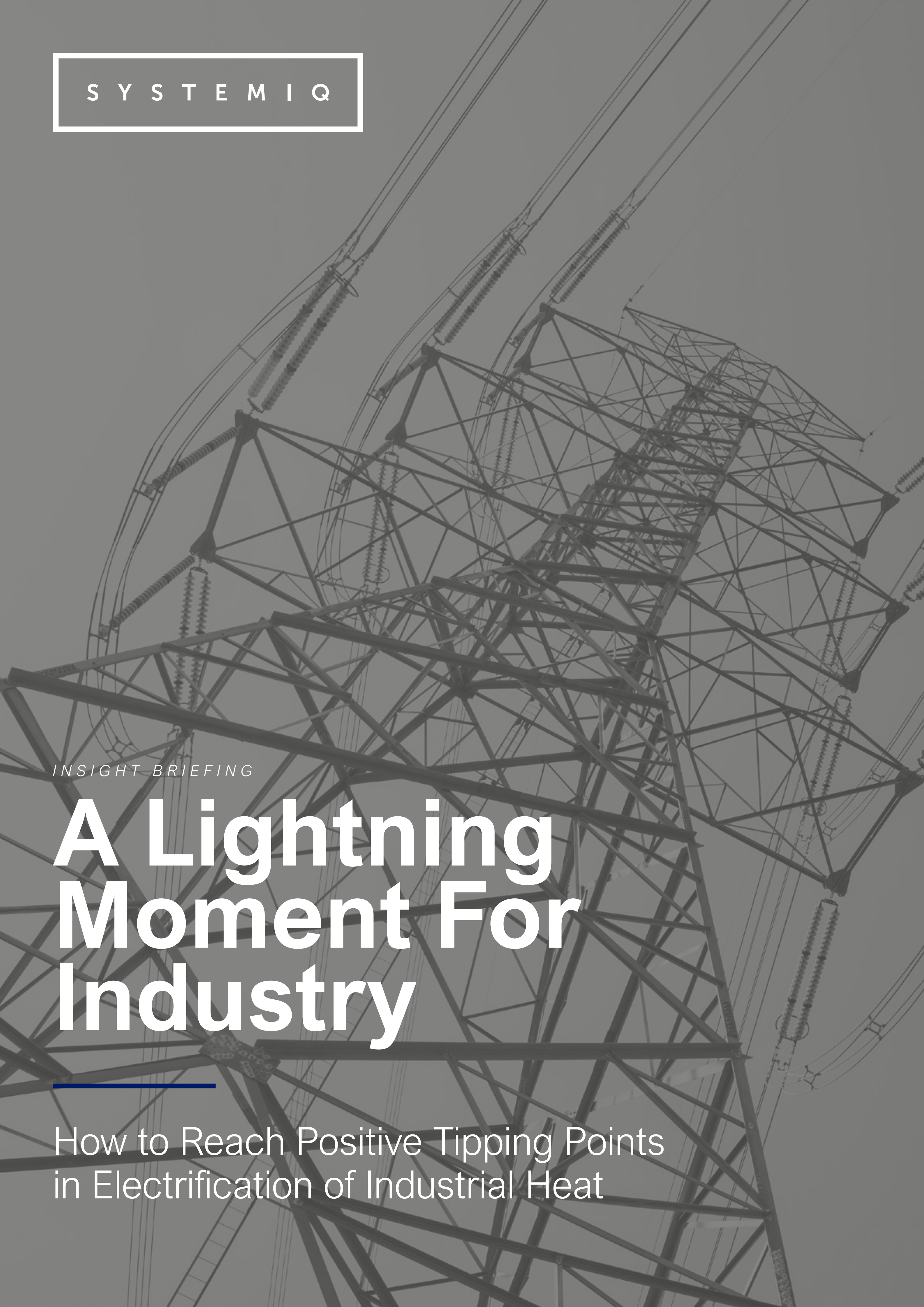


SYSTEMIQ

INSIGHT BRIEFING

A Lightning Moment For Industry

How to Reach Positive Tipping Points in Electrification of Industrial Heat

Preface

Industrial companies make the products we use every day, and heat is an important part of many manufacturing processes. Rotating kilns heat limestone to make cement, industrial boilers pasteurise milk or activate chemical processes; iron ore is turned into iron in blast furnaces, and pulp is dried in a furnace to create paper sheets. A quarter of global energy demand is for industrial heat, and almost all of it is currently generated using fossil fuels. Industrial heat contributes almost 20% (6 gigatonnes) to yearly global CO2 emissions.[1]

Industrial heat below 400°C is called low- to medium-temperature heat, and is responsible for about 40% of total industrial heat emissions.[2] As we will argue later, direct electrification is often the optimal solution to mitigating these emissions. In practice, that includes replacing fossil fuel boilers or furnaces with electric technologies, including heat pumps, mechanical vapour recompression, electric boilers, and thermal energy storage systems. A promising range of electrification technologies is being developed that can reach much higher temperatures[3], but these are often several years from being commercially available and only applicable to specific sectors. Therefore, this paper focuses on electrification of low- to medium-temperature processes, for which multiple technologies are available for implementation today.

"Exponential growth of the electrification of industrial heat can commence when technology tipping points are reached"

When tipping points are reached for electrification technologies, exponential growth in electrification of industrial heat can be achieved. That typically requires, among other things: access to low cost electricity; a supportive grid cost structure; timely access to grid capacity; suitable commercially available technologies; and a thorough understanding among industrials of the benefits, selection process and eventual technical integration of site-specific electrification solutions.

We hope that this paper contributes to the acceleration of electrification of industrial heat by showing that electrification of industrial heat is edging closer towards such a tipping point and by setting out a three-phased approach for companies planning to adopt electric technologies.

