TECHNICAL REPORT OCTOBER 2024

Decarbonizing High-Temperature Heat in Industry

Technology assessment and policy recommendations for Europe

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Executive Summary

High-temperature heat processes, such as steel forging and cement production, are vital for modern society and achieving net zero, but currently still rely on burning fossil fuels for generating high temperatures (500-2000°C). However, they can be largely electrified in the medium term, often in combination with thermal storage. Commercialization is already underway for many applications, and while significant engineering R&D and economic challenges remain when scaling up, no fundamental scientific breakthroughs are necessary to electrify these processes. In contrast, biomethane, hydrogen, and carbon capture are not a sustainable solution for high-temperature heat processes, due largely to low availability, inefficiency, and the risk of carbon lock-in.

Availability of and operating costs for clean electricity are the main obstacles for electric heat, as electricity is currently on average 2-3 times more expensive than gas. Among the most promising solutions to this is thermal storage, which could greatly reduce electricity costs in the short to medium term. It allows for the generation of electric heat to be timed at periods of low prices independently of its use and enables operators to be compensated for grid flexibility services, while costing less than electrochemical batteries.

Nonetheless, thermal storage alone is not sufficient. Abundant, cheap, clean electricity is not only a necessity to reach net zero, it would also greatly benefit electric high-temperature heat. Expanding grid capacity and coverage increases electricity supply locally, reducing costs and enabling currently insufficiently connected plants to electrify (especially SMEs). Solar and wind power generation are cheap if their intermittency can be addressed at low cost, which is uniquely feasible using thermal storage in the short to medium term. Moreover, it is crucial to strongly and continuously support renewable expansion through a combination of other storage technologies and the development of dispatchable clean power (e.g. advanced geothermal).

In addition to electrification, there are multiple potential options to directly generate clean heat, especially at low and medium temperatures. These options include concentrated solar, geothermal, or nuclear, and could have advantages over electric heat in the future, in particular if grid access remains a bottleneck for direct electrification.

Based on these considerations, Future Cleantech Architects recommends the following policy priorities:

- Support the replacement of fossil heat with electric heat and thermal storage.
- Steer usage of scarce alternative fuels towards applications without other options. High-temperature heat could be eligible for biogas prioritization where no competitive alternatives exist yet.
- Policy must target significantly lower electricity costs.
    - Incentivize thermal storage, including necessary changes in market regulation.
    - Deploy all available energy system tools, such as grid storage and firm, dispatchable power, to produce synergies that lower electricity costs.
    - Accelerate permitting and build more transmission lines and substations to ensure availability of electricity for all consumers.
- Fund R&D for the engineering work required to integrate electric heat into industrial processes, whether by retrofit or new builds.
- Fund R&D into advanced clean process heat from solar, geothermal, or nuclear sources to secure additional benefits.

Table of Contents

High-temperature heat for net zero and energy security

Every day, 7 million people in the EU go to work to keep the continuous production of steel, minerals, chemicals and other materials going. These 7 million represent a fifth of the EU manufacturing industry workforce, and they enable and support the rest of the manufacturing industry to produce wind turbines, high-speed trains, hospital equipment, fertilizers to grow food, and other basic goods in well-established value chains. They themselves depend on another 19 million EU citizens whose jobs indirectly contribute to the process sector of the manufacturing industry [1].

Steel beams or glass panes may be rarely on our mind, but we cannot do without the process industry's outputs. They are – often quite literally – the building blocks of our modern society. They are also the building blocks of our future: on a mass basis, wind turbines are around 20% steel and up to 80% concrete [2], while the much lighter blades are made from plastics reinforced with glass fiber. Metals, minerals, petrochemicals, and the companies that produce them are indispensable for building our future energy infrastructure.

With so many relevant jobs and societal needs on the line, policymakers must focus on clearing a key obstacle to decarbonizing EU industry: our dependency on fossil fuels for heat, in particular natural gas. The plants and factories of the processing industry consume large quantities of energy (952 TWh) to generate high-temperature heat (HTH). Intense use of heat essentially defines these industries, which is why they are also called the 'energy-intensive industries' (EII)[1]. However, the heat used is almost always provided by the combustion of natural gas, resulting in greenhouse gas (GHG) emissions and air pollution (about 166 $MtCO_{2e}$ are emitted by industrial use of gas, which is about 40% of overall EU industrial emissions [3], [4]). Most of this gas is imported, with more than half coming from non-NATO countries, including 16% from Russia (albeit down from 49% in 2021) [5]. To meet the bloc's climate targets and achieve energy security, but also to keep enjoying the benefits of technological leadership, Europe's leaders must enact policies that promote the adoption of technologies that can eventually fully replace natural gas with clean heat while maintaining economic competitiveness.

European gas imports and consumption

The natural gas the EU imports is delivered mainly via two transport methods: ships (40%) and pipelines (60%). The ships are liquified natural gas (LNG) tankers, that unload natural gas as a liquid at -160°C at special harbor terminals. Compared to gas, the liquid form is about 600 times denser, which is necessary for making transport via ship practical and economical. The greater fraction is delivered in the regular compressed gas form via various pipelines, which connect EU gas grids to Africa via Algeria, to Azerbaijan via Turkey, as well as to the North Sea gas fields, Scandinavia, and Russia. As can be seen in Figure 1, the main suppliers are Norway (29%), the United States (19%), Russia (16%), and Algeria (16%).

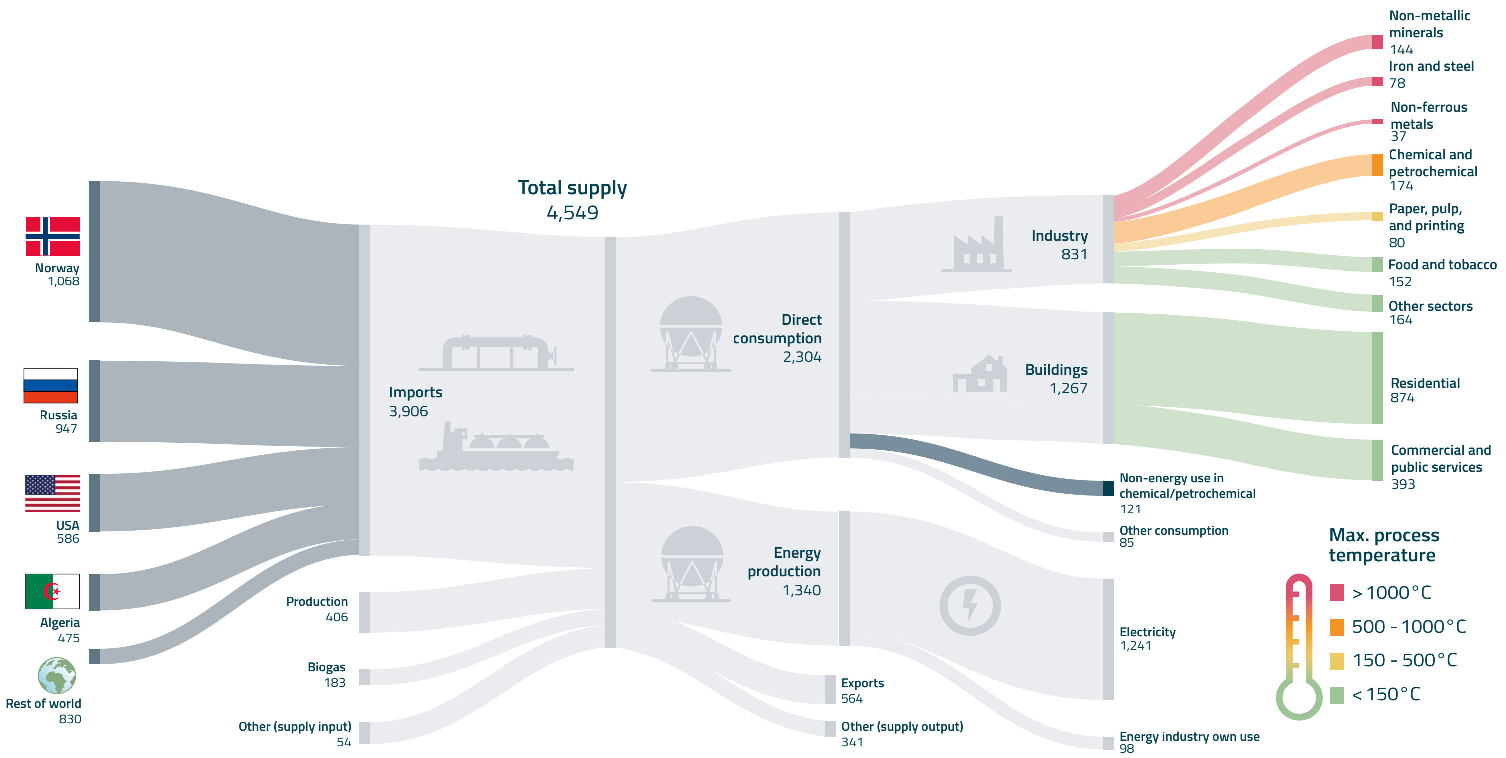


Figure 1: Natural gas flows (TWh/year) in Europe, 2022. Thermal end uses are color coded as green below 150°C, yellow up to 500°C, orange up to 1000°C, red beyond 1000°C of typical process temperature. Data from Eurostat and analysis by FCA.

[1] The usage of the term 'energy-intensive industries' in this report encompasses steel, cement, chemicals, minerals, ceramics, pulp and paper, non-ferrous metals, and refining. 'Process industry' additionally refers to raw materials, water and waste treatment, as well as closely integrated or related engineering and other services.

After the gas has entered the network, consumers use it in two main ways: as fuel (96.7%) for electricity and heat, or as a chemical feedstock (3.3%). Burning gas for heat is its predominant application (58%). The flames produce the heat needed to raise the temperature of buildings, food, chemicals, or metals to a desired value. The temperature of the heat at the point of use varies greatly, depending on the application: from 20°C for comfortable room temperature to over 2000°C for the most demanding industrial processes, such as making specialized metals and ceramics.

Producing electricity is the second most common use of gas as a fuel (34%). Flexibly filling gaps in the electricity supply is currently one of the important uses of natural gas, as gas generators can be ramped up and down quickly and clean flexibility tools are still insufficiently deployed. Gas power plants can be more efficient than coal power plants, because they can be designed to use the energy from burning gas in two combined cycles for an efficiency of around 55%, compared to about 40% for coal.

Chemical feedstock is a much smaller but equally vital application (3.3%). Here, natural gas is used as a feedstock to produce another chemical instead of converting it into heat by burning it. For example, natural gas (which is >95% methane, CH_4) is used to synthesize the basic chemical ammonia (NH_3), which is then used to produce fertilizers. About 40% to 50% of the world population depends on fertilizers for food production to survive [6].

Decarbonizing the applications towards the higher end of the 20-2000°C range is the most difficult and neglected set of problems, and this is the focus of this report. This report will only briefly touch upon gas as a chemical feedstock or as fuel for heating buildings or generating electricity, as commercially available alternatives already exist for these applications. Instead, it focuses on the challenges a company with high-temperature heat processes, like the one forging wind turbine gears in Box 1, currently faces. Before zooming in on this end of the temperature range, it is helpful to assess the overall state of the replacement of natural gas.

Steel forging

Box 1

One illustrative example of the use of heat in large amounts and at high temperatures is the forging of wind turbine gearbox components. To make these meter-long steel pieces, the steel must first be heated to yellow heat (1200°C) and then hammered and rolled into shape, not unlike a traditional blacksmith would do, but with truck-sized handling machines and large steam-driven hammers, forging presses, and ring-rolling mills. Both heating water for steam pressure and heating the work piece to make it malleable are currently almost exclusively achieved using natural gas. This example represents only one of many ways in which natural gas is used as an integral part of high-temperature processes, and how that is making it difficult to replace it.

The state of solutions for replacing natural gas

When considering the entire temperature range of industrial heat needs, there is reason for optimism about electrification: in principle, 78% of heat demand can be satisfied with electricity and technologies already available, and 99% of heat demand could technically be satisfied in future with innovative clean technologies on which engineers and entrepreneurs are already working [4]. The gaps and challenges that remain are concentrated on the upper half of the temperature range (especially >1000°C). Most of this report is concerned with the specifics of those challenges, in particular economic ones, and discussing their solutions.

Low-temperature applications (up to ~165°C) represent 75% of the natural gas used for heat in Europe (Fig. 1) and can be electrified relatively easily with mature and market-ready technologies such as heat pumps (both domestic and industrial), electric boilers, or using district heating. The clear advantage of the clean alternatives in this temperature range is that they are already cheaper than fossil competitors (Fig. 2) thanks to their efficiency (Box 2). For any application of heat that can make use of heat pumps, it is more economic to use electricity instead of gas for heating when the heat pump's efficiency or coefficient of performance (COP) is higher than the price ratio shown on the map. For heating buildings, the COP is 2-5, depending on the weather. Although prices fluctuate, it is overall clear from Fig. 2 that, for temperature ranges with a COP above 3, heat pumps are more economic than gas across Europe. Given the optimistic outlook in this temperature range, the authors refer the reader to several other publications [7] [8] [9] concerned with making sure that these low-hanging fruits are exploited quickly.

