



Current sources of energy emissions



Total emissions (scope 1 and 2[54]) = **220 k t CO2 p.a.**

Process assumptions

Description	Value
Exemplary plants/ use-cases	On-grid food processing, e.g., meat, beverage, dairy
Production	1.4 m t p.a.
Load factor	95%
Baseline demand	38 MWe | 68 MWt
Required temperature & pressure	120°C at 2 bar
Existing technology	Natural gas boiler, grid elec.
Fuel type	Natural gas
Efficiency	92%

Cost assumptions

Description	Value
2023 fuel price[55]	3.87 USD/mmbtu
Fixed OPEX	2.4 USD/kWt-yr
Variable OPEX	0.001 USD/kWht
CO2 2023 price[55]	30 USD/t CO2
Electricity prices	C&I TOU rate | Wholesale

54 Carbon price applicable only to scope 1 emissions

55 2023 starting point, escalated over time

Source: Roland Berger

Appendix E: **Long Duration Energy Storage Council Members**

All of the organizations that form the Council are depicted in Figure 35:

FIGURE 35

LDES Council membership

Membership overview as of September 2023

Source: Long Duration Energy Storage Council

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The Long Duration Energy Storage Council (LDES Council) is global non-profit organization committed to decarbonizing global energy systems by 2040 through the development, deployment, and integration of long duration energy storage technologies (LDES). The LDES Council's mission is to facilitate the transition to a more sustainable and resilient energy future by advocating for policies, fostering innovation, and promoting collaboration among its membership and stakeholders in the energy industry. As the leading voice in advocating for the widespread adoption of diverse long duration energy storage technologies, the LDES Council provides guidance and reports to enable the integration of renewable energy sources and enhance grid stability using LDES technologies to achieve a flexible, secure, reliable, affordable, and fossil fuel free energy system.

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Working in cross competence, teams across all relevant industries and business functions, Roland Berger provides the best expertise to meet the profound challenges of today and tomorrow. Roland Berger is a global expert in energy transition expertise, especially in the deployment and dispatch of renewable, carbon free baseload and energy storage technologies.

Photo credits: artjazz/Adobe Stock

Roland Berger was commissioned to conduct this study on behalf of the LDES Council and its members, who both had input into the report.

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