CASE STUDY

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Electrification and Thermal Energy Storage in the Steel Forging Industry

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Executive Summary

Steel forging is an energy- and emissions-intensive process. It requires heating large steel workpieces to approximately 1200°C in natural gas-fired furnaces, so they become malleable for deformation. Decarbonization of steel forging requires replacing the gas-fired burners with electric heating technologies, which in certain cases can be integrated with thermal energy storage (TES) to enable flexible electricity consumption and reduce operating costs. This report presents a case study on the electrification of steel forging furnaces, using a large open-die facility in Germany as the reference case. The findings are relevant to the wider European steel and metals processing sector, and more broadly to any industry requiring high-temperature process heat.

Main Findings

- **Compared to other decarbonization options, electrification of steel heating furnaces is a "safe bet" [1] –** Hydrogen, biomethane, and carbon capture and storage are likely to remain costly and constrained by realistic supply. These pathways are also less energy-efficient than direct electrification, as they introduce additional conversion steps. With large-scale renewable deployment, flexible electricity consumption has the potential to be cost-effective. Prioritizing industrial electrification also reduces risk as it maintains a high degree of optionality across many electric heating and storage technologies.

- **The economic case for electrification depends on the continued buildout of renewables and the resulting increase in periods of low wholesale electricity prices -** Current natural gas and electricity price ratios in Germany mean that electrification is more costly than continued gas firing. In the near term, biomethane may offer a transitional role, reducing process emissions cost-effectively without requiring major capital investment. However, this strategy is unlikely to be scalable and risks dependence on subsidies which, if reduced, would leave biomethane more expensive than the electrified alternative.

- **The underlying principles of steel furnace operation mean that electrification technologies should aim to create a radiative heating environment -** In conventional furnaces, 80-95% of heat transfer to the steel workpiece is dominated by radiation from hot refractory walls, which are initially heated with a combustion burner. Electrification options that similarly heat the refractory lining are therefore most practical and more amenable to retrofit, enabling reuse of the existing furnace. However, the available space within these furnaces is already tight, and geometric constraints must be considered.

- **Thermal energy storage integrates well with certain electrification technologies, but not all -** TES pairs well with indirect resistive heating systems, which sit outside the furnace and heat an intermediate medium such as air. This decouples electricity consumption from heat delivery, thereby reducing operating costs by enabling the plant to consume electricity preferentially during low-price hours. Other electrification options, such as in-furnace resistive elements which have no intermediate heat-transfer medium, are better suited to battery storage, albeit at a likely higher capital cost than thermal storage.

- **The business case and design of the storage system will depend on electricity price variability and the grid connection -** Optimization of storage dispatch using 2024 hourly German wholesale electricity prices indicates a clear trade-off between grid connection capacity (MW) and thermal storage energy capacity (MWh) when minimizing operating costs. Under current conditions in Germany, achieving an average electricity input cost below the price of natural gas requires "over-powering" the charging capability. A larger grid connection allows more electricity to be stored during low-price hours, but it increases grid connection costs. However, a similar level of operating cost can be achieved with a smaller connection if it is paired with an even larger thermal store. In general, the forge's existing grid connection will need to be increased by a factor of 5-20, representing a multi-million euro capital expenditure at current grid connection costs of approximately 300,000 EUR/MW.

- **At the EU level, the fastest route to scale is to make electrified high-temperature heat investable [2] -** Align de-risking instruments with retrofit needs, reform network charges to reward flexibility, fast-track grid connections and permitting, and make additional grid connections a state-driven and state-financed topic. Thermal energy storage should be treated as a system asset that supports renewablintegration and can likely reduce operating costs.

For citation purposes, the case study should be referenced as:
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1. Introduction

1.1 Overview

The steel forging industry requires large quantities of high-temperature process heat, typically in the range 1200-1250°C. Today, this demand is primarily met by natural gas-fired furnaces, which heat the steel to forging temperature and make it malleable for forming. This paper presents a case study on the electrification of these furnaces and qualitatively explores practical pathways for integrating thermal energy storage (TES). It then quantifies the value of this flexibility using an hourly-electricity price dataset.

The forging of steel is just one part of a large and complex steel supply chain. There are three main processes before forging:

- i) Ironmaking: where iron ore is reduced to iron.
- ii) Steelmaking: where iron is converted into liquid steel.
- iii) Continuous casting: where liquid steel is cast into semi-finished "crude" steel products (slabs, blooms, billets, and ingots).