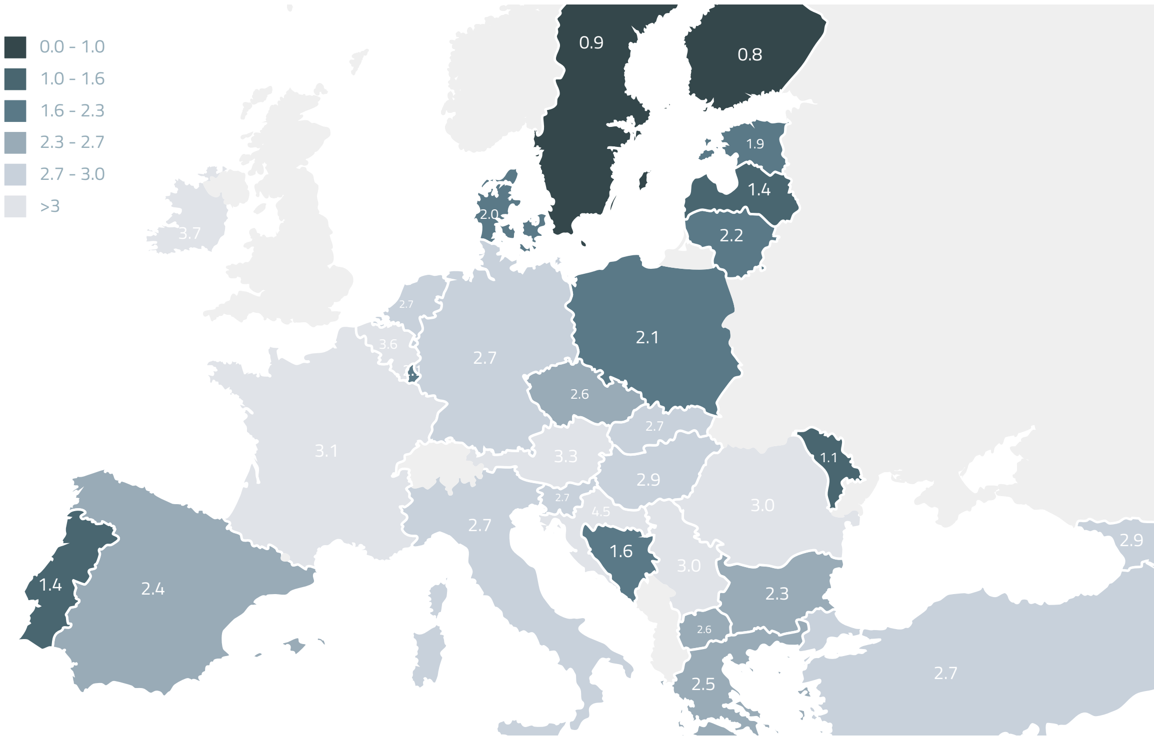


Figure 2: Ratio of electricity to gas prices, first half of 2023. Price data is for the most representative gas consumption band of 10-100 TJ (i.e. 2.8-28 GWh) and the energy equivalent 20-70 GWh band for electricity. Data from Eurostat.

Box 2

Heat pumps are the preferred solution for low-temperature heat and can be deployed today.

Heat pumps are essentially refrigerators working in reverse, cooling the environment and providing heat inside. They are especially competitive because they use electricity to collect and concentrate environmental heat rather than simply converting electricity into heat. This allows a high "return on investment" for the energy that is put in. This can go up to 500%, which is properly referred to as a coefficient of performance of 5 (COP = heat energy delivered to application / electric energy consumed). It is thermodynamically impossible to surpass 100% with natural gas, which is equivalent to a COP of 1.

While so-called high-temperature heat pumps (currently up to 165°C [10] [11], i.e. suitable for producing steam, as opposed to ordinary domestic heat pumps below 100°C) have lower COPs of around 2, they can still come out ahead depending on the price difference between electricity and gas. In addition, avoiding the need to burn gas has other practical advantages, e.g. not having to take care of the exhaust. Because of this, it can even be economical to use simple electric boilers (COP of 1). Both electric boilers and heat pumps can usually be retrofitted easily; especially in the case of heat being provided as steam, it is mostly a matter of connecting new steam-generating equipment to existing pipes. Overall, barring specific technical reasons and given access to clean electricity, heat pumps have become an almost universal solution for decarbonizing low-temperature heat.

As shown in the Sankey diagram of Fig. 1, given the high proportion of domestic and industrial heat that lies within the suitable temperature range of heat pumps, deploying them more aggressively would have a massive impact in terms of emissions reductions and the EU's dependency on natural gas imports.

The small fraction of natural gas used as feedstock for making other products can and should be replaced too. However, different considerations apply for these specific but important applications than for industrial heat, as the respective chemical processes differ more from each other than industrial heat applications. They are therefore excluded from this report and the authors refer the reader to other publications [12].

Energy storage and grid expansion would be a doubly effective solution for both high-temperature heat and keeping the grid stable and flexible while phasing out gas-based electricity. As mentioned above, one of the advantages of gas power plants is that they can be flexible and serve a balancing role in the grid. Natural gas must be replaced in this role as well, and this can be achieved by a combination of energy storage and developing clean, firm, dispatchable forms of electricity supply. While these challenges are mostly out of scope for this report, the best solutions - expanding the grid and deploying energy storage - are directly relevant to decarbonizing high-temperature heat as well. Electrified heat needs precisely that: clean, low-cost electricity from a robust energy system with firm energy sources and other flexibility tools. In return, heat storage could benefit the energy system by providing that flexibility. This report will address these critically important synergies in the section on thermal energy storage.

Overview of the solution pathways

In principle, every form of energy can be converted to heat, so there are many potential pathways to clean heat. Electric energy can be dissipated in a resistive heating element, chemicals can be burned as fuels, nuclear fuel rods heat up through nuclear reactions, sunlight focused by mirrors can be used to heat up raw materials or water. Figure 3 shows an overview of several high-level categories of low to zero-carbon high-temperature heat technologies, and which are most promising.

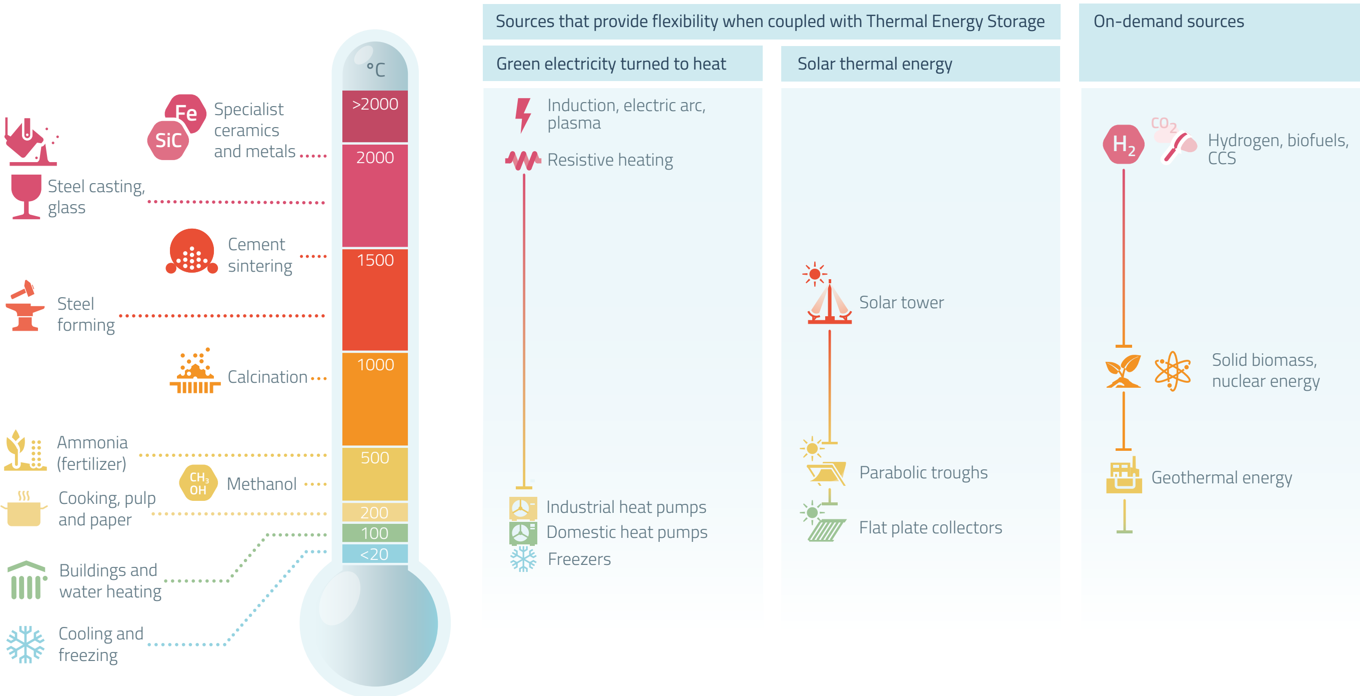


Figure 3: Potential pathways for low-carbon, high-temperature heat. Source: Future Cleantech Architects factsheet on thermal energy storage [13]

General challenges

In order to set the scene for discussing approaches that could make clean high-temperature heat possible in the short, medium, and long term, but also treat those that are unsuitable for the task, it is helpful to highlight what makes the task challenging in general.

While dense energy flows[2] are at the heart of all high-temperature heat processes, these processes are usually tailored to the specifics of the application. For example, an oven might be designed for the dimensions of the workpieces or a precise temperature profile. Consequently, a rotary cement kiln and a glass-making oven have little in common. This is qualitatively different from (and more challenging than) sectors where the same set of technologies covers the whole spectrum with little to no customization required: for example, the same battery and electric motor technology can be applied from microcars all the way to long-haul trucks.

This heterogeneity in industrial processes is relevant for how the EU should approach the challenge of industrial heat, as it means there is no "one size fits all" solution. It is usually considered difficult or impossible to add only a few electric modifications to retrofit gas-burning plants with electric heating or electrify a design devised around gas. This is somewhat less true for switching fuel and retrofitting natural gas burners to burn hydrogen, though that is far from a drop-in solution either. Industry should therefore be ready to replace fossil-fueled equipment in most cases, once the conditions for doing so have been achieved. As the section on mature solutions and economic challenges will show, capital expenditure for electric equipment is usually not a fundamental barrier in the medium term, although the changes required to facilities and operations are likely to be comprehensive in many cases. Whether companies will make that transition, i.e. decide to invest in clean processes instead of traditional equipment, or to transform an existing plant, or even retire it early (as will be required to reach net zero targets on time), will very much

[2] i.e. high quantities of energy delivered per unit volume and time.

depend on their confidence in the overall business case, which is driven by operational expenditure. This in turn depends on sustainable and predictable policy.

The energy-intensive industries face highly competitive markets, with some industry sectors having small profit margins. In addition, energy costs make up a high percentage of total cost. This means that higher energy prices, be it due to hypothetical electrification or the volatility of gas markets, can reduce those small margins further and could force companies out of the market or shift production offshore, i.e. causing carbon leakage. Across the selection of energy price-sensitive sectors of the European energy-intensive industries shown in Fig. 4, energy costs can be as high as 13% of total cost [14]. Crucially, operating surpluses are of similar magnitude; consequently, if energy costs were to double, this would directly and substantially reduce profits by 33% to 79%.