Electrification of industrial heat is close to a tipping point

Direct electrification is often the optimal solution for the decarbonization of low- to medium-temperature industrial heat

The decarbonization of industrial heat generation is required to reach global net-zero. Around 25% of global energy demand is for industrial heat, which is responsible for ~20% of global CO2 emissions. All sectors have at least some heat demand below 400°C (totaling about 40% of emissions from industrial heat). Sectors in which almost all heat demand is in that temperature range are food, beverages and tobacco; textiles; and pulp, paper and print - see Figure 1.

There are a range of solutions to decarbonize low- and medium-temperature industry heat (<400°C), which are typically grouped into three categories: direct electrification, low-emission fuels, and other zero-emission heat sources. Each one has its own benefits and challenges along the tipping point dimensions of affordability, attractiveness and accessibility – see Figure 2.

When initially assessing decarbonization options, it can be tempting to gravitate towards low-emission fuels, such as biogas or hydrogen. This route can require minimal alterations to existing manufacturing processes, which is a big plus for existing sites. However, we find that – especially on affordability and accessibility – low-carbon fuels can rarely compete with direct electrification, and that process alterations are not always necessary even with direct electrification. Today, low-emission fuels are scarce and are traded in captive markets, and costs can be prohibitively high due to conversion inefficiencies.[4] It is unlikely that th ese costs will come down and supply will go up sufficiently to compete with direct electrification at scale in the long run, especially where production of low-emission fuels relies on electricity as a major input.

The competitiveness of other zero-emission heat sources is limited to specific locations. Examples include geothermal in volcanic regions, or solar-thermal and nuclear when the significant scale of the site(s) can justify a high initial investment. In summary, compared to alternative decarbonization technologies, direct electrification is often the most competitive option.

Figure 1: Global combustion energy usage in selected industries[5]

	TWh per year (2030)	Very low 0°-100°C	Low 100°-200°C	Med 200°-400°C	High >400°C
Total for selected industries globally	25,400	11%	16%	6%	67%
Food, beverage and tobacco	2,000	41%	39%	11%	8%
Pulp, paper and print	2,000	11%	83%	4%	2%
Textiles	500	11%	65%	25%	
Chemicals	5,000	21%	10%	3%	66%
Alumina	400		60%	10%	30%
Cement	4,500	2%	10%	14%	73%
Iron and steel	11,000	3%		3%	94%

Figure 2: Comparison of decarbonization options for low to medium temperature industrial heat

Advantages Disadvantages Location dependent

Category	Technology	Affordability	Attractiveness	Accessibility
Direct electrification	**Closed loop heat pump[1]** **Open loop heat pump[1] (Mechanical vapor recompression)** **E-boiler** **Electrothermal energy storage (combined with e.g., boilers)**	High efficiency gains of up to 300-500% for heat pumps Ability to operate flexibly and capture low-cost electricity hours for thermal storage, hybrid e-boilers Lower cost of heat than conventional fossil-based technologies, for certain processes and locations	Significant emission reduction in scope[1] High precision control Potentially significant integration effort for higher temperature heat pumps	Technologies available and location agnostic Limited grid capacity in many regions
Low emission fuels	**Green hydrogen** **Biofuel**	Currently prohibitively expensive	Minimal alterations to existing equipment needed Significant emission reduction in scope[1] Strict regulations around low carbon fuels	Very limited supply and captive markets Inherent and persistent scarcity in supply chains
Other zero-emission heat sources	**Solar thermal** **Geothermal** **Nuclear**	Dependent on the site-specific insolation and the type of geothermal resource Typically high development costs (geothermal, nuclear)	Significant emission reduction in scope[1] Strict regulations (around nuclear and sometimes geothermal)	Dependent on the presence of a geothermal resource (geothermal) Dependent on the availability of land (solar thermal) Dependent on local regulation (especially for nuclear)

[1] Temperature range is limited to approximately 180C

Electrification of industrial heat has started, and a tipping point for electrification of low- to medium-temperature industrial heat is getting closer

The Breakthrough Effect report makes the case that once a tipping point is reached, technologies can reach widespread adoption within one or two decades.[6] When a tipping point occurs, a technology becomes more affordable, attractive and available than the conventional technology, leading to exponential uptake as users adopt the technology decisively. There are numerous precedents, some of them related to emission reduction. For example, in recent years positive tipping points have been reached for several zero-emission technologies, including solar PV, wind and battery-electric vehicles. From their moment of tipping, they reached exponential growth rates of 29%, 15% and 58%, year on year, respectively.

There are numerous indicators that electrification of low to medium industrial heat has started and is gaining momentum. The share of electricity used in light manufacturing globally increased from 41% to 47% between 2017 and 2022.[7] Thermal energy storage is now a mature technology, provided by more than 40 companies, many at an industrial scale.[3] And there is increasing governmental pressure. A group of 15 EU governments has called for the EU Heat Pump Action Plan (that included industrial heat pumps) to be published, as the plan was delayed until after the European Commission's 2024 elections.[8]

The tipping points in solar and wind mentioned above are also impacting the tipping point in the electrification of industrial heat. The decarbonization of heat by electrification is enabled by the costs of solar and wind coming down (between 2013 and 2023, the levelized cost of electricity (LCOE) from wind fell by 70% and the LCOE of solar by 76%),[9] and by the increasing availability of renewable electricity (global solar generation has been doubling every 2-3 years, wind generation every 5 years).[10]

Despite the momentum, no technology for low or mid-temperature heat direct electrification has reached a tipping point. Electrification of industrial heat is now mostly happening at sites with specific characteristics, such as a direct connection to renewable energy generation, very low grid electricity prices, an attractively structured power purchase agreement, favorable on-site operating regimes, specific process steps such as evaporation (for which mechanical vapor recompression is a highly energy-efficient alternative), and/or strong regulatory or customer pressure to decarbonize.