After casting, the semi-finished products then undergo either rolling or forging. During both processes, the steel is heated in furnaces and shaped into the final steel products. Typical rolling outputs include solid bars, coils, and structural beams, while forging produces more complex components such as heavy machinery axles, bearings, discs, rings, and shafts. These products then undergo a series of heat treatment and finishing steps which typically occur on the same forging site. Forging provides superior strength and fatigue resistance compared to rolling. As expected, approximately 95% of steel (by mass) is rolled for common structural and flat products, while less than 5% is forged for more specialty components which are essential for mechanical engineering products. Nevertheless, both rolling and forging rely on broadly similar reheating furnaces, so the remainder of this case study is, in large part, applicable to both routes.

Figure 1 summarizes the main steps in steel production and the associated share of employment and emissions. The steel industry accounts for 4-6% of the EU's total greenhouse gas emissions, with approximately 70-80% occurring during ironmaking [3], [4]. Although primary ironmaking and steelmaking are the most energy-intensive (>50% [4]), the majority of jobs and value creation occurs downstream, in processes such as forging. **The rolling, forging, and finishing of steel accounts for over 70% of sector employment [3].**

1.2 European Forging Industry

Figure 2 provides an overview of the European steel forging industry. The annual throughput is approximately 5 million tonnes of specialty steel components, accounting for around 0.05% of the EU's total emissions (if the boundary is extended to include similar rolling processes, this increases to 1.3%). Fabrication takes place in roughly 500 forges and employs 60,000 people, with half of sites and total employment located in Germany alone.

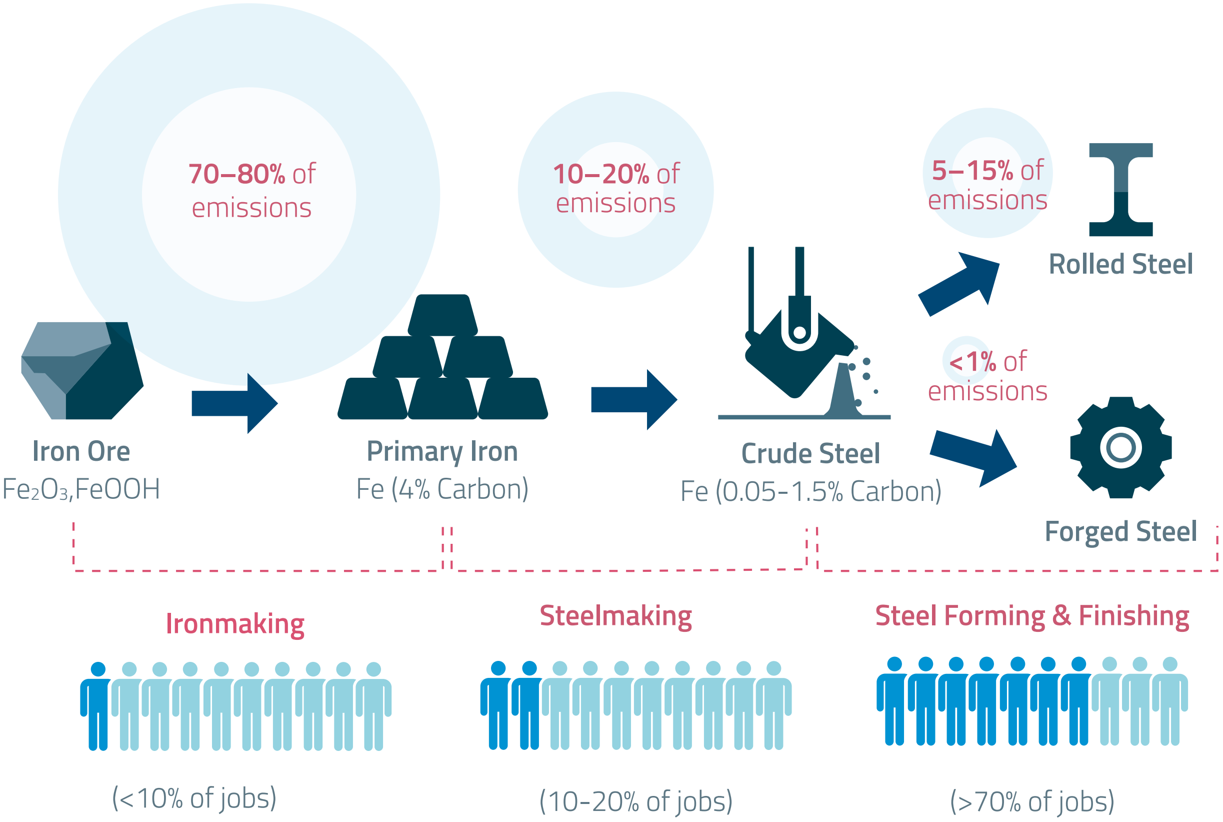


Figure 1: Steel production process [3], [5]. Forging and rolling emissions data from [6], [7], [8], [9].