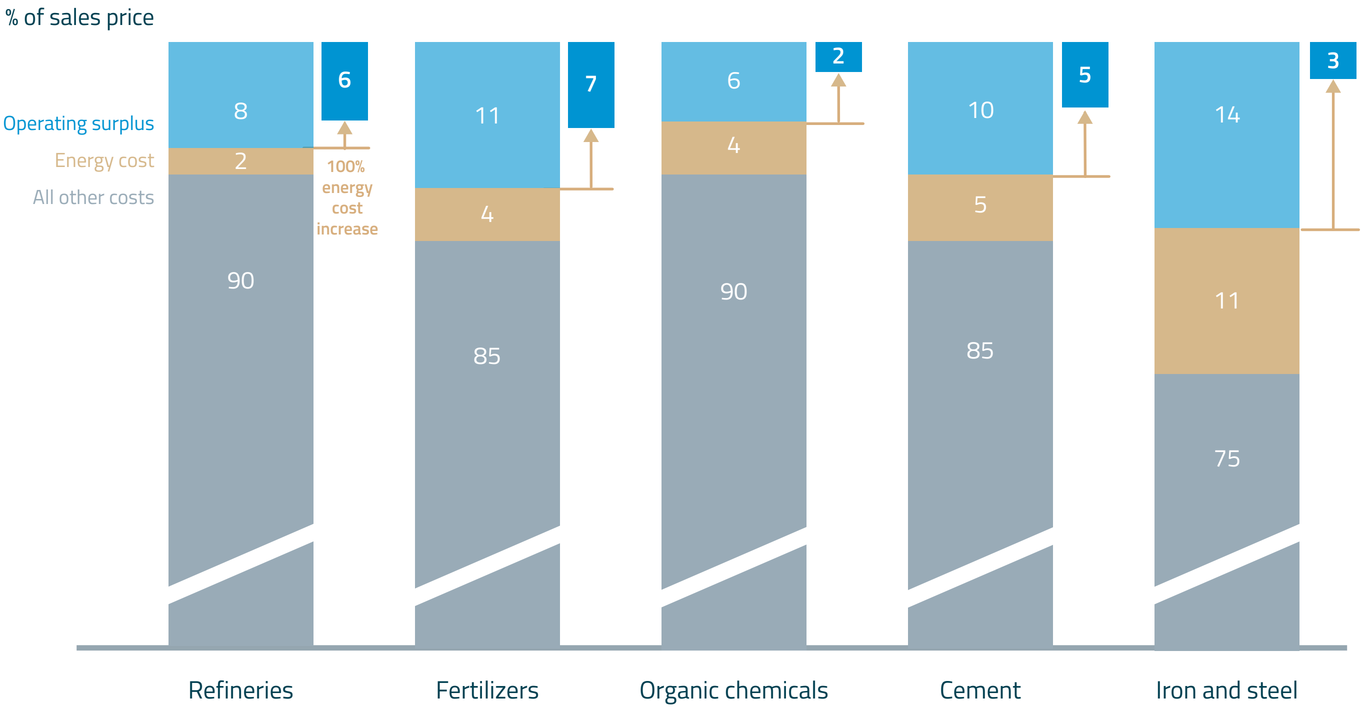


Figure 4: The contribution of energy to cost for energy-intensive industries is of similar magnitude as operating surpluses. Data from 2017 [14].

Insufficient solutions

Before focusing on the most promising high-temperature heat solution pathways, it is important to discuss alternatives that are frequently considered but fall short in reality.

Increased efficiency

Energy efficiency is already high for most existing high-temperature heat processes. Small margins and high energy costs have been a fact for most industries for many decades, and recent years have also seen a redoubling of efforts to improve efficiency to reduce emissions (-14% since 2010 [3]), so most low-hanging fruit have already been exploited (hence the plateaus in Fig. 5). In the EU, scientists and engineers have come impressively close to many processes' fundamental thermodynamic limits [15]. High-temperature waste heat escaping as exhaust heat without recycling makes up 9% of industrial energy consumption [16]. More recycling is usually not attempted because it is simply not practical to do so, in part reflecting already high heat recovery rates. However, it is important to note that there may be worthwhile efficiency improvements possible with more fundamental technological changes, away from mature gas burner technology.

Beyond energy efficiency, there is significant room for improvement in terms of material-use efficiency on the demand side. For example, building designs often use excessive amounts of structural steel and concrete elements to save on labor costs; by simply making better choices in early-stage design, building frames could reduce embodied carbon by 40-60% [17]. Material efficiency can thus help to make decarbonizing high-temperature heat a smaller and more manageable task for society as a whole by reducing demand for materials and the resources involved in their production. Still, even with the most ambitious approaches, efficiency is necessary but not sufficient for a full solution and requires further considerations beyond the scope of this report.

Biomass and biomethane

Biomethane is chemically identical to natural gas, apart from trace compounds, which means once it is produced, its advantages and disadvantages as a fuel are very similar to those of natural gas. Unfortunately, this includes that it is a potent greenhouse gas in itself (80 times worse than CO_2 over 20 years, 30 times worse over 100 years) when released unburned, commonly from leaky tanks and pipes.

Biomethane is produced by fermenting organic materials and wastes, i.e. by using microorganisms to convert carbon-containing agricultural feedstock into a carbon-containing gas (methane, CH_4), with some loss of energy for the metabolism of the microorganisms. Plants produce

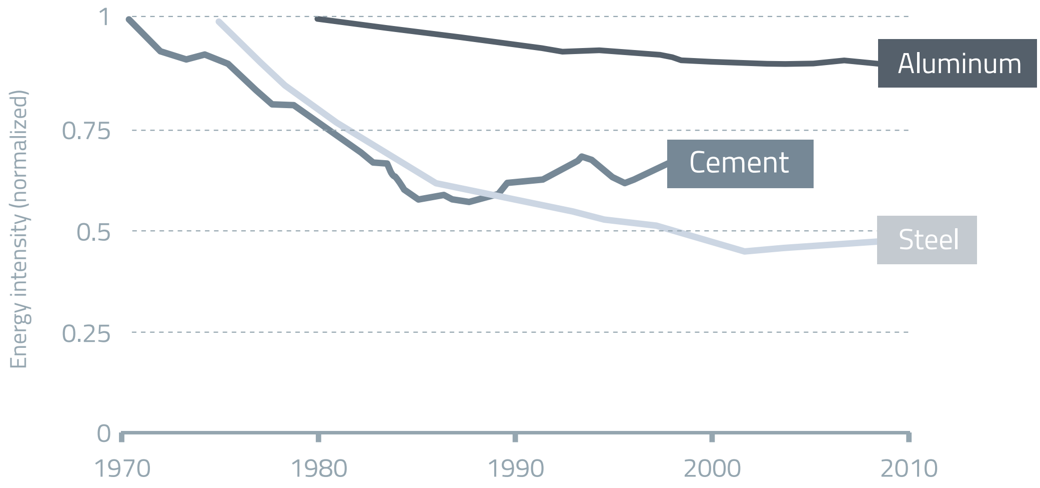


Figure 5: Historical trends and plateaus of the normalized energy intensity for the production of industrial materials. Data from Allwood et al [15], normalized by Future Cleantech Architects.

the feedstock by capturing carbon as CO_2 from the air and fixing it as wood, leaves, fruits, and other biomass via the process of photosynthesis. This growth requires energy, which is supplied by sunlight and to some degree fertilizer, which itself is mostly derived from natural gas. On paper, assuming almost all inputs into the system are decarbonized and leakage is negligible, biomethane is a zero-emissions fuel, as the carbon that ends up in the air after combustion of plant matter was originally taken from the air by the plants and did not come from fossil deposits as is the case for natural gas. In practice, the picture is much more complex and depends on thorough lifecycle analyses [18], the results of which depend on multiple factors such as the feedstock considered and leakage rates along the value chain, which are probably under-estimated in many cases [19]. Consequently, the LCA literature spans a broad range (from -1700 to +500 $gCO_{2,eq}/kWh_{el}$[20], i.e. the upper end is in the same range as unabated natural gas), making it difficult to definitively conclude as to the climate benefits of a switch to biomethane for industrial heat.

The supply of biomass and biomethane is highly constrained. While there may be scope for increasing the scale of biomass production - the EU currently produces 200 TWh of biogas compared to a potential of 600 TWh (17% of current consumption), according to the IEA [19] - the supply of all forms of biomass will remain constrained compared to the numerous applications competing for it, such as fuel for shipping or aviation, high-temperature industrial heat, and balancing the power grid over seasonal timescales[3]. While it will be important for a net-zero energy system as a whole, the role of biomass in high-temperature heat specifically is likely to be limited.

Hydrogen

Hydrogen gas can theoretically be produced in many ways. The most mature production method for clean hydrogen is electrolysis, but it is relatively inefficient, expensive, and capital-intensive. Electrolysis uses electricity to split water (H_2O) into hydrogen (H_2) and oxygen (O_2) gas (where the former is also known as green hydrogen if the electricity used is renewable). On the molecular level, this is simply the reverse of combustion, but a significant percentage of the electric energy – about 35% – is lost as low-temperature heat when producing hydrogen in this way. While there are potential ways to make production more efficient, some loss is thermodynamically inevitable. It will likely always be energetically and economically advantageous to avoid the conversion of electricity and use it directly instead [12].

[3] To name the most deserving ones. By contrast, biomass is still used today for many other applications, such as low-temperature heat, where other low-carbon options are available. Given the scarcity of the resource, the world will have to prioritize the use of biomass and biomethane for applications that have very few or no alternatives.

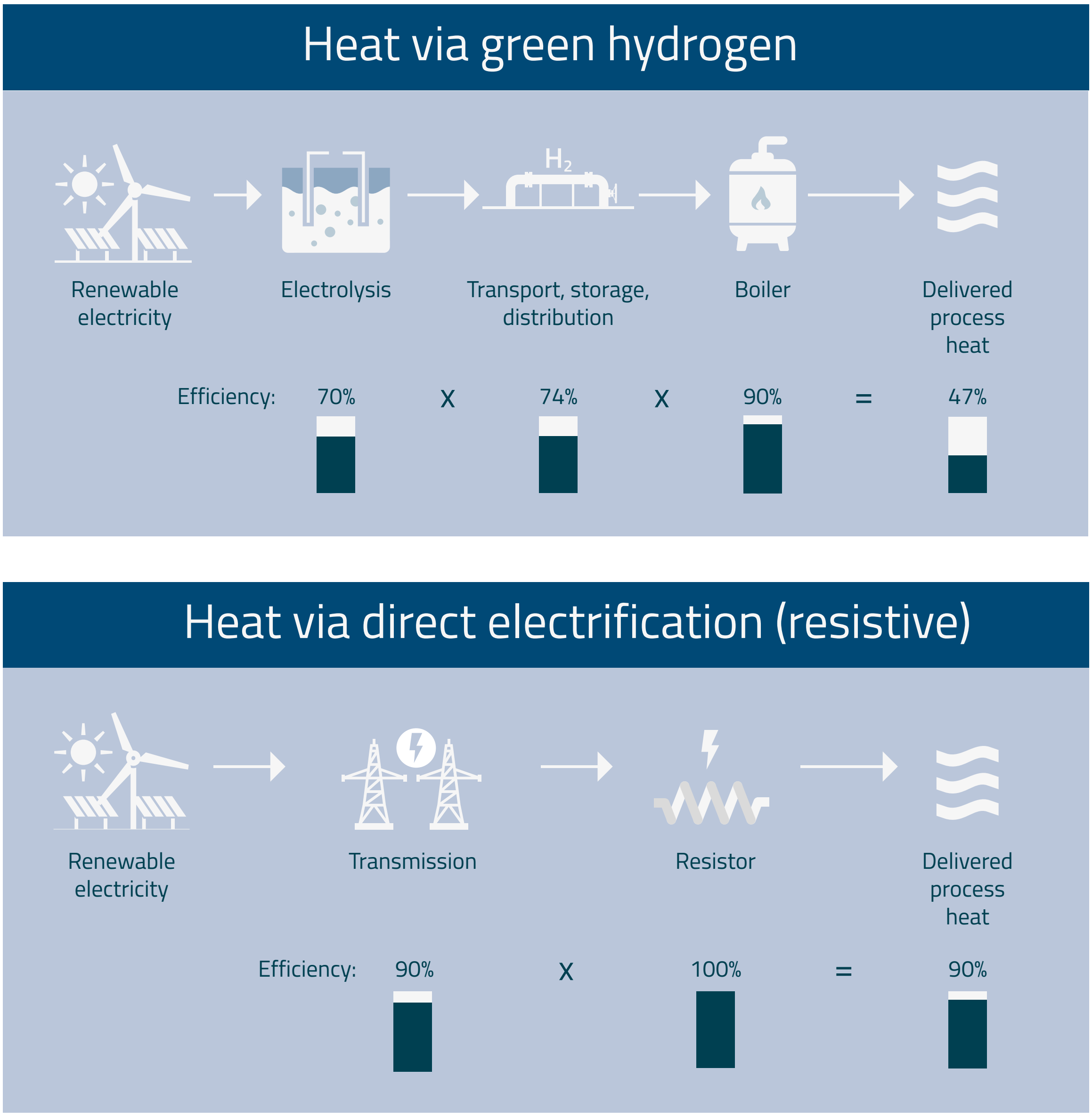


Figure 6: Efficiency losses of hydrogen combustion for heat compared to direct electrification. Data on hydrogen from [21].

Hydrogen cannot directly replace natural gas, as it behaves and handles very differently, further increasing its cost. Hydrogen is chemically different from natural gas; notably, its low volumetric energy density means it takes up much more space in tanks, **even when it is cooled to lower temperatures or put under higher pressure than natural gas,** which is one of the main reasons why transport is expensive [22]. In addition to energy losses from production, many transport methods incur yet more losses, e.g. for pressurization, and natural gas distribution lines cannot be easily retrofitted to deliver hydrogen. Conversion steps such as producing synthetic carbon fuels (also known as e-fuels) by combination of hydrogen with captured CO_2 are even more costly in terms of energy and capital costs: not only is more energy lost in the conversion, but additional energy must also be expended to capture dilute CO_2 from the atmosphere, which also requires stringent accounting to ensure the fuel is indeed net-zero and does not contain fossil CO_2 from point sources, e.g. from cement production. On top of these drawbacks, synthetic fuels produce essentially the same combustion products as fossil fuels, including harmful particulates. Pure hydrogen burns differently than fossil or synthetic natural gas and is consequently not a drop-in fuel for high-temperature heat processes. Among other issues, tanks, fuel lines, and burners must be adapted to its propensity for diffusion through many materials, on account of the small size of the H_2 molecule. Additionally, hydrogen flames exhibit low radiative heat transfer and require higher flowrates to compensate for the low energy density. Finally, the changed combustion atmosphere also has an increased tendency to form harmful NOx gases, while the pure hot water vapor it is composed of may be chemically detrimental to some processes.