Several barriers remain to reach a tipping point; the most common ones are highlighted in Figure 3 and further detailed in the Technical Annex. They are often systemic, such as unattractive grid fee structures or lack of compensation for grid services, but others can be unlocked by a specific party, such as a technology provider tailoring its product to a specific process and thereby lowering investment costs.

There is typically significant regional variation in both the barriers and the actions to overcome them. For example, when assessing tipping points in electrothermal energy storage, both the barriers and stakeholder actions differed significantly by country (see Global opportunities for Electrothermal Energy Storage). But across countries, we find that reaching a tipping point requires coherent actions from government, regulators, grid operators, industry, technology providers and utilities.

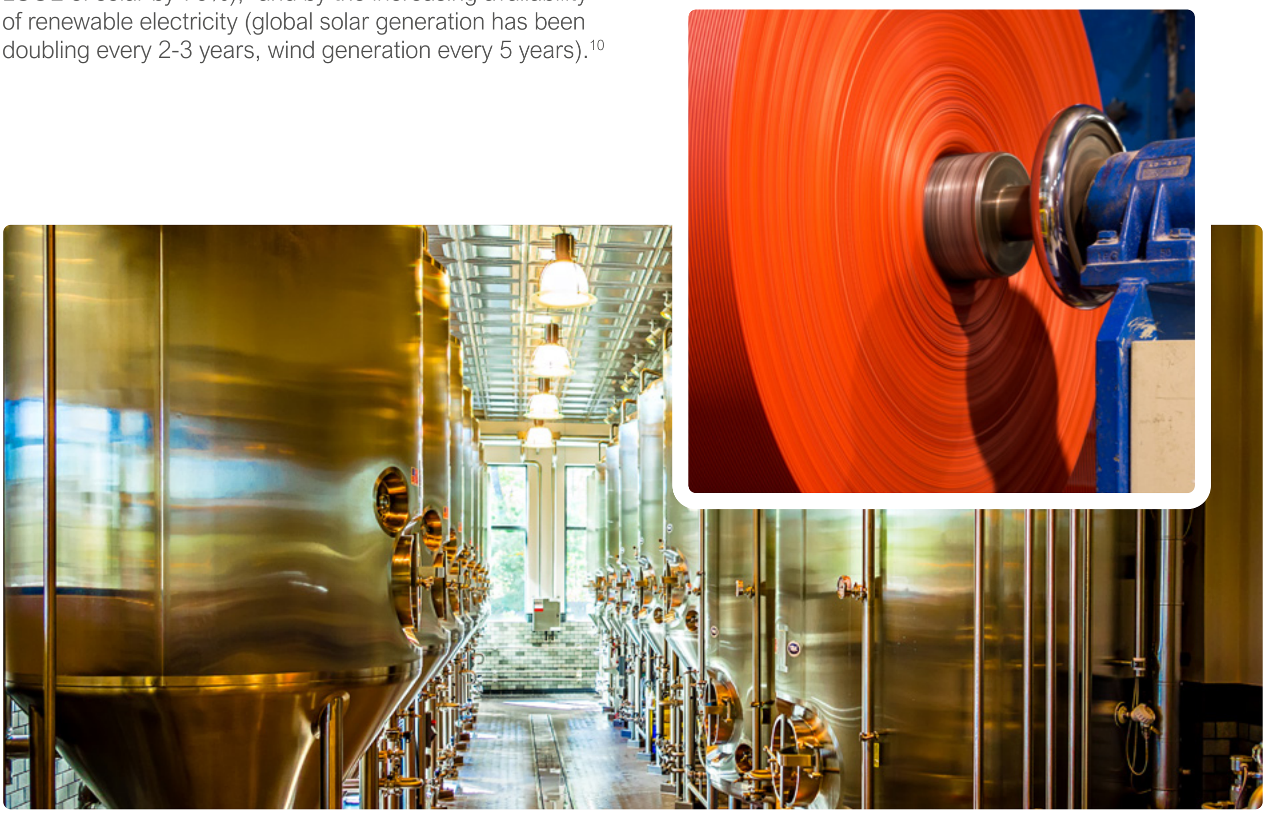
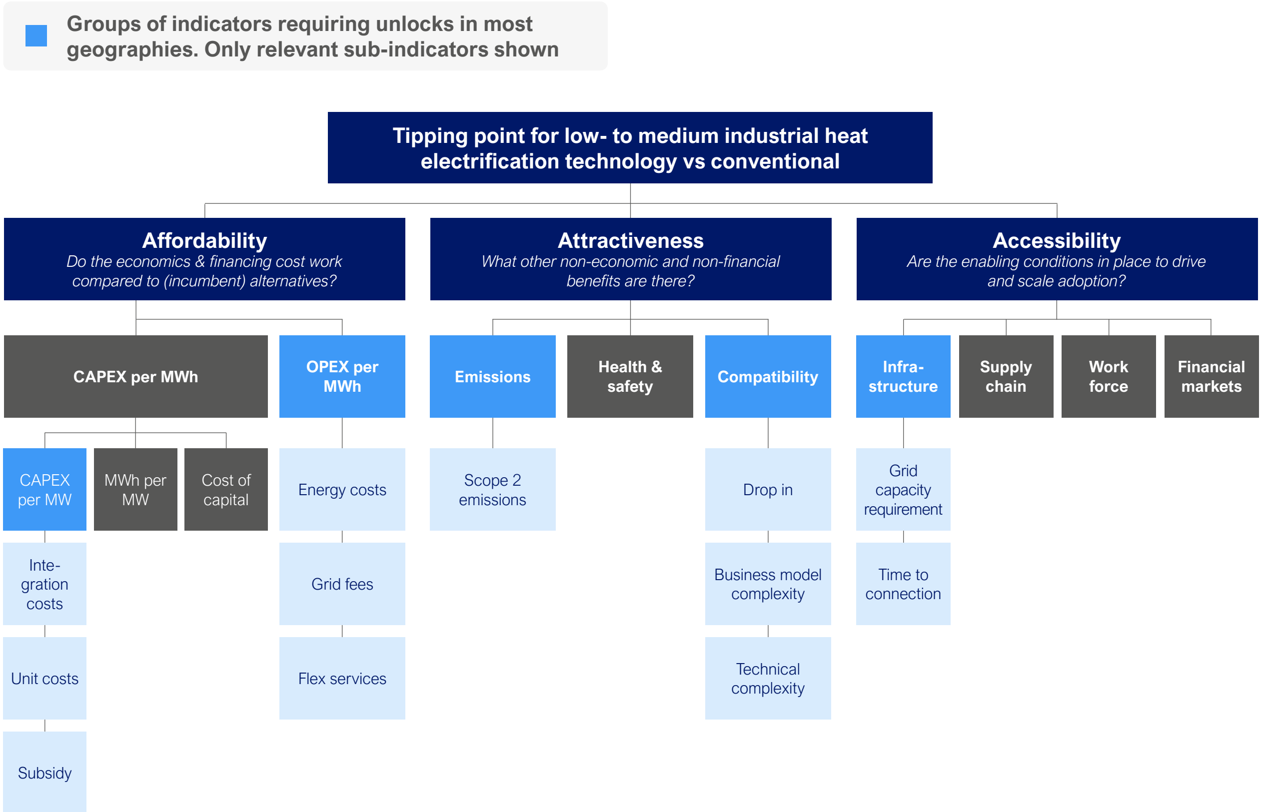