The steel forging industry has undergone major energy transitions before. In the middle of the 20th century many European forges shifted from coal to heavy oil, and then in the 1970s from heavy oil to natural gas [10]. This historical precedent demonstrates that large-scale transitions in industrial heat supply are feasible when supported by advancements in technology, infrastructure, and global economic pressures. However, the European forging industry faces significant competitive pressures. Global steel markets are characterized by strong competition from lower-cost producers, particularly in Asia, where energy prices and environmental constraints are often lower. At the same time, European producers face rising costs associated with carbon pricing under the EU Emissions Trading System (ETS).

The European forging sector remains heavily exposed to volatile natural gas prices, as demonstrated during the 2021–2023 energy crisis. Replacing gas-fired furnaces with electric heating technologies, combined with thermal energy storage, will be shown to enable greater price stability, improved resilience, and better integration with an increasingly renewable electricity system. However, at current electricity-to-gas price ratios electrification is more costly than the unabated gas option. **From an energy security perspective, electrification also reduces dependence on imported fossil fuels, if electricity is generated with renewables or nuclear.** This contributes to the EU's strategic industrial autonomy targets [11], [12].

1.3 Approach of Case Study

The case study focuses on the electrification of an open-die steel forging facility and is based closely on the layout and operating conditions of the Dirostahl Plant in Remscheid, Germany [13]. The site was chosen due to its large size and dependence on natural gas for high-temperature heating, which makes it a particularly challenging (and therefore informative) case for decarbonization. Importantly, the decarbonization pathways analyzed for open-die forging are transferable to other processes such as steel rolling, which also require high-temperature heating furnaces.

The case study begins with an overview of the steel forging process and the main energy inputs for each step. It is shown that decarbonization of forging will be driven by the decarbonization of the heating furnaces. This is followed by a discussion of electrification options and how they integrate with flexibility options, such as thermal energy storage or electrochemical batteries. Finally, the operation of a storage system in the 2024 German electricity grid is modeled to explore the trade-off between storage capacity and charging power (grid connection size).