Hydrogen mostly faces the same problem as electric heating, namely high electricity cost, but it is made significantly worse by inefficient production, likely outweighing its advantages for retrofitting. In a side-by-side comparison with hydrogen, electric heating is superior on almost every count. Electric heating has inherently lower energy losses and therefore lower costs for production. This is both because of the electric heating itself being more efficient than hydrogen combustion and because hydrogen contains less energy than the electricity needed to produce it. To be clear, both hydrogen and electric heating require companies to modify their equipment and operations, but replacing natural gas with hydrogen does require smaller changes to existing equipment while switching to electric heating equipment usually amounts to a full replacement. Still, because energy costs dominate the lifetime cost difference between the alternatives (typically around 85%), hydrogen's advantage in CAPEX is not enough to overcome its main drawback, namely the additional costs from production, energy losses, and transport. Hydrogen can be made to come out ahead with optimistic assumptions around long-distance transport from very renewable rich regions, but these do not apply widely enough to justify relying on hydrogen instead of electric heating. Moreover, long-distance imports of hydrogen would directly contradict European aspirations to energy security, as would inefficient domestic hydrogen production for applications where direct electrification is possible. Finally, however, it is important to note that none of this should detract from the fact that green hydrogen is still vital for several chemical and industrial applications, where it needs to be scaled up to replace natural gas, most importantly for producing steel via the DRI route and producing ammonia for fertilizer, as discussed above.

Box 3

Special cases for hydrogen heating: refineries

Blue hydrogen produced from residual gases, primarily methane and ethane, has emerged as a viable option to decarbonize medium-temperature heat processes (below 600 °C) in oil refineries. Currently, these facilities generate heat using a combination of residual gases and natural gas. Potential methods to achieve decarbonization of heat in refineries include deploying carbon capture and storage (CCS) in furnaces or producing low-carbon hydrogen from the residual gases to use as fuel. Ongoing efforts in the UK [23] and the Netherlands [24] are focused on implementing low-carbon hydrogen produced from residual gases and natural gas in refineries to reduce carbon emissions from medium-temperature heat processes.

However, to ensure blue hydrogen is beneficial for the climate, it requires high carbon capture rates and stringent control of upstream methane emissions. An alternative decarbonization pathway involves electrifying the medium-temperature heat processes in oil refineries and then using residual gases solely as feedstock for downstream processes, such as the petrochemical industry, where the carbon from these residual gases is not released. This alternative should be assessed against other routes, such as using hydrogen as fuel or implementing CCS, to determine the most effective approach for decarbonization.

Carbon capture

Carbon capture for high-temperature heat works essentially like any other CO_2 capture technology: instead of releasing CO_2 from burning natural gas into the atmosphere, it can be captured and stored, e.g. underground in stable rock formations[4]. A mix of burnt gas and air is called flue gas. While it is rich in CO_2 compared to ambient air, it is otherwise much like regular air, containing 78% nitrogen, so storing all of it would be inefficient. To separate out the CO_2, the flue gas stream is made to interact with an adsorption medium, a material that CO_2 preferentially "sticks to" on a molecular level, instead of being carried along with the rest of the gas stream.

These techniques are well established but require extensive infrastructure and additional cost and coordination. CO_2 separation is common in industry, for example when shipping natural gas via LNG tanker, where CO_2 content must be as low as 0.005%, as otherwise solid CO_2 ice may form at the temperatures of LNG and block pipes. However, such high capture efficiency is very expensive: even when allowing for 10% of the CO_2 to escape, the avoidance costs are at least 60 EUR/tCO_2 or roughly 12 EUR/MWh for gas [25], in part due to the energy needed for the separation process. More importantly, CCS would also require the EU to build an entire new infrastructure system: capture systems at the industrial site, pipelines to potentially far-flung storage sites, and the storage sites themselves. This is not accounted for in the above figure, and, in addition to the financial price tag, carries with it significant political costs as well. Moreover, CCS only works when the facility is part of a hub such that appreciable quantities (say above 1 Mt/year) can justify the infrastructure buildout. Consequently, CCS and its associated infrastructure would pose challenges that are certainly not easier than electricity grid expansion, where more tools are available.

Even if the use of CCS could be enforced globally, it could lock in fossil fuel dependency and fail to curb other harms of fossil fuels. The dilemma for CCS is that any plant's operators could always increase their profits by disconnecting the carbon capture subsystem if they are not compelled to keep capturing CO_2 by extrinsic incentives, e.g. carbon prices. If there are no incentives to begin with, e.g. because reducing poverty by economic growth is the more pressing priority, as will be the case in many parts of the worlds for decades to come, there is no reason to use CCS. Indeed, even where the green premium could be affordable, economic competition would lead to operators being forced to work without CCS in most cases. Finally, decarbonization is not just about the climate impact of gas burners, but also about energy security concerns, emissions from upstream methane leakage [26], or the particulates that still escape filters and damage lungs and hearts [27]. CCS does much less to help solve any of these, making it an even poorer choice for decarbonizing high-temperature heat.

[4] There are many different variants of carbon capture. Blue hydrogen removes carbon from natural gas before burning it by converting it to hydrogen and CO_2, capturing the CO_2 and burning the hydrogen later. One can also avoid the need to separate the CO_2 entirely by combustion of natural gas in pure oxygen, i.e. without the 80% nitrogen from ambient air present, which yields mostly pure CO_2 (oxyfuel combustion). However, at the level discussed here, the differences are not significant to the overall picture.

Mature solutions

Multiple solutions are in advanced stages of technological development and close to being deployed, some with decades of technological experience backing them up on the path to large-scale application. Electric heat and thermal energy storage are a very complementary combination that promises to not only decarbonize high-temperature heat, but thermal storage also offers additional benefits such as lowering operating costs of electricity and providing flexibility to the rest of the energy system.

Electric heating

Electric high-temperature heat is a mature technology with many variants (see Box 4) [4]. **Given the right policy interventions to reduce electricity prices to shrink the price gap with gas, it can be the main solution for many high-temperature heat processes.** Electric heat devices have previously been used mostly at smaller scales for specialized applications. However, the scale of total use and the size of individual applications are not linked to technological maturity here, as they often are in other upcoming decarbonization solutions. Apart from prominent exceptions like electric arc furnaces (EAF), the applications of electric heat are smaller and specialized today, but that does not mean that they are at a low technological readiness level. Quite the contrary, they have many decades of experience behind them, which stands ready to be applied to scaling up. Although one should not underestimate the required engineering work to redesign existing processes, expanding electric heat use to large scales is not a big technological step in most cases.

Electric heat is an ubiquitous everyday technology. From toasters to electric tea kettles, the operating principle is the same as for their most common industrial equivalents: electric current is driven through a resistive heating element - a material with suitable electric resistance and ability to tolerate high temperatures - which converts the electric energy directly into heat. How the heat is then transferred to the workpiece, i.e. the food in the analogy of cooking, may be quite different though. In the case of electric high-temperature heat, a toaster is often the best analogy, because at high temperatures radiative heat, as emitted from glowing heating elements, is the most important heat transfer mechanism.

The entire range [28] **of industrial temperatures can be covered with electric heat,** as seen in Fig. 3. In fact, the range is wider than for burning fossil fuels or hydrogen, especially when considering more advanced methods such as plasma, lasers, electric arc, or electron beam heating (see Box 4). Many electric heating methods also have an efficiency advantage of 10% or more [29] over burning gas, as much of a flame's heat energy remains in the exhaust gas and is always only partially recoverable [30] [31].

Box 4

Variants of electric heating: resistive, induction, arc

Apart from driving current through heating elements that give off heat to the work piece, there are many other variants of directly or indirectly making use of electric energy for heat generation. In some applications, such as melting certain glasses, the current can be driven through the workpiece itself, heating it directly and very efficiently. Inductive heating is a variant of this where, for appropriate materials, applying electromagnetic fields creates loops of electric current in the material itself, heating it from within.

One of the largest applications of electric heating today is in electric arc furnaces for melting metals, mostly steel. Here, the electricity goes through the materials in the crucible as well as through the air in the form of rapidly changing electric arcs that also radiate heat.

For specialized applications, electric energy can also be used to produce beams of laser light or electrons hitting the material to be heated in precisely controlled ways. Radio or microwave frequency radiation (RF heating) is another way to cause movement of electric charges within a material that dissipates into heat.

There are many ways to enhance or modify the transfer of heat, such as air fans or heat transfer media, as well as many other techniques or variants of the techniques mentioned here. Although most of them are currently mainly used in specific processes, they are in principle mature technologies, highlighting the broad applicability of electric heat.

Thermal energy storage

Thermal energy storage has the potential to make electric heat economically competitive with gas in the medium term, if its use is properly incentivized and enabled by policy. It is a straightforward technology that has been used in some forms for millennia, e.g. storing snow and ice for the summer months. Essentially, it is a battery for heat or cold.

Heat can be stored in three ways: by increasing the temperature of a material, by changing its physical state, or by a thermochemical reaction. Subsequently holding the material in a large, insulated container enables the heat to be retained for a long time (though not indefinitely, as heat losses will still occur). The first way is called sensible heat and involves heating a material to a higher temperature (e.g. water from 20 to 60 °C in a domestic boiler). Alternatively, heat can be stored as so-called latent heat, by causing a physical change in a substance that can be later reversed to release heat (e.g. melting/freezing water), or in a conceptually similar manner using thermochemical changes to a substance. Reusable hand warmer packages employ one variant of this principle. When delivering the heat from the thermal store to the industrial process, there are also several options: transferring heat through an opening as radiation, i.e. infrared light, or by passing some fluid through it, like air or water, to pick up the heat and transport it from the storage to the process via heat exchangers.

The combination of electric heat and heat storage has the potential to reach cost-parity with gas in the medium to long term, because renewable energy has the potential to be very cheap if demand can be made to follow supply, which heat storage would enable at low cost and at scale thanks to the relative simplicity of the technology.

Most mature heat storage techniques use sensible heat storage in very cheap and durable materials like water, thermal oils, molten salts, or sand, which are around 6 times cheaper per kWh of capacity than lithium-ion batteries[5] [29] [32] [33] [34]. Because of this, heat storage plausibly solves a major problem for renewables in the cases where it can be used, namely the gap between levelized cost of electricity and levelized cost of load coverage. The latter includes costs related to storage, demand flexibility, and grid fees, among others, many or all of which could be greatly reduced by suitable combinations of electric heat and heat storage. The economic analysis is detailed further in a subsequent section of this report.

Apart from much lower cost, thermal storage has advantages over batteries and many other energy storage technologies operating on the timescale of hours to days. Among these are higher efficiency (95% [29] [35]), no rare material requirements, and no capacity degradation over time. Heat storage is unique among energy storage methods because charging efficiency in other technologies is often about minimizing energy wasted as heat, while for a heat battery, turning the input energy into heat is the goal. For discharging, the temperature of the heat battery must be a bit higher than that of the target process and transfer is not perfectly efficient, but these losses are low if the system is well designed. Another minor source of energy losses is the leakage of heat in the charged state, i.e. the gradual cooling of the storage medium, which depends on how long the stored heat is held before being used; for most cases of industrial heat, thermal storage is cycled on a timescale of days, so these losses are minor too.

Thermal storage can, in principle, cover most of the industrial temperature range. Currently, storage above 1000 °C is not exceptional and there is little technical reason to doubt that 1800 °C will be commercially available within a few years. This is sufficient to cover more than 93% [4] [29] of industrial heat needs. There already exists a growing industry of startups and scaleups offering solutions for high-temperature heat storage. Scaling these ideas up from toasters, domestic boilers, and hand warmers to industrial heaters, large thermal tanks, and high temperatures is a matter of engineering rather than scientific breakthrough. Historically, the prevalent use of natural gas, which is easy to store and can be burned on demand, has meant there was no need to store heat, resulting in an only recent emergence of new companies working on thermal storage. However, as intermittent renewables become more prevalent and industries electrify, there is a growing market for energy storage as European and international companies become aware of the growing potential to charge when it is cheap or with their own low-cost supply.