Figure 3: Systemiq's tipping point framework for industry electrification technologies, generalized version. A summary assessment of electrification technologies along the tipping point dimensions can be found in the Technical Annex.



Despite the challenges, industrial companies can now begin to explore the direct electrification opportunities at their sites, especially in the context of sustainability strategies. Acting early to electrify industrial heat can have material benefits.

- By being a first mover, a company may be able to access government incentives ahead of competition, depending on geographic footprint. For example, a large international food and beverage company decarbonized their Dutch sites through thermal energy storage systems, using significant demonstration subsidies from central government.
- Early adopters could also be better positioned to timely secure the infrastructure needed, notably grid connections or attractive Power Purchase Agreements (PPAs).
- Smaller-scale adoption could allow companies to capture cost-saving measures early on, and simultaneously build up the competencies and contacts required to decarbonize remaining operations.
- Finally, early adopters could position themselves as leaders in sustainable business practices. This can be attractive because of pressure from shareholders or customers, or the opportunity of capturing a green premium on their products.

Industrial companies can act now to begin decarbonizing low to medium heat demand on their sites via electrification

Electrification of industrial heat can seem daunting for individual companies. It requires, among other things, knowledge of the technology options, site-specific engineering plans and process upgrades, and a deep understanding of the local power markets. This complexity can be reduced by taking a structured approach. Going through step-by-step plans can help to identify and capture the early electrification opportunities.

For industrials with a multi-site footprint, there are three main phases:

1. Determine a heat- and power-decarbonization plan for a single site or for site archetypes
2. Prioritize sites for electrification based on local characteristics and build the business case for a first wave of implementation
3. Execute pioneering projects and capture benefits and learnings

Phase 1. Determine a heat- and power-decarbonization plan for site archetypes

For companies with a multi-site footprint, individual sites are clustered in site archetypes to make it easier to identify solutions.

For heat, archetypes are defined based on products, processes, and associated heat requirements (Figure 4). For each archetype, a heat decarbonization plan:

- identifies the share of heat that can be decarbonized through electrification, and
- determines a list of the most suitable technologies to do so using the hierarchy of decarbonization options set out in Figure 2.

For power, on-site space and market dynamics – such as power prices and grid availability – define the archetypes. A power decarbonization plan is then built that addresses procurement or generation for the new total power demand, including the required grid capacity expansion. The heat and power decarbonization plans are combined for the overall site decarbonization plan (Figure 5).

Figure 4: Illustrative example of creating site archetypes for power

NA sites | Rest of World sites | Decreasing power options | Increasing urgency to solve access to power