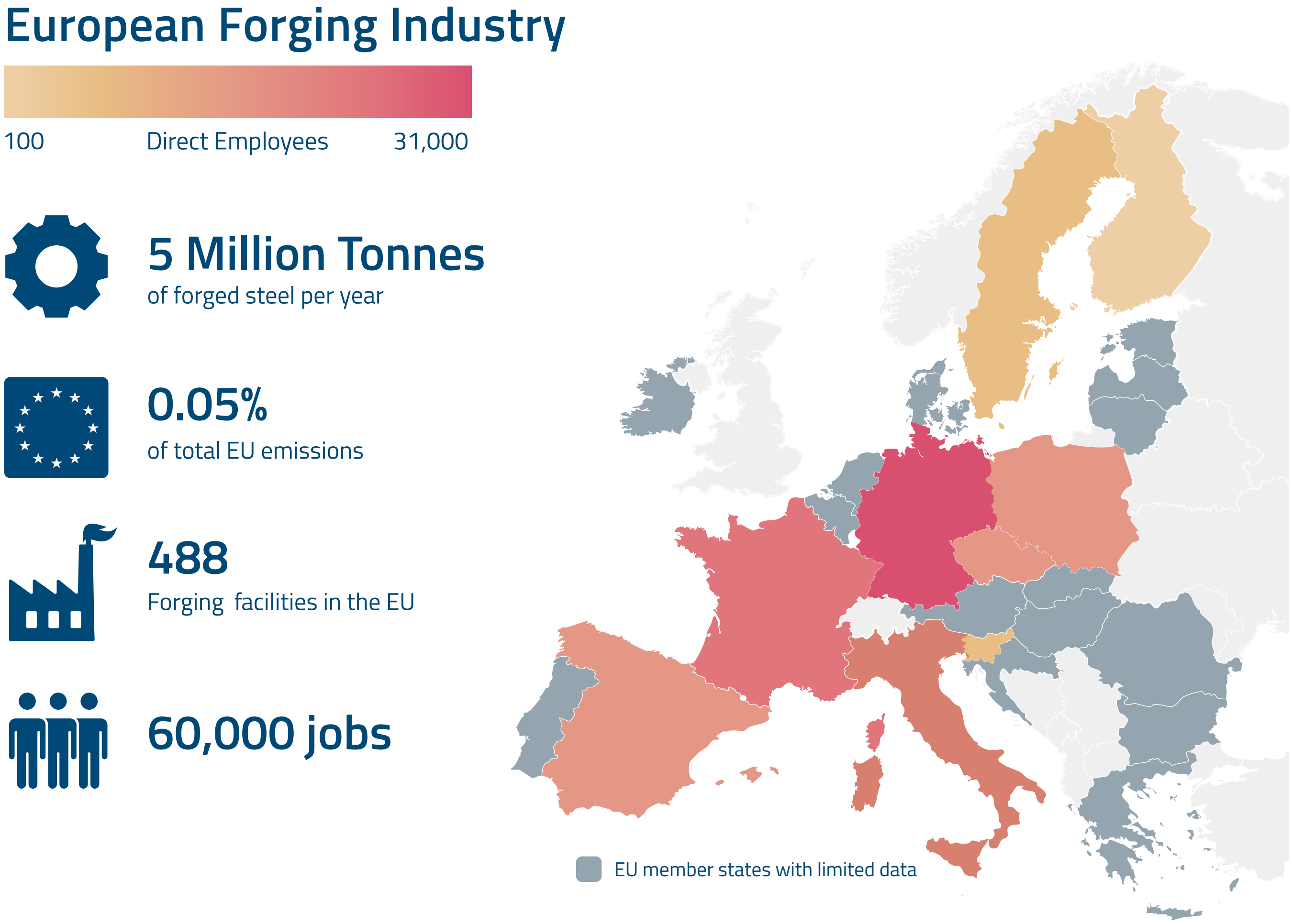


Figure 2: Overview of the European steel forging industry. Employment, facility, and product throughput data are taken from [6]. EU Member States with limited forging data are highlighted in dark gray. Emissions data is from [8], [9]. Note: the hot rolling of steel products processes 26 times more steel by mass [7], bringing the combined emission from forging and rolling to approximately 1.3% of total EU emissions.

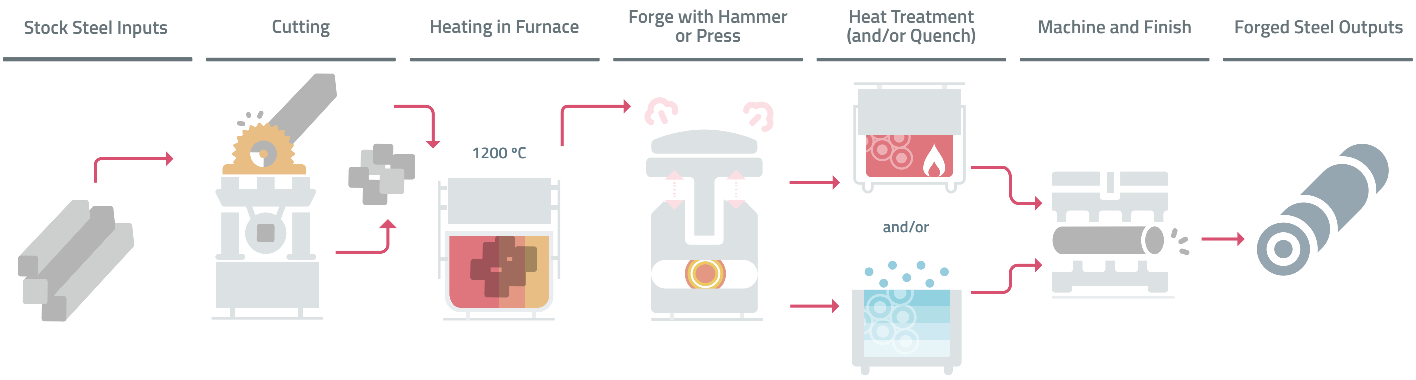


Figure 3: Open-die steel forging process.