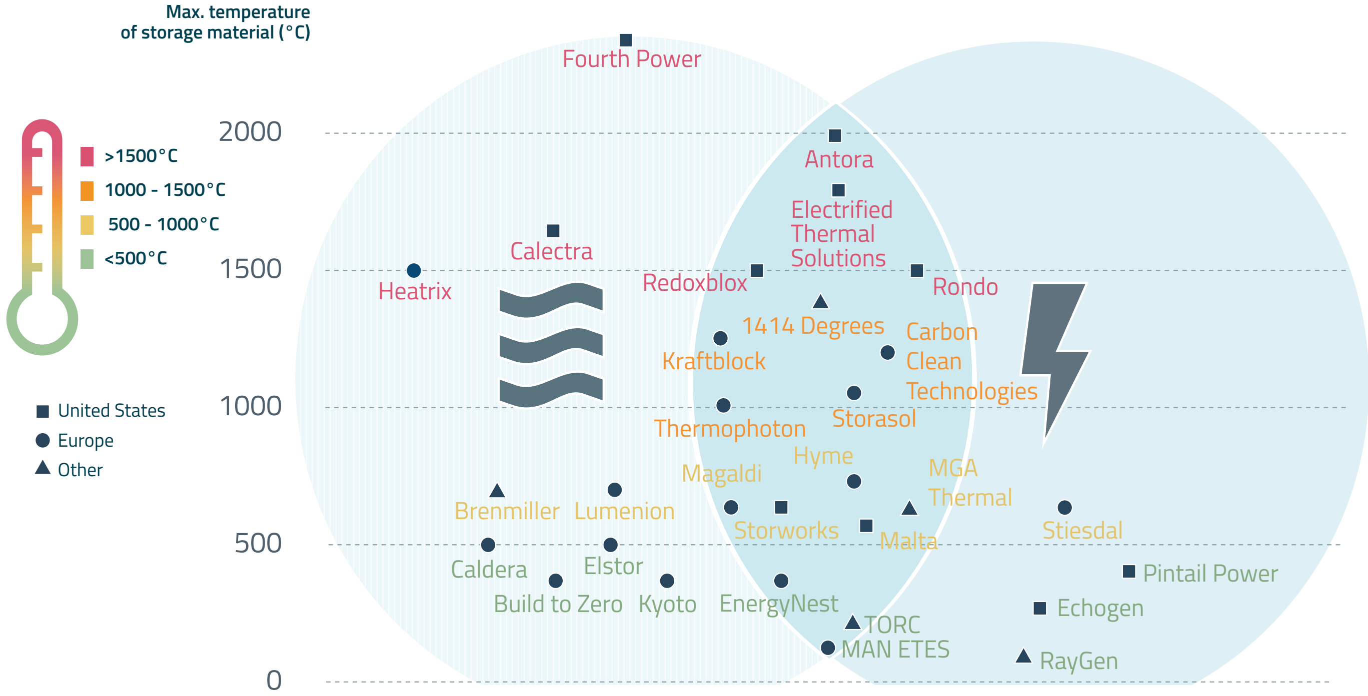
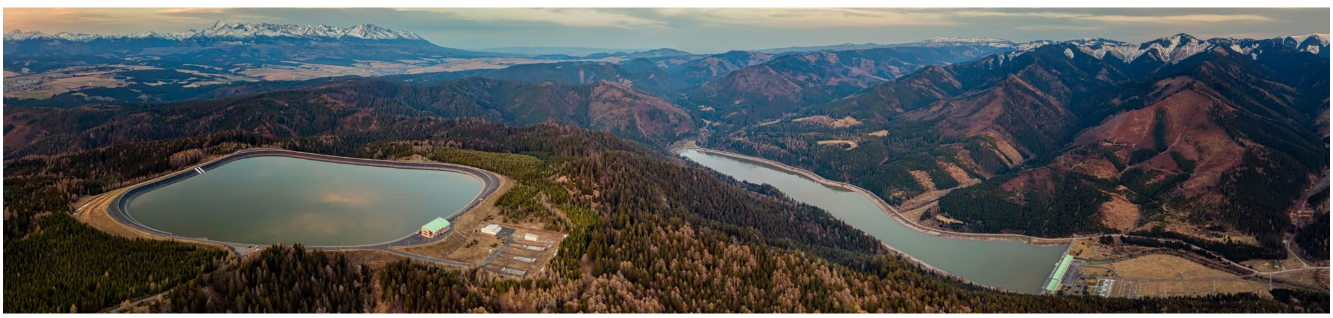


Figure 7: Non-exhaustive overview of main thermal storage companies, ranked by temperature, target application (industrial heat[6], power, or both), and location of headquarters. Data taken from company websites.



[5] These advantages are, in fact, big enough that there are innovators who propose the same technology for electricity storage, accepting the high conversion losses from turning electric heat back into electricity.

[6] Not shown here: thermal storage for domestic and district heating.

Obstacles

Technical challenges

Despite the maturity of electric high-temperature heat, it is still at the pilot stage for some applications, mainly those with high throughput at the high end of the temperature range, such as cement. Rotary kilns for cement production are a type of industrial oven in the form of a large inclined rotating steel pipe. Inside, there are powerful burners that can produce over 10 m long flames, carefully shaped to control the process, in order to heat the cement clinker to 1450 °C.

High power density and high intensity of radiative heating are some of the key advantages of flames over electric heating elements, keeping the physical dimensions of the process compact and thereby reducing heat losses and cost. Carbon-fueled flames are bright yellow, thanks to glowing particles formed in the combustion process, and they radiate their heat as light over a broad spectrum. This is challenging to replicate with electricity because the heating elements would melt or vaporize at these power levels. To solve this problem, electric plasma burners and other approaches are in development, which will be showcased in a later section of this report.

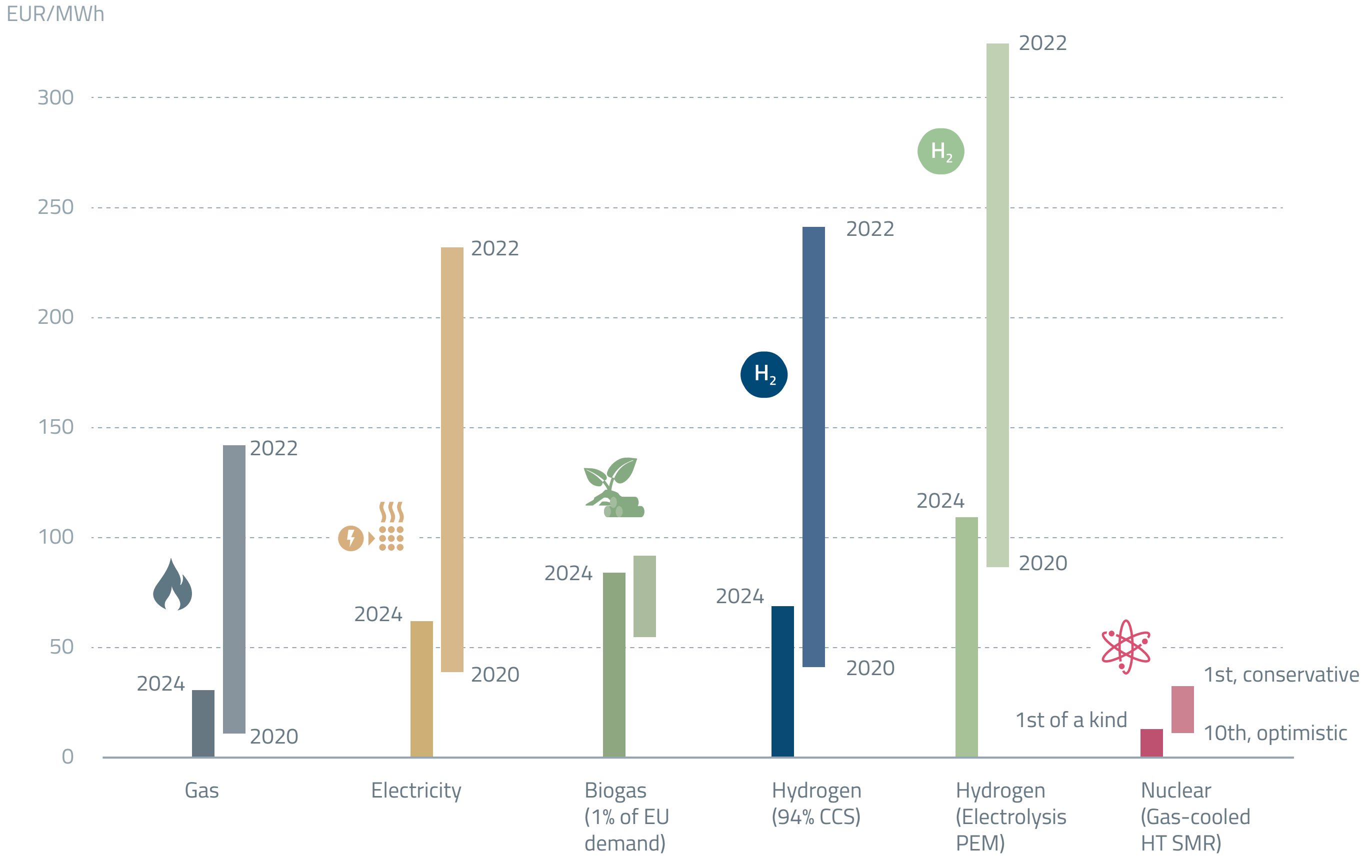


Figure 8: Comparison of the cost of industrial heat from clean sources versus the natural gas benchmark. Note that the nuclear high-temperature heat cost estimates are for up to 950 °C, somewhat lower than the other options shown; biogas cost range depends on scale of production facility. Sources: CATF hydrogen finance model[7] [36]; ENTSO-E [37] [38]; ICE [39]; literature review of advanced nuclear reactor cost estimates [40].

Economic challenges

The main economic challenge for electric high-temperature heat is not capital cost but rather the higher operating costs of electricity compared to gas. For most companies with high-temperature heat needs, going electric would, in principle, not mean sinking capital costs into a risky experiment, but rather installing proven technology. However, in most cases, operating costs for energy dominate (5-6 times higher than investment costs [41]), often outrunning installation cost within a few years [42]. Because of this, operating costs are a large lever on profitability, and with electricity usually being 2 to 3 times more expensive than natural gas, the economic balance is currently very much in favor of gas, as demonstrated in Fig. 2. This is especially true for high-temperature heat applications, as opposed to low-temperature heat applications, since there is no heat pump efficiency advantage to make up the difference (COP > 2 to 3). Crucially, this price gap is between the averages; while gas prices are relatively stable on a daily basis, electricity prices can actually go much lower on this time scale, which heat storage systems could take advantage of for charging. As can be seen in Fig. 9 from the substantial fraction of the red curve close to or below zero, the variability of renewables is currently driving an increase in the occurrence of low-price periods, which thermal storage technologies could take advantage of.

Thermal energy storage has the potential to eventually make electric heat cheaper than gas, though this is not necessarily guaranteed as it depends on several enabling conditions.

[7] Optimistic assumptions were used as inputs in CATF's calculator tool for hydrogen costs. Green: 100% capacity factor, low CAPEX, high electrolyzer efficiency. Blue: free electricity, no carbon price, only the cost of the natural gas and 90% CCS.

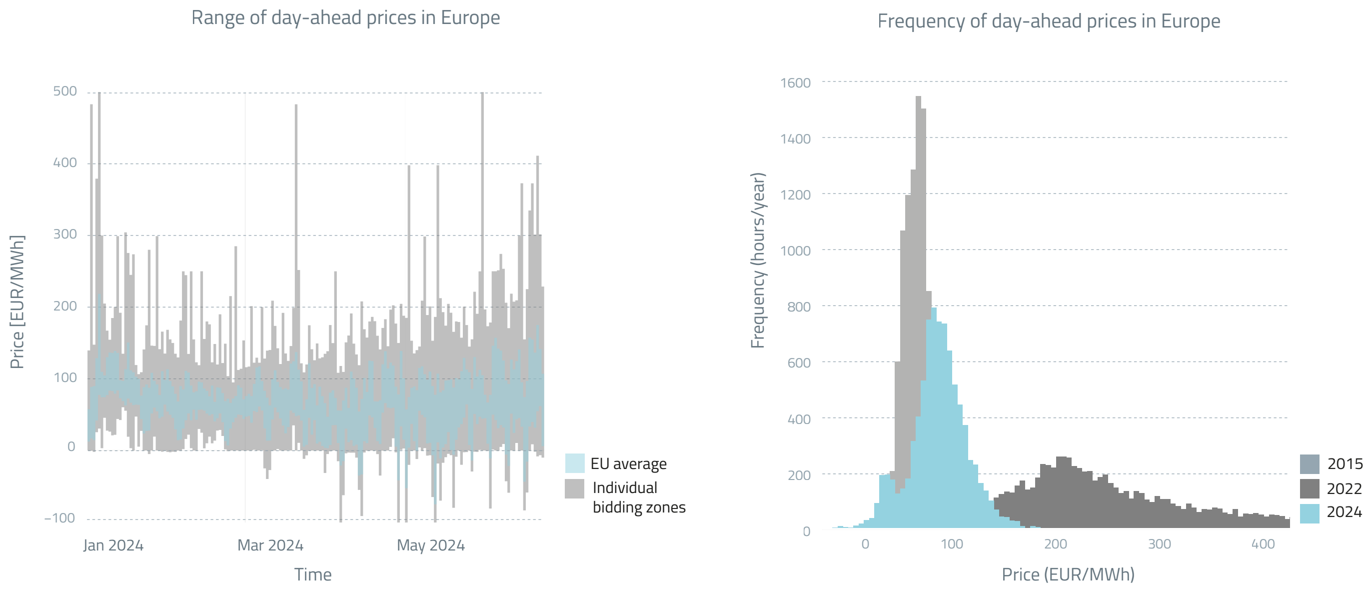


Figure 9: Temporal distribution of electricity prices in Europe. Left: day-ahead prices in 2024 for all bidding zones (grey) and the weighted EU average (blue). Right: frequency of prices in 5 EUR intervals for selected years. The 2022 data shows the massive increase and broadened range of electricity prices, due to the very high cost of the gas used to operate the price-setting peaker gas power plants. Compared to 2015, prices are still elevated in 2022, while the frequency of oversupply of electricity has increased, causing hours of low or negative prices. Data: ENTSO-e [37] [38]