Geographic factors[1] →

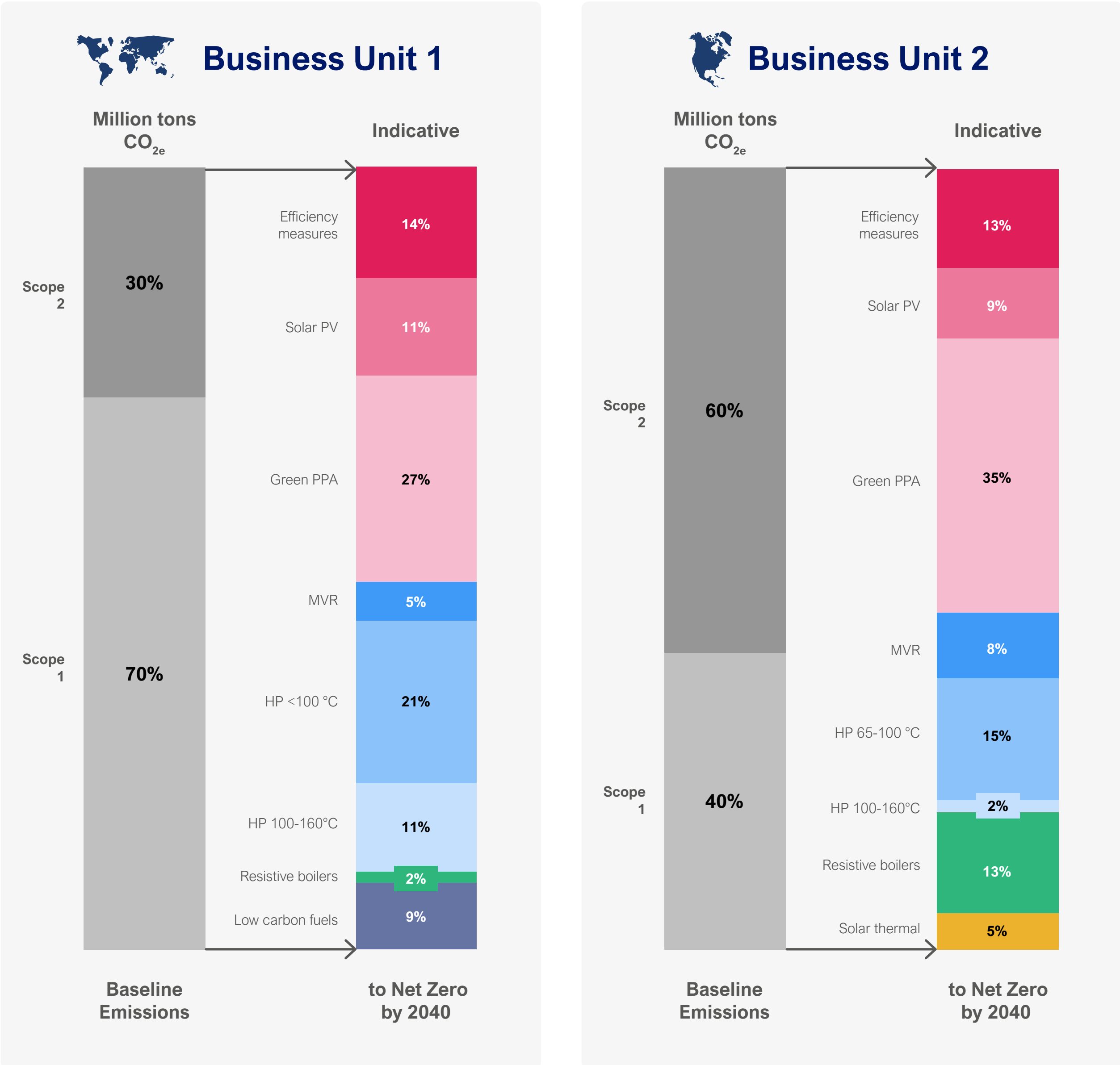
Space factors →

	Strong solar capacity factor; less-congested grid	Strong solar capacity factor; congested grid	Weaker solar capacity factor; less-congested grid	Weaker solar capacity factor; congested grid
Rooftop and ground space	NA Plant 1, NA Plant 2, NA Plant 3, NA Plant 4	Europe Plant 8, Europe Plant 9, NA Plant 5, NA Plant 6	NA Plant 7, NA Plant 8, NA Plant 9, NA Plant 10, NA Plant 11, NA Plant 12, NA Plant 13, NA Plant 14	No sites
Ground space only	No sites	No sites	No sites	Europe Plant 1
Rooftop space only	APAC Plant 9, Latam Plant 2, Latam Plant 3, Latam Plant 4, Europe Plant 10, NA Plant 22, NA Plant 23, NA Plant 24, NA Plant 25, NA Plant 26, NA Plant 27, NA Plant 28	APAC Plant 9, APAC Plant 10, ME Plant 1, NA Plant 19, NA Plant 20, NA Plant 21	APAC Plant 7, APAC Plant 8, Europe Plant 7	APAC Plant 1, APAC Plant 2, Europe Plant 2, Europe Plant 3, Europe Plant 4, NA Plant 15, NA Plant 16, NA Plant 17, NA Plant 18
No space outside	Latam Plant 1	APAC Plant 7, Europe Plant 6	APAC Plant 3, APAC Plant 4, APAC Plant 5, APAC Plant 6	Europe Plant 5

Maximize focus on solar PV & get grid access

Urgently prioritize grid access

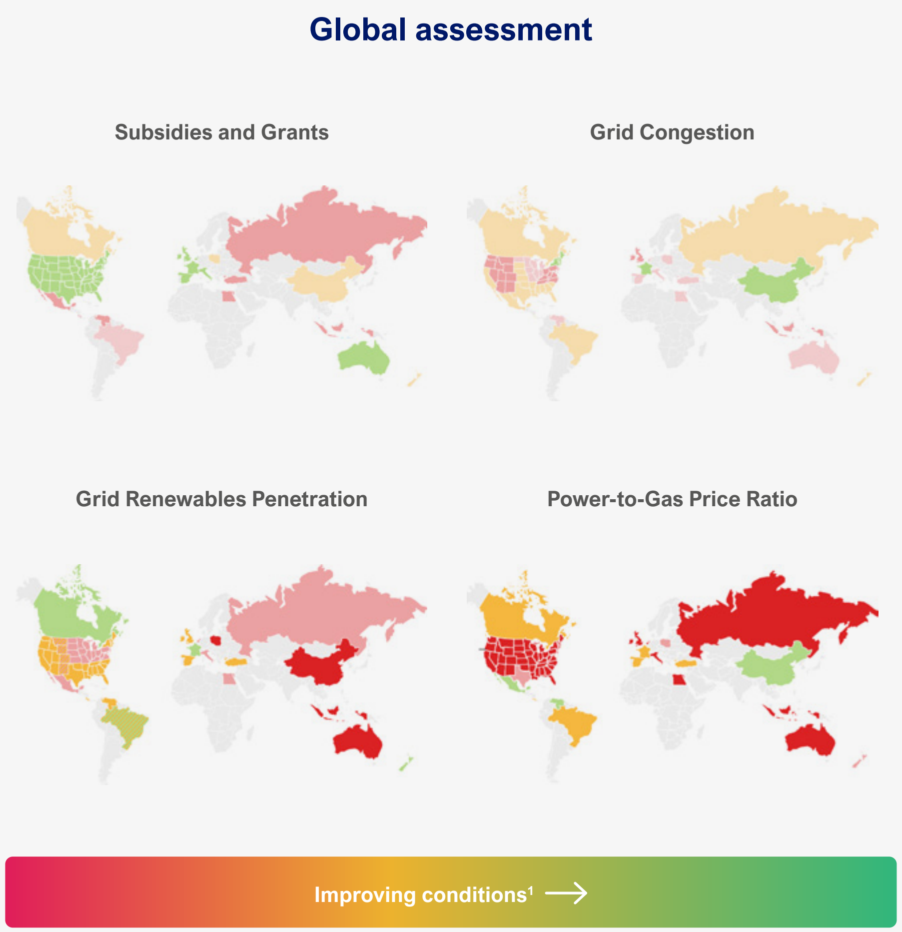
Figure 5: Illustrative example of overall decarbonization plan for two business units



Phase 2. Prioritize sites based on local characteristics and build the business case for implementation

The next phase is to prioritize the sequence of projects. This is especially relevant for companies with a multi-site footprint, as it can lower the overall decarbonization costs. A higher-level scan can consider relevant local conditions, such as the presence of grants and taxes, grid capacity and attractively priced zero-emission electricity (Figure 6). Alongside higher-level prioritization, local and site-specific insights are needed to shed light on factors such as the materiality of current emissions, grid tariffs, required flexibility in electricity demand or the production process on site.

Figure 6: Illustrative snapshot of characteristics that inform global sequencing



Note: Countries in grey are out of scope for this illustrative analysis.
[1] Power-to-Gas-price-ratio is favourable with low power and high gas prices

Local assessment

Plant 1 (California)

- Subsidies available
- Grid congestion
- Grid renewables penetration
- Power:Gas price ratio
- Materiality – 15% of Scope 1 & 2 emissions

Sequencing recommendation: Pioneer site

Plant 2 (Australia)

- Subsidies available
- Grid congestion
- Grid renewables penetration
- Power:Gas price ratio
- Materiality – 7% of Scope 1 & 2 emissions – coal-fired

Sequencing recommendation: Wait and see

To build the business case, the technology must be selected from the suitable options identified in Phase 1. This decision must consider local grid constraints and the local business case, which can vary quite significantly due to differences in energy prices, taxes, and grid fees.

The business case depends on both upfront capital expenditure and the ongoing impact on operating expenditure (below). The availability of grants, subsidies, and tax credits can defray capex costs. For operating expenditure, the local power-to-gas price ratio or power-to-coal price ratio (including marginal taxation) is a key driver of the business case. In countries with relatively high prices for fossil fuels compared to electricity (e.g., China), the effect on opex is more likely to be positive, whilst in regions with cheap fossil fuels (e.g., USA) it is more likely to be negative. Finally, the business may reduce costs through a reduction in its carbon tax exposure (or mitigate the risk of future carbon taxes). As electrification involves long-life assets, the business case should consider how costs and external factors are likely to evolve.

Figure 7: illustrative examples of varying opex impacts of electrification

Note: does not account for impact of carbon taxes

Phase 3. Execute pioneering projects

Pioneering projects can serve as a starting point, allowing a company to capture learnings early on, partially offset their capex investments through economic incentives such as subsidies and grants whilst they are available, and apply for grid capacity expansion, in the event that . It furthermore allows for the establishment of strategic partnerships with stakeholders such as power suppliers and technology firms. Focusing on these pioneer projects lays the groundwork for a broader decarbonization roadmap while leveraging available resources and support.

Decarbonizing industry can be complex. Each site is unique and will have specific challenges to electrification, for example related to the temperature needed by its processes, space constraints, and sometimes its existing equipment. Companies must also understand and plan for the external challenges and opportunities such as grid congestion, the availability of government support and the roll-out of variable electricity generation from wind and solar. And, when broken down into concrete barriers to overcome within the energy system and concrete steps for industrials, we see that electrification of heat is increasingly possible.

Acknowledgements

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About Systemiq

Systemiq is a leading system change company that partners with business, finance, policy-makers, and civil society to make economic systems truly sustainable and meet the objectives of the Paris Agreement and the Sustainable Development Goals.

Further reading

The Breakthrough Effect: https://www.systemiq.earth/wp-content/uploads/2023/01/The-Breakthrough-Effect.pdf

The Breakthrough Effect in ASEAN: https://www.systemiq. earth/breakthrough-effect-asean/

The Global Opportunity for Electrothermal Energy Storage: https://www.systemiq.earth/electrothermal-energy-storage/

Grid access and permitting: https://www.energy-transitions.org/publications/planning-and-permitting/

Electrification: https://www.energy-transitions.org/publications/making-clean-electricity-possible/

Delivering Net Zero in the Food Sector: https://www.systemiq.earth/wp-content/uploads/2023/06/Food-white-paper.pdf

Technical annex: Tipping point assessment. Summary of affordability, attractiveness, and accessibility of direct electrification of low and medium temperature industrial heat

In this Technical Annex three electrification technologies are compared with a conventional fossil fuel boiler along the tipping point dimensions; heat pumps, e-boilers, and electrothermal energy storage combined with a boiler. Across virtually all technologies, there is a path towards a tipping point, which will be reached when the technology is on par with the conventional technology in affordability, attractiveness, and accessibility.