Most importantly, thermal storage for electric heat needs low-cost electricity for at least some fraction of the time. However, the conditions causing periods of low prices must be sustainable over the long term, meaning they should not be a symptom of systemic or local oversupply of electricity or similar temporary circumstances. Rather, they should reflect market conditions that reward flexible consumers, like thermal batteries, for the valuable service of shifting their consumption to take advantage of the less valuable – from the perspective of the rest of the market – hours of the day. Moreover, the uncertainty in forecasting the fluctuations of future electricity prices, especially in a future with various sources of flexibility competing for low price periods, is in itself another barrier when planning the business case for industrial electrification. Even so, low average costs of electricity are still a necessity for electrification. Among other reasons, this is due to the fact that thermal batteries would compete with each other as well as with lithium-ion batteries or similar electricity storage systems that are more expensive but can also supply their energy to more potential customers via the grid. In general, renewable resources need to be plentiful, diverse, reliable enough, and ideally close to the thermal battery to achieve a low levelized cost of electricity. This depends on the development of the power system as a whole, which is uncertain. Even if that development generally goes relatively well thanks to decisive and effective policy, in the short term, gas prices may remain too low for electricity to be competitive in some locations if no subsidies or carbon prices intervene. However, it is important to note that gas and other fossil markets have suffered from severe volatility on many occasions (with equally severe consequences for industry), so uncertainty must be faced either way, with one difference being that electric heat has a plausible path to become much less uncertain in the future, as illustrated in Fig. 11.

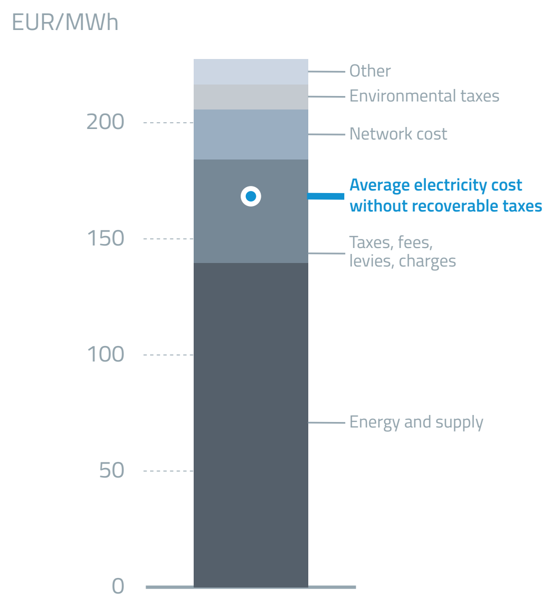


Figure 10: Breakdown of the average factors behind electricity prices (2023 EU average) for a large consumer in the 20-70 GWh band, comparable to the most representative gas consumption band (2.7-27 GWh). Depending on the applicable tax law, different kinds and amounts of taxes are recoverable, but, on average, large consumers pay mostly for energy supply and network cost, and much less for taxes. Data: Eurostat [43]

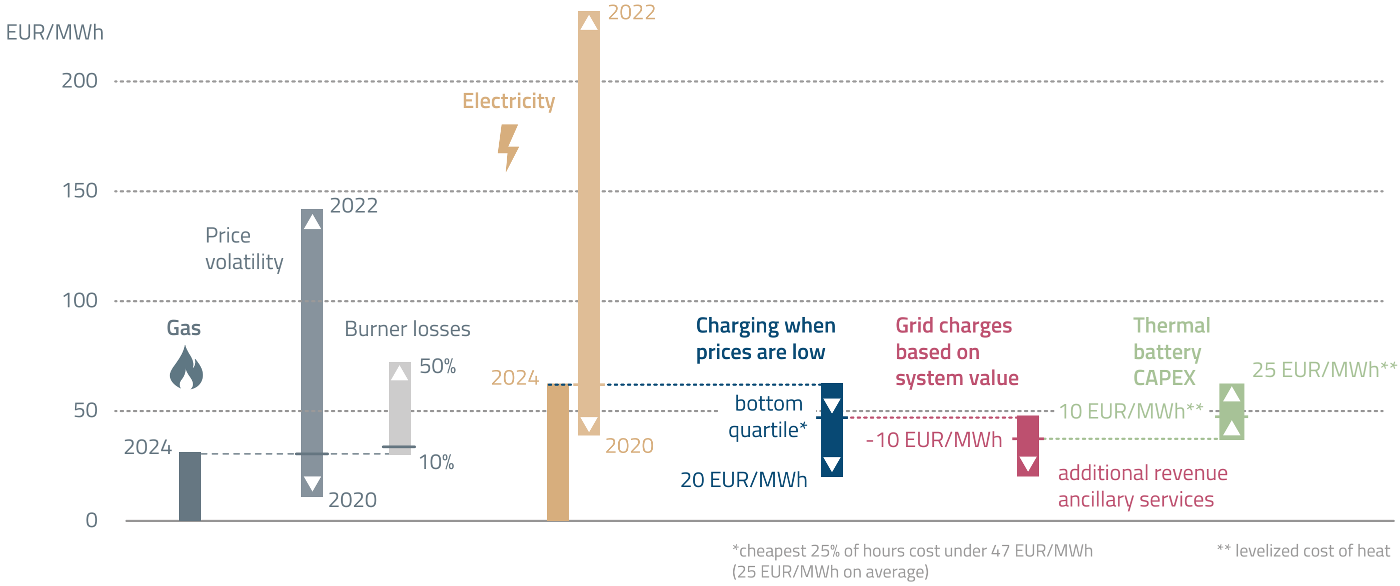


Figure 11: Comparison of cost of heat for gas versus electricity with thermal storage (excluding gas CAPEX). Bars show ranges of plausible values for cost components, from conservative to optimistic and a central estimate (center line). Comparing the final central cost estimates to the right of the figure shows that the potential for cost parity is there, but also that it is highly uncertain and dependent on the electricity price and consequently dependent on circumstances and effective policy. Data: ENTSO-e [37] [38]

Thermal storage is technologically relatively simple and can therefore be cheap. However, to capture the full potential, it is still necessary to reduce capital costs for heaters and heat extraction equipment (charge and discharge power, both in $kW_{thermal}$), and the heat storage material itself (capacity, in $kWh_{thermal}$). Today, this is roughly 100 USD/$kW_{thermal}$ for charging and 300 USD/$kW_{thermal}$ for discharging power capacity, and around 5 USD/$kWh_{thermal}$ for energy capacity. In the future, these values may fall to 40 USD/$kW_{thermal}$ for charging and as low as 1.50 USD/$kWh_{thermal}$ [29] [35] [44]. As European companies will most likely consider brownfield sites, the proper case to compare this potential investment to is that of refurbishment of gas fired equipment, which is likely to be cheaper than an electric heat setup with storage. Nonetheless, because the lifetimes of most industrial processes, including high-temperature processes, are more than 15 years, these differences in investment cost would be outweighed by lower energy costs in almost all cases, highlighting the importance of low electricity prices once more[8].

Additional revenue streams for owners of thermal storage may include providing grid-related services, but how much this could contribute depends on local conditions. For example, ancillary services markets are usually shallow, meaning only few thermal batteries may have this additional opportunity. Moreover, in many cases these markets are not set up to take full advantage of flexible consumers such as thermal storage and reward them, as we will see in the next section.

Infrastructural challenges

The electric grid is not ready to handle the amounts of energy required for the energy transition. In most of Europe, there are too few power lines and substations to transmit enough electricity to every place that needs it. This is a large-scale problem that stands in the way of many decarbonization solutions, not just widespread use of electric high-temperature heat. 222 GW of mainly solar renewable generation capacity are expected to be complete, but not connected to the grid, by 2030 under business as usual [45]. Consequently, clean electricity is more expensive and less accessible than it could be.

Electricity must become cheaper. This means that grid expansion must not only catch up with the expansion of renewables, but also accelerate to encompass many new assets [46]. The entire range of tools to reduce power system costs – renewable deployment, long duration energy storage, flexible demand tools, firm power generation, and others – needs a grid with much larger capacity than the EU currently has in order to be fully effective. Both deploying these tools and expanding the grid must be accelerated by all available means. Cheap, abundant, clean electricity is not optional; this is true for almost all decarbonization efforts, not just high-temperature heat. Therefore, any effective effort in this direction constitutes a no-regrets policy.

In particular, the SMEs of the processing industry are often not connected to enough high-capacity transmission lines and substations. High power connections require space near the plant as well as capital in addition to that for the new electrified equipment. Space and other such practical problems can be severe for individual small companies. Even more challenging is the immense organizational and political coordination work that company management needs to undertake, together with local authorities and transmission and distribution system operators, to get a new connection built between their plant and the nearest substation. Compared to larger companies, SMEs often have less experience with large-scale infrastructure projects requiring extensive permitting, which puts a disproportionate burden on them[9].

[8] For a rough illustrative order-of-magnitude calculation, consider a system with 48 h of heat storage, charging for about a quarter of all hours while continuously supplying 1 MW of heating power to an industrial high-temperature process. With the current equipment cost quoted above, it would have an estimated investment cost of 840 000 USD. However, the energy costs over this time are much higher: assuming 75% uptime and an average electricity price of 35 EUR/MWh, this yields 3.45 million EUR over 15 years. Hence a price difference of less than 10 EUR/MWh would be sufficient to offset the additional investment cost for electric equipment in this simplified but also conservative example (neglecting other factors, and assuming no cost for refurbishing fossil equipment).

[9] One reason is that, in many cases, there would not have been such needs in the past. Existing plants were most likely built at a site where connecting to energy infrastructure was easy, i.e. close to gas distribution lines. Even if this was not possible, delivery of liquified or pressurized natural gas by truck is relatively easy.

Thermal storage could potentially not only lower energy costs of electric high-temperature heat, but also alleviate grid bottlenecks at the same time, tackling the electricity infrastructure challenge from two sides. A relevant contributor to the economics of thermal storage is that the owner can not only consume cheap off-peak electricity but can also offer valuable flexibility services to grid operators. Thermal storage could enable grid controllers to balance supply and demand quickly and reliably: with remote control of the storage device's heating elements, they could rapidly shut them down or ramp them up to remove excess power from the system in a useful and safe manner. Companies with thermal storage could also relieve grid congestion if they quickly free up transmission capacity and switch to stored heat when a critical line nears its rated capacity. Naturally, this would alleviate only the urgency but not the need for grid capacity expansion [29] [47] [44].

Currently, electricity market structures and regulations often hinder thermal storage instead of incentivizing it. They are set up for legacy consumption and demand-following generation patterns, both presumed to be relatively homogeneous and neatly separated, whereas thermal storage is a new asset class that straddles both consumption and generation. Consequently, grid fees related to transmission, line losses, reliability, and other non-energy costs are distributed mostly equally, despite some consumers contributing far less to them. There can also be other kinds of obstacles to thermal storage, such as lack of access to wholesale electricity prices or direct contracts between local, potentially off-grid, power suppliers and consumers not being possible.

In general, the rules should reward contributors to the system and charge stressors, in proportion to the effect they have, while allowing most other activity. Companies with high-temperature heat processes would control large flows of power and energy with thermal storage, so the possibility of the correspondingly large rewards or at least a lack of disincentives would be central to the decision to electrify. Key to making this decision easy is to have modern rate structures and market rules that are defined in technology-neutral terms and allocate costs based on causation.

Future solutions

As shown above, most process industry companies in the EU (and globally) can very plausibly decarbonize high-temperature heat via the combination of electricity and thermal storage if policy can set up the right incentives and manage a transition to sustainably low electricity prices. However, there are cases in which innovators and entrepreneurs still have work to do to cover technology gaps, notably the production of cement. Further innovation, from the laboratory to pilot plants, still holds the promise for potentially more cost savings and prospects of global European technology leadership.

Electric plasma torches

Plasma-based approaches try to circumvent a limitation of electric heating, namely that it is typically harder to transfer lots of heat quickly, which limits how fast and how much material can be made or treated. For natural gas and other carbon fuels, one can roughly say that pumping in more fuel and air creates a bigger flame that transfers more heat. For electricity, driving more electric current through the heating element is limited by the maximum temperature the material can sustain without melting. Plasma torches get around this limitation by essentially using gas as a heating element. They drive current through the gas to turn it into plasma, which can be described as an "electric flame", not unlike a natural gas flame, but often much hotter (4000°C).

Plasma technology is especially relevant for decarbonizing cement. The hottest step of cement making, sintering (heating limestone to produce clinker), requires very high temperatures of around 1450°C. Cement is also a high-volume product – a ton can be had for around 50 EUR – so transport and other volume-related costs are high, and plants must have a high throughput to be economical. Calcination involves removing CO_2 from limestone, causing significant process emissions independent of those from burning fuel. Some prototype plasma calcination reactors and demonstration plants therefore use CO_2 both for pre-heating and as the plasma medium [48], making cement in a pure CO_2 atmosphere. This way, the inevitable process emissions are not mixed with air and can be sequestered much more readily. Currently, plasma heating has only been demonstrated at the few MW [49] scale, but burners for rotary kilns typically have a capacity of around 75 MW to 250 MW [50], so significant innovation is needed for scaling up. Finally, while plasma heating can be very efficient, the core issue of expensive electricity relative to cheap gas applies here as well.

Direct co-located thermal methods

All of the potential clean high-temperature heat solutions discussed so far use clean electricity to make clean heat, but there are also ways to make clean heat directly. They deserve a closer look, despite being less technologically mature or broadly applicable, because they may prove complementary to electrification, for example by circumventing grid bottlenecks.

- Geothermal process heat

New drilling techniques may unlock access to high-temperature heat from hot rocks at 10 km depth, which could either be used for electricity or directly for some high-temperature heat processes. Conventional geothermal energy is only available in certain regions, often near volcanoes and hot springs, where the heat from Earth's core is relatively close to the surface. Deeper rock layers several kilometers below the surface are much hotter essentially everywhere, and reaching them in an economical manner would unlock access to about 200°C or potentially even 400°C heat [51]. Over the past few decades, the engineers of the oil and gas industry have advanced drilling technology considerably, and such depths may be within reach soon. Besides the global availability of this clean energy source, 200°C rocks also put approximately 30% of heat applications within reach of a hypothetical geothermally powered factory [52], while 400°C would start to become relevant for high-temperature heat, if only on the lower end of the temperature scale. Upgrading this heat to higher temperatures with electric power is also possible, which would open up even more applications. However, whether drilling costs can come down fast and low enough remains to be seen (and depends on investment into R&D). The social acceptability of drilling activities would also need to be taken into account. Still, the potential payoff of tapping into these new geothermal energy sources is already quite large when considering electricity production alone, but the relevance of heat applications makes investing in geothermal innovation even more worthwhile.

Nuclear process heat

Nuclear power plants produce electricity from heat, but industrial processes could also use the heat directly. Conventional plants with steam-driven generators can typically use only 33% of the nuclear heat energy; the rest is dissipated in large cooling towers as low-quality heat, i.e. at low temperature. Nuclear heat might well be competitive in a scenario where nuclear electricity is more expensive than wind or solar, because a nuclear heat application could use roughly three times more of the energy produced, for the same price as the electric one[10]. Another key advantage unique to nuclear heating would be its extremely low footprint and reduced infrastructure needs. Small modular reactors would fit well in most existing sites and would not require grid connections if used only for heat.

Most nuclear process heat concepts are still in early development stages, but they could be a major contributor to a diversified energy system. With current reactor designs, only medium temperatures of <300°C are possible, although high temperature designs have been studied for decades and reactors for about 950°C [53] have relatively high technology readiness levels. Beyond technical hurdles, nuclear energy's more serious issues are around social acceptance, complex regulations and permitting processes, although there are significant differences between jurisdictions. Essentially, all considerations around nuclear energy in general are likely to apply to nuclear process heat. However, a full analysis of these aspects is beyond the scope of this report. Still, the efficiency advantage for heat and circumventing grid bottlenecks are significant enough that this technological avenue should be explored further and seriously considered in most cost benefit calculations.

Concentrated solar thermal

Concentrated solar power (CSP) plants produce heat from focusing direct sunlight and converting it to electricity with steam turbines, but processes could also use that heat directly. Focusing the light onto the material to be treated to get the highest achievable temperatures (around 1500°C [54]) is a challenging task and limits the range of applications somewhat, but heating fluids can still deliver heat at 1000°C [55].

Solar process heat can build on mature CSP technology, but is less viable outside the global solar belt, i.e. outside of the desert regions close to the equator. CSP needs considerable land area for mirrors, very high light intensity, and a suitable climate to get long stretches of sunny weather for uninterrupted production. CSP in itself is quite mature, but the technologies required to use the light directly in a high-temperature heat process are still being developed. CSP electricity is usually more expensive than photovoltaic electricity at the same location, but, as with nuclear heat, the advantage of using the energy directly as heat may still be sufficient to win out under the right circumstances and with innovative approaches.

[10] With high-temperature nuclear reactors, the conversion efficiency is higher, but an advantage of around 150% would remain in favor of direct heat utilization. If only medium temperatures are required (200-350°C), costs would be lower.

Policy recommendations

Focus on electric heat

- **Support industrial electric heat in combination with heat storage technologically** as both technologies are efficient, technologically mature, scalable, can cover all temperatures, have medium to low capital cost, have the potential for low operating costs when combined, and emit no harmful particulates.

- **Avoid reliance on biomethane** because feedstock is insufficiently available and true zero-emissions biomethane is hard to achieve due to methane leakage. Prioritize applications with scant viable alternatives, such as methanol production for shipping fuel or seasonal balancing of the power grid. Select high-temperature processes could be eligible for biogas prioritization where no competitive alternatives exist yet.

- **Avoid reliance on hydrogen and derived synthetic fuels** because of their costly and inefficient production and transport and lack of advantages over electric heat in terms of infrastructure needs. Prioritize applications with no other viable alternative, like steel reduction and ammonia for fertilizer.

- **Avoid reliance on carbon capture** because of carbon dependency lock-in, energy security concerns, lack of cost reductions potential, additional infrastructure needs for CO_2 pipelines and storage sites, and harmful particulate emissions. Restrict usage to unavoidable process emissions, mainly in cement [56].

Expand renewables & grid

- **Aim for universal access to low-cost electricity by making clean energy abundant,** as the reality of higher operating costs for electricity compared to gas is the main obstacle to industry's transition to electrification. This includes ending subsidies and tax breaks for fossil fuels wherever competitive clean solutions become available. **Support energy storage** at all timescales (from hours to seasons), **clean firm power** (such as geothermal, hydropower, nuclear, or concentrated solar with thermal storage), **alternative renewables** with complementary intermittency profiles (from conventional wind and solar to wave power), and demand flexibility to create a low-cost electricity system consisting of mutually complementary technologies without energy shortfalls or excessive curtailment due to supply-demand mismatch or grid congestion.

Key actions for:

- **Utilities and systems planners and utility regulators**: Conduct case studies into adapting new approaches to energy system management for local conditions, such as, among others, new techniques for load-following demand, from incentivizing domestic heat and cold storage to automated load tripping of industrial electric heaters or thermal batteries in response to contingencies.

- **EU policymakers**: Maintain the course of the European Green Deal, directing investments, grants, and financial schemes (including guarantees that help spur private investment) from the various European funds towards European cleantech start-ups.

- **Member state and regional policymakers**: Launch ambitious projects with an ecosystem approach to achieve critical mass and mitigate risk, helping to accelerate the transformation and encouraging the entire sector to develop and deploy clean solutions.

- **Invest in the grid by reducing permitting times and increasing funding** to accelerate the buildout of new transmission lines and substations, and upgrades of existing ones. This reduces costs by equalizing spatial differences in electricity supply and enables the many companies that currently lack sufficient grid access, especially SMEs, to electrify.

Incentivize thermal storage

- **Support adoption of heat storage at existing and future plants,** as it could lower electric heat costs enough that it may become competitive with gas in the near to medium term - given the right policy interventions - by allowing electricity consumption to shift to times of abundance. This will also enable additional income from offering grid services, improve grid congestion issues, and reduce pressure on much delayed grid expansion.

Key actions for industrial planners:

- Invest time into understanding the potential and economics of electric heat and thermal batteries, reliability requirements of processes and operations, and the possibility of transitional electric-fossil-hybrid approaches.

- Select pilot project sites based on availability of renewable resources and the potential for supplementary revenue from grid-related services with thermal batteries.

- Consult with local transmission system operators on possible synergies.

- **Change electricity market structures** so that thermal storage owners are compensated for the value they provide by making the grid more flexible. This can be an important additional source of revenue, bringing thermal storage closer to cost parity.

Key actions for utilities and systems planners and utility regulators:

- Adopt modern rate structures with pricing based on cost causation.

- Enable universal access to wholesale electricity prices and minimization of non-energy cost that loads do not contribute to.

- Actively reward load profiles that are beneficial to the system, such as thermal batteries.

- Define ancillary services in technology-neutral terms to reward energy assets only based on merit and utility to the system.

- Allow flexible and specialized direct arrangements (such as Power Purchase Agreements) between consumers and suppliers of energy or self-supply, either grid-delivered or off-grid.

- Allow for hybrid prosumer strategies mixing self-supply, charging from the grid, or supplying energy back to the grid during times of high demand.

Fund R&D on heat pathways

- **Support electrification by funding and incentivizing near-term engineering efforts** to deploy and scale up technologically mature electric heating. This will help replace previously gas-burning processes as quickly as possible and secure EU technology leadership.

- **Fund and incentivize R&D for less mature or high-leverage technologies,** such as high-temperature thermal storage, plasma heating, innovative geothermal, nuclear, and solar process heat. This will further reduce costs and increase energy security, while boosting EU technological competitiveness.

Conclusion

The future of the EU energy system relies on decarbonizing high-temperature heat.

Every part of a clean energy system, from wind turbines to transmission lines, relies on vital materials made by the processing industry and its 7 million workers. Currently, industry still depends on burning natural gas as a fuel, which emits CO_2 and harmful soot, but this can and must change if there is to be a successful transition to a clean energy system by 2050.

Clean high-temperature heat is a challenge for policymakers, but with the right policies, it is also an opportunity:

- to fulfill national commitments to voters and international pledges by demonstrating progress towards getting off natural gas and moving closer to net zero.
- to improve energy security and, consequently, EU foreign policy options in matters of security and development cooperation.
- to reduce long-term climate impacts while generating tangible near and medium-term benefits such as energy cost savings, creation of sustainable jobs, technology leadership, and reduced air pollution.

However, biomethane, hydrogen, and carbon capture are not a sustainable solution in most cases. Biomethane does not have sufficient feedstock available and emits harmful soot particles. Green hydrogen is expensive and inefficient to produce, which negates its potential short-term retrofitting benefits for industrial processes. Therefore, its scant supply is much better reserved to decarbonize existing production of grey hydrogen. Where alternatives are available, carbon capture risks unnecessarily locking in carbon dependencies because it requires building up a whole new infrastructure and value chain. Even if successfully deployed, carbon capture is structurally unable to undercut unabated fossil fuels. Finally, carbon capture does not address the problem of non-CO_2 air pollution inherent in burning carbon-containing fuels. Delivering heat with molecules instead of electrons is therefore an insufficient solution in most cases.

Contrary to popular expectations regarding the so-called hard-to-abate sectors, the trend towards electrification also increasingly applies to industrial heat, even at high temperatures, with many different technologies ready to scale up. In most cases, these face engineering challenges rather than requiring fundamental scientific breakthroughs. However, the economic feasibility of heat electrification is to a large degree dependent on the cost of electricity. It is therefore particularly crucial to build an energy system that can guarantee low cost to companies for this transition to happen. This can be facilitated if thermal storage technologies are used to access lower electricity prices and provide flexibility to the grid. However, thermal storage and the willingness of industrial players will not suffice. In order to incentivize the shift to electrification of high-temperature heat, electricity must become more competitive with gas. To achieve this, cohesive industrial policy is necessary, from expanding clean power supply and transmission grids, to lowering market barriers and funding R&D for the engineering challenges remaining.

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References

[1] "CEDEFOP Skills intelligence." Jul. 26, 2024. Accessed: Jul. 26, 2024. [Online]. Available: https://www.cedefop.europa.eu/en/tools/skills-intelligence/sectors?sector=02.05#1

[2] A. Farina and A. Anctil, "Material consumption and environmental impact of wind turbines in the USA and globally," Resour. Conserv. Recycl., vol. 176, p. 105938, Jan. 2022, doi: 10.1016/j.resconrec.2021.105938.

[3] "Industrial emission statistics." Accessed: Jun. 13, 2024. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Industrial_emission_statistics

[4] S. Madeddu et al., "The CO_2 reduction potential for the European industry via direct electrification of heat supply (power-to-heat)," Environ. Res. Lett., vol. 15, no. 12, Art. no. 12, Dec. 2020, doi: 10.1088/1748-9326/abbd02.