Please note that this is a simplified and generalized assessment. In practice, specific technology assessments will differ significantly by site. From the figure below and the text later in this appendix, it will become apparent that each technology has its pros and cons. In short – there is no 'silver bullet' that would be perfect for each application. Instead, sites can typically choose the optimal option between several technologies and set-ups.

ETES is the only technology that can combine full electrification of heat with grid flexibility services

Well positioned | Neutral | Not well positioned
TRL 8+ | TRL4-7

[1] Assumptions for all technologies: 10 MW capacity for thermal discharge 95% capacity factor (except for e-boilers at 40%); 25-year lifetime for the calculation of annualized capital expenditures 8.5% cost of capital

[2] Is technically capable of participating in ancillary, capacity and balancing mechanism services

[3] ETES lower bound uses stand-alone wind/solar

Sources: P2H Cost Calculator (2022) — Agora, IRENA Remap 2030, TNO Technology Fact sheet (2015), Thermal Energy Storage (2023) — RTC, Industrial Thermal Batteries (2023) — LDES, Prospects for LDES in Germany (2022) — Aurora

Affordability

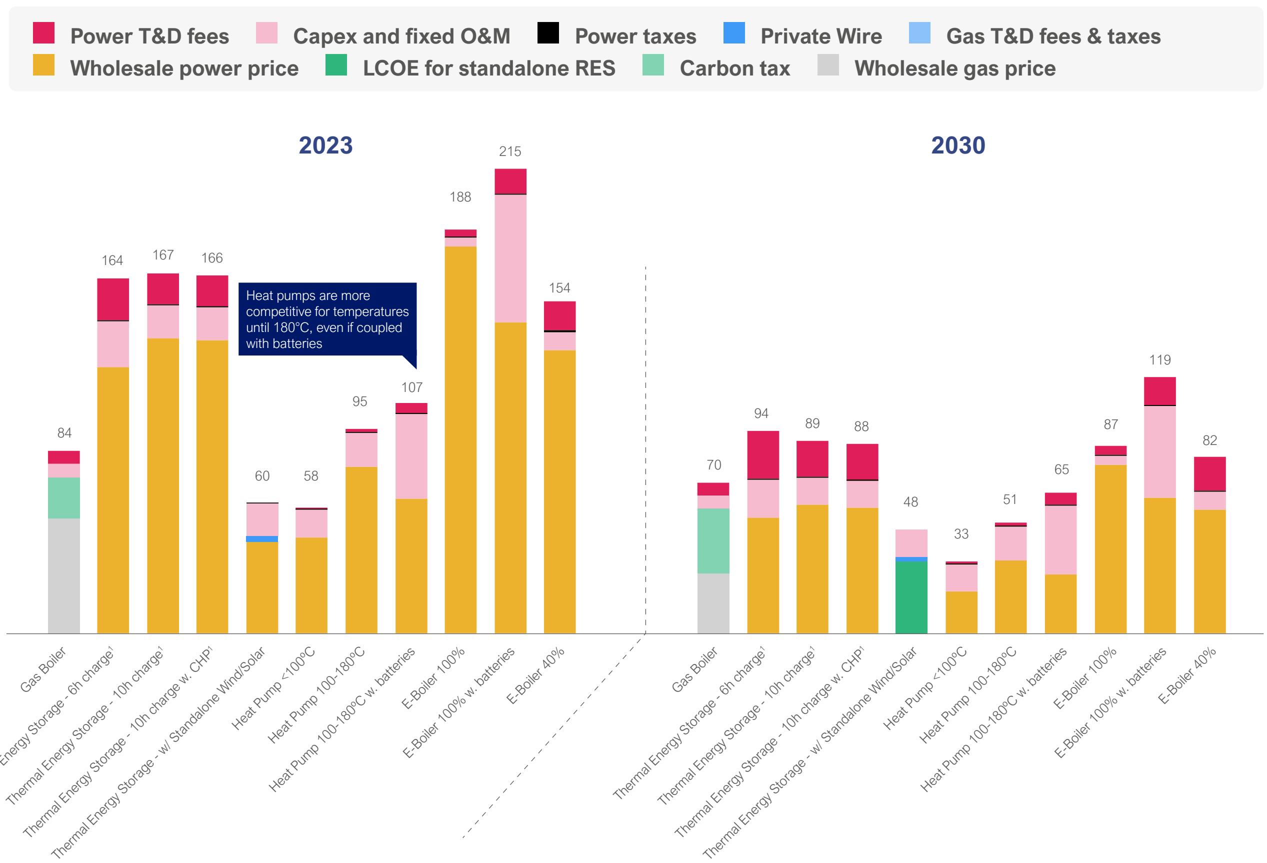
The cost of heat is determined by the upfront capital investment and the operating costs. The latter includes energy costs and maintenance costs. For fossil fuel boilers, e-boilers and electrothermal energy storage, the energy costs (including grid costs) typically contribute more than 5 times as much to the cost of heat compared to the capital investment. Heat pumps have a very high energy efficiency that can reach 300-500%. For that technology, there is typically an equal contribution to the cost of heat of the capital investment and the energy cost, see also the Figure below.[11]

Although direct electrification is often more affordable than other decarbonized heating technologies, it is not always more affordable than conventional fossil-fuel boilers today. Heat pumps and recompression technologies are an exception, as these can typically be more affordable than conventional boilers, because of the efficiency gain described above. Capital investments can be at least twice as high as for a conventional boiler, with heat pumps that reach temperatures above 100°C sometimes more than five times higher. However, these investments are often more than overcome, especially for the lower temperature ranges, by significant energy cost reductions due to the high energy efficiencies.

Electric boilers have a similar capex to gas boilers while electrothermal energy storage assets can be more than twice as expensive. Both technologies are no more efficient per unit of energy than modern gas boilers, using about the same amount of energy to produce a unit of heat. Today, the gas price per unit of energy is often less than half the average electricity price per unit of energy, meaning that these two electrification technologies lead to a higher cost of heat.

However, e-boilers and electrothermal energy storage technologies have other features that can lead to a competitive cost of heat, depending on the site location and heat demand. The assets can be operated flexibly (turned on and off at will), thereby capturing the lowest market prices in the fluctuating electricity market, and can add other revenue streams by providing grid services (which depend on the structure of the local electricity market). Additional actions to reduce the cost of heat can include the procurement of advanced PPAs or self-generation of renewables on site. Some regions are developing or piloting grid-fee incentive structures for these flexible assets and have financial support schemes available. That can potentially further reduce the cost of electrified heat and bring it to a par with the cost of heat from fossil fuel boilers in these regions.

Comparison of affordability of different industry electrification technologies – Germany
Generalised levelised cost of heat in 2023 and 2030 of different technologies *EUR/MWh thermal*



Notes: Does not include current subsidies schemes, changes in T&D fees and Taxes, Balancing costs. Battery storage of 10h included in battery cases, which is shorter duration than ETES thermal storage. LCOH for a specific case can be different from the generic numbers represented in this graph. More details can be found at the **Electrothermal energy storage report.**
Sources: Tennet – Dutch network operator, P2H Cost Calculator (2022) - Agora, IRENA Remap 2030, TNO Technology Fact sheet (2015), Thermal Energy Storage (2023) - RTC, Industrial Thermal Batteries (2023) - LDES, Prospects for LDES in Germany (2022) – Aurora, NREL (2021) Commercial scale Li-Battery storage costs

Attractiveness

Because of the emission reduction achieved, electrification technologies are often perceived as more attractive than conventional fossil fuel boilers. Electrification can reduce emissions in scope 1, 2 and 3. Scope 1 emissions are abated directly by avoiding the need to burn fossil fuel; electrification also avoids scope 3 emissions from fossil fuel production.

Scope 2 emissions from the purchase of electricity can also be abated. Electrification alone does not equal reduced emissions without matching the demand with green electricity, such as via (timebound) zero-emission PPAs, on-site renewables or country-wide grid decarbonisation. The availability of green electricity can be matched especially well by flexible electricity demand from e-boilers or electrothermal energy storage. It should be noted that e-boilers cannot fully decarbonize scope 1, 2 and 3 at the same time. E-boilers must run continuously to fully reduce the use of fossil fuels (scope 1 and 3). However, when doing so, they cannot at the same time operate flexibly in line with the availability of zero-carbon electricity that is often required to reduce scope 2.[12] Electrothermal energy storage assets can reduce emissions in scope 1, 2 and 3 at the same time. These assets store electricity as heat and can be flexible in choosing the times to charge (reducing scope 2)[13], while providing continuous heat to the industrial process (reducing scope 1 and 3).

Other benefits will depend on the industrial process. Direct electrification can, for example, allow for increased product quality via precise temperature control, uniform heat distribution and fast temperature-change capabilities.

Direct electrification can be less attractive because of the (initial) integration effort. This will differ substantially between sites and depending on the choice of technology. Although switching from a fossil fuel boiler to an electrified alternative can be almost a ‘drop-in’ replacement, the cascading of heat might also have to be restructured. This effort can be sizeable especially for heat pumps for temperatures above 80-100°C, as these require a lower temperature heat stream as input.

Accessibility

With timely action, the accessibility of electrified technologies can be similar to that of fossil fuel boilers. The direct electrification technologies that are currently commercially available can meet virtually all heat and process requirements for temperatures up to 400°C and sometimes even above. There are ongoing technology improvements and a scaling-up of value chains.

The grid connection can be a barrier that makes electrification less accessible than fossil fuel boilers. If the electricity demand is rising in a region, but grid expansion is not keeping pace, there may be long waiting times for a new or larger grid connection – 7 to 10 years in some locations. Typically, industrial sites require a larger grid connection when electrifying their heat demand. This differs per technology: heat pumps have a relatively low but continuous electricity demand, while boilers and thermal storage assets need much larger connections but can be flexible in when they require electricity from the grid. For individual sites, applying for a grid connection sooner rather than later is often advisable.

Endnotes

1 "Renewables 2019, Heat," IEA, 2019; "Energy System Overview, Industry," IEA, 2023.

2 The 400°C temperature is a generic representation of the temperature range that can be reached with indirect heat transfer (such as water, steam, heating oil). In practice, higher temperatures can be reached as well in specific set-ups.

3 For example, the large-scale electrically heated steam cracking furnace that was developed by BASF, Sabic and Linde and started up in April 2024. See: https://www.basf.com/global/en/media/news-releases/2024/04/p-24-177.html

4 Conversion inefficiencies arise from the energy losses if electricity is converted to hydrogen.

5 "Catalysing the global opportunity for electrothermal energy storage", Systemiq 2024.

6 "The Breakthrough Effect," Systemiq 2023.

7 "Tracking clean energy progress 2023, light industry," IEA 2023.

8 "15 Member States call for publication of Heat Pump Action Plan," EHPA 2024.

9 "The Cleantech Revolution", RMI 2024

10 "The Cleantech Revolution", RMI 2024

11 See the Technical appendix of "Catalysing the global opportunity for electrothermal energy storage," Systemiq 2024.

12 Of course, scope 2 will be fully decarbonised regardless of the time that the e-boiler is operating if all power on the grid is fully decarbonised.

13 Often significant availability of green power happens at the same time as low electricity prices.

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