[5] "Market analysis - European Commission." Accessed: May 27, 2024. [Online]. Available: https://energy.ec.europa.eu/data-and-analysis/market-analysis_en

[6] H. Ritchie and M. Roser, "How many people does synthetic fertilizer feed?," Our World Data, Feb. 2024, Accessed: Jun. 13, 2024. [Online]. Available: https://ourworldindata.org/how-many-people-does-synthetic-fertilizer-feed

[7] J. Rosenow, "Factcheck: 18 misleading myths about heat pumps," CarbonBrief. Accessed: Jul. 26, 2024. [Online]. Available: https://www.carbonbrief.org/factcheck-18-misleading-myths-about-heat-pumps

[8] "Heat pump rollout in France and the UK - A comparative analysis." [Online]. Available: https://mcsfoundation.org.uk/wp-content/uploads/2023/10/MCSCF-HeatPumpReport2023.pdf

[9] "Heat pumps." Accessed: Jun. 13, 2024. [Online]. Available: https://energy.ec.europa.eu/topics/energy-efficiency/heat-pumps_en

[10] J. Rissman, "Decarbonizing Low-Temperature Industrial Heat in the U.S.".

[11] S. Klute, M. Budt, M. van Beek, and C. Doetsch, "Steam generating heat pumps – Overview, classification, economics, and basic modeling principles," Energy Convers. Manag., vol. 299, p. 117882, Jan. 2024, doi: 10.1016/j.enconman.2023.117882.

[12] Ghassan Wakim and Magnolia Tovar, "Hydrogen for Decarbonization: A Realistic Assessment," Clean Air Task Force. Accessed: Jun. 13, 2024. [Online]. Available: https://www.catf.us/resource/hydrogen-for-decarbonization-a-realistic-assessment/

[13] "The Basics & The Gaps Thermal Energy Storage," Future Cleantech Architects. Accessed: Aug. 12, 2024. [Online]. Available: https://fcarchitects.org/content/future-cleantech-factsheet-thermal-energy-storage/

[14] S. de Bruyn, C. Jongsma, B. Kampman, B. Görlach, and J.-E. Thie, "Energy-intensive industries: Challenges and opportunities in energy transition," EU committee on Industry, Research and Energy, 2020. Accessed: Aug. 12, 2024. [Online]. Available: https://www.europarl.europa.eu/RegData/etudes/STUD/2020/652717/IPOL_STU(2020)652717_EN.pdf

[15] J. Allwood et al., Sustainable materials: with both eyes open. Cambridge, UK: UIT Cambridge Limited, 2012. [Online]. Available: https://www.uselessgroup.org/publications/book/chapters

[16] G. Bianchi et al., "Estimating the waste heat recovery in the European Union Industry," Energy Ecol. Environ., vol. 4, no. 5, Art. no. 5, Oct. 2019, doi: 10.1007/s40974-019-00132-7.

[17] C. F. Dunant, M. P. Drewniok, J. J. Orr, and J. M. Allwood, "Good early stage design decisions can halve embodied CO2 and lower structural frames' cost," Structures, vol. 33, pp. 343–354, Oct. 2021, doi: 10.1016/j.istruc.2021.04.033.

[18] J. Giuntoli, A. Agostini, R. Edwards, and L. Marelli, "Solid and gaseous bioenergy pathways: input values and GHG emissions. Calculated according to the methodology set in COM(2016) 767," European Commission Joint Research Centre, 2017. [Online]. Available: doi:10.2790/27486

[19] S. Bakkaloglu, J. Cooper, and A. Hawkes, "Methane emissions along biomethane and biogas supply chains are underestimated," One Earth, vol. 5, no. 6, pp. 724–736, Jun. 2022, doi: 10.1016/j.oneear.2022.05.012

[20] J. Bacenetti, C. Sala, A. Fusi, and M. Fiala, "Agricultural anaerobic digestion plants: What LCA studies pointed out and what can be done to make them more environmentally sustainable," Appl. Energy, vol. 179, pp. 669–686, Oct. 2016, doi: 10.1016/j.apenergy.2016.07.029.

[21] "Hydrogen Science Coalition," Hydrogen Science Coalition. Accessed: Aug. 12, 2024. [Online]. Available: https://h2sciencecoalition.com/data-resources/

[22] "Techno-economic Realities of Long-Distance Hydrogen Transport," Clean Air Task Force. Accessed: Aug. 08, 2024. [Online]. Available: https://www.catf.us/resource/techno-economic-realities-long-distance-hydrogen-transport/

[23] "Stanlow could be 'world's first decarbonised refinery,'" Essar. Accessed: Aug. 08, 2024. [Online]. Available: https://www.essar.com/inthenews/stanlow-could-be-worlds-first-decarbonised-refinery/

[24] "H-vision." Accessed: Aug. 08, 2024. [Online]. Available: https://www.h-vision.nl/en

[25] S. O. Gardarsdottir et al., "Comparison of Technologies for CO2 Capture from Cement Production—Part 2: Cost Analysis," Energies, vol. 12, no. 3, Art. no. 3, Jan. 2019, doi: 10.3390/en12030542

[26] "Analysis of Lifecycle Greenhouse Gas Emissions of Natural Gas and Coal Powered Electricity," Clean Air Task Force. Accessed: Jul. 08, 2024. [Online]. Available: https://www.catf.us/resource/analysis-lifecycle-greenhouse-gas-emissions-natural-gas-coal/

[27] "Air pollution." Accessed: Jun. 13, 2024. [Online]. Available: https://www.eea.europa.eu/en/topics/in-depth/air-pollution

[28] S. Lupi, Fundamentals of Electroheat. Cham: Springer International Publishing, 2017. doi: 10.1007/978-3-319-46015-4

[29] "Thermal Batteries: Decarbonizing U.S. Industry While Supporting A High-Renewables Grid," Energy Innovation: Policy and Technology. Accessed: May 27, 2024. [Online]. Available: https://energyinnovation.org/publication/thermal-batteries-decarbonizing-u-s-industry-while-supporting-a-high-renewables-grid-2/

[30] U. Renz, "Handbook of Burner Technology for Industrial Furnaces," 2009, p. 28/45.

References

[31] S. R. Mickey, "High-efficiency gas burners make good economic sense | Thermal Processing Magazine." Accessed: Jul. 10, 2024. [Online]. Available: https://thermalprocessing.com/high-efficiency-gas-burners-make-good-economic-sense/

[32] F. Boshell et al., "Innovation Outlook: Thermal Energy Storage," IRENA, 2020. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Innovation_Outlook_TES_2020.pdf?rev=6950b7b9792344b5ab28d58e18209926

[33] "Batteries and Secure Energy Transitions – Analysis," IEA. Accessed: Jul. 10, 2024. [Online]. Available: https://www.iea.org/reports/batteries-and-secure-energy-transitions

[34] Z. Ma, "Economic Long-Duration Electricity Storage by Using Low-Cost Thermal Energy Storage and High-Efficiency Power Cycle (ENDURING)," NREL/TP--5700-84728, 2001484, MainId:85501, Sep. 2023. doi: 10.2172/2001484

[35] L. Pompei, F. Nardecchia, and A. Miliozzi, "Current, Projected Performance and Costs of Thermal Energy Storage," Processes, vol. 11, no. 3, Art. no. 3, Mar. 2023, doi: 10.3390/pr11030729

[36] "Hydrogen Finance Model," Clean Air Task Force. Accessed: Aug. 08, 2024. [Online]. Available: https://www.catf.us/hydrogen-finance-model/

[37] ENTSO-e Transparency Platform, "Total Load - Day Ahead / Actual." Accessed: Aug. 08, 2024. [Online]. Available: https://transparency.entsoe.eu/load-domain/r2/totalLoadR2/show

[38] ENTSO-e Transparency Platform, "Day-ahead Prices." Accessed: Aug. 08, 2024. [Online]. Available: https://transparency.entsoe.eu/transmission-domain/r2/dayAheadPrices/show?name=&defaultValue=false&viewType=GRAPH&areaType=BZN&atch=false&dateTime.dateTime=12.07.2024+00:00|UTC|DAY&biddingZone.values=CTY|10YNL----------L!BZN|10YNL----------L&resolution.values=PT15M&resolution.values=PT30M&resolution.values=PT60M&dateTime.timezone=UTC&dateTime.timezone_input=UTC

[39] "Dutch TTF Natural Gas Futures Pricing." Accessed: Aug. 08, 2024. [Online]. Available: https://www.ice.com/products/27996665/Dutch-TTF-Natural-Gas-Futures/data?marketId=5786628&span=3

[40] A. Abou-Jaoude, L. Lin, C. Bolisetti, E. Worsham, L. Larsen, and A. Epiney, "Literature Review of Advanced Reactor Cost Estimates," INL/RPT--23-72972-Rev000, 1986466, Jun. 2023. doi: 10.2172/1986466

[41] M. Rehfeldt, "Direct electrification of industrial process heat. An assessment of technologies, potentials and future prospects for the EU," Fraunhofer ISI, Jul. 2024. Accessed: Jul. 09, 2024. [Online]. Available: https://www.agora-industry.org/publications/direct-electrification-of-industrial-process-heat

[42] T. Fleiter, M. Rehfeldt, S. Hirzel, L. Neusel, and A. Aydemir, "CO2-neutrale Prozesswärmeerzeugung. Umbau des industriellen Anlagenparks im Rahmen der Energiewende: Ermittlung des aktuellen SdT und des weiteren Handlungsbedarfs zum Einsatz strombasierter Prozesswärmeanlagen," Umweltbundesamt. [Online]. Available: https://www.umweltbundesamt.de/sites/default/files/medien/11850/publikationen/161_2023_texte_prozesswaerme-pumpen_zs_0.pdf

[43] Eurostat, "Electricity prices for non-household consumers - bi-annual data (from 2007 onwards)." Accessed: Aug. 08, 2024. [Online]. Available: https://ec.europa.eu/eurostat/databrowser/view/nrg_pc_205/default/table?lang=en

[44] Spees, Hagerty, and Grove, "Thermal Batteries: Opportunities to Accelerate Decarbonization of Industrial Heat," Oct. 2023. Accessed: Jun. 04, 2024. [Online]. Available: https://www.renewablethermal.org/tes-assessment-report/

[45] "Grids for Europe's energy transition," Ember. Accessed: Jun. 13, 2024. [Online]. Available: https://ember-climate.org/insights/research/putting-the-mission-in-transmission-grids-for-europes-energy-transition/

[46] "Future Cleantech Priorities 2024," Future Cleantech Architects. Accessed: Aug. 08, 2024. [Online]. Available: https://fcarchitects.org/content/future-cleantech-priorities-2024/

[47] X. Qin, B. Xu, I. Lestas, Y. Guo, and H. Sun, "The role of electricity market design for energy storage in cost-efficient decarbonization," Joule, vol. 7, no. 6, Art. no. 6, Jun. 2023, doi: 10.1016/j.joule.2023.05.014.

[48] C. Blackman, L. Croon, and B. Ljungdahl, "Plasma cyclone reactor," US 2024/0215144 A1 [Online]. Available: https://patentimages.storage.googleapis.com/c4/f2/b6/352af181428459/US20240215144A1.pdf

[49] T. Hanein et al., "Clay calcination technology: state-of-the-art review by the RILEM TC 282-CCL," Mater. Struct., vol. 55, no. 1, Art. no. 1, Dec. 2021, doi: 10.1617/s11527-021-01807-6.

[50] J. Hercog et al., "Pilot testing and numerical simulations of the multifuel burner for the cement kiln," Fuel, vol. 342, p. 127801, Jun. 2023, doi: 10.1016/j.fuel.2023.127801.

[51] K. Hunt, "Superhot rock geothermal energy could unlock terawatts of clean, firm power worldwide, finds CATF," Clean Air Task Force. Accessed: Jul. 10, 2024. [Online]. Available: https://www.catf.us/2024/03/superhot-rock-geothermal-energy-unlock-terawatts-clean-firm-power-worldwide/

[52] R. M. Johannsen, B. V. Mathiesen, K. Kermeli, W. Crijns-Graus, and P. A. Østergaard, "Exploring pathways to 100% renewable energy in European industry," Energy, vol. 268, p. 126687, Apr. 2023, doi: 10.1016/j.energy.2023.126687.

[53] W. R. Stewart, E. Velez-Lopez, R. Wiser, and K. Shirvan, "Economic solution for low carbon process heat: A horizontal, compact high temperature gas reactor," Appl. Energy, vol. 304, p. 117650, Dec. 2021, doi: 10.1016/j.apenergy.2021.117650.

[54] S. Zoller et al., "A solar tower fuel plant for the thermochemical production of kerosene from H2O and CO2," Joule, vol. 6, pp. 1606–1616, Jul. 2022, doi: 10.1016/j.joule.2022.06.012.

[55] "DLR – Study solar thermal power (CSP)." Accessed: Jun. 13, 2024. [Online]. Available: https://www.dlr.de/en/latest/news/2021/01/20210330_study-solar-thermal-power

[56] D. Vangenechten, J.-J. Andreas, R. Bain, D. Treß, and G. Kobiela, "Carbon Capture and Storage Ladder: Assessing the Climate Value of CCS Applications in Europe," E3G, 2023. [Online]. Available: https://www.e3g.org/wp-content/uploads/CCSL_briefing.pdf

About Future Cleantech Architects:
We are a climate innovation think tank. We exist to close the remaining innovation gaps to reach net-zero emissions by 2050. To reach this objective, we accelerate innovation in critical industries where sustainable solutions are still in very early stages.

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