2. Steel Forging Process

2.1 Forging Process

Steel forging is a hot-forming process applied to semi-finished steel products from the initial steelmaking and casting steps. The cast inputs can either be "rolled", for high-volume products like beams or rails, or "forged" for larger, custom-made components such as wind turbine bearings and heavy machinery shafts [14]. Figure 3 shows the main process steps in a steel forging facility.

The process begins with cutting the incoming steel stock to an appropriate size for forging. Large continuous cast billets are sawn into smaller sections using a large, water-cooled bandsaw. This ensures the pieces are of manageable size for heating and forging. Energy usage for cutting is minimal, with only a small amount of electricity required for the saw. Note, the cutting of large ingots is an exception and occurs after forging.

After cutting, the steel workpiece (also known as a "charge") is loaded into a heating furnace and brought to the forging temperature. These furnaces are often referred to as "reheating" furnaces because they raise the solid steel back to a high temperature after it has already been cooled following casting. The furnace is usually natural gas-fired and heats the steel to 1200°C, so that the workpiece becomes malleable for deformation. Forging facilities typically operate several furnaces of varying capacity, ranging from 1 MW to 5 MW (natural gas thermal input). Across the entire forging facility, the average continuous gas demand is 10–15 MW, with occasional peak loads of 35–40 MW.

The heating process is relatively slow and energy intensive and must follow a prescribed heating-curve. The internal furnace environment is uniformly held at 1200°C to avoid thermal gradients in the workpiece. Heat transport through the workpiece is 100 mm per hour, this is governed by an intrinsic property of steel known as the thermal diffusivity (for example, after 2 hours, a point 200 mm from the surface will reach 1200°C) [13]. As a result, a medium-sized billet will require 6-8 hours to fully get to temperature, while a large ingot (45 tonnes) will need 24–48 hours. The furnace heating is a batch process (non-continuous) where multiple pieces are heated at once. A typical furnace requires 1000–1500 kWh of natural gas per tonne of steel, plus a small amount of electricity for blowers and control systems [13]. Once the workpiece reaches the target temperature throughout, it is withdrawn from the furnace. This is done using motorized manipulators or cranes, due to the temperature and weight.

Immediately after heating, the steel is forged into shape by forceful deformation. In an open-die forge, this occurs in the "open" space between a top and bottom die. The workpiece is placed on a stationary lower die and compressed by either (1) repeated hammer blows or (2) a steady press force. The steam hammer (also known as a drop hammer) repeatedly strikes the workpiece while an operator positions it between blows. The steam used to drive the hammer is generated by burning natural gas and consumes approximately 600–1000 kWh/tonne of steel [13]. In contrast, press forging is slower and more controlled, allowing large cross-sections to be pressed into shape or for operations like ring rolling. Modern presses are electrically driven with hydraulic pumps and the electricity use is typically 150–300 kWh/tonne of steel [13]. For both the hammer and pressing processes, operators use handling equipment to maneuver the hot workpiece to achieve the desired shape.

After the hot forging is complete, the workpiece undergoes heat treatment to attain the required mechanical properties. This usually involves reheating the steel to a specific temperature and controlling the cooling rate. The purpose is to alter the steel's microstructure (grain structure) to achieve the desired combination of hardness, toughness, and internal stresses. Heat treatment furnaces are often natural gas-fired as well, and consume roughly 500 kWh/tonne of steel, in addition to 10 kWh/tonne of steel for electrical energy for circulation fans, pumps, etc. [13].

The final step is finishing, which brings the forged part to the exact dimensions and surface requirements. Excess material is removed, and machining operations are performed to achieve precise tolerances and features. These operations are typically done with large electric-powered machine tools (lathes, mills, CNC machines); however, the electricity demand for finishing is negligible compared to the hot-forming steps.

2.2 Open-Die vs. Closed-Die Forging

The process described above is typical of open-die forging, where the steel is not confined in a shaped cavity during deformation. It is used for very large or custom pieces and small batch sizes, typically for mechanical engineering applications. This contrasts with "closed-die" forging, which uses specifically shaped dies to enclose the workpiece, similar to a mold [14]. Closed-die forging is used for smaller workpieces (crankshafts, gears, wrenches) produced in greater volumes and has tighter tolerances and high repeatability, for example, automotive parts [15], [16]. Figure 4 shows the difference between open-die and closed-die forging.

One important distinction between open-die and closed-die forging is how the metal is heated. While open-die forging has to use large batch furnaces due to the large dimensions of the workpieces, closed-die forging is able to employ electric induction heating or small continuous furnaces for its billets [16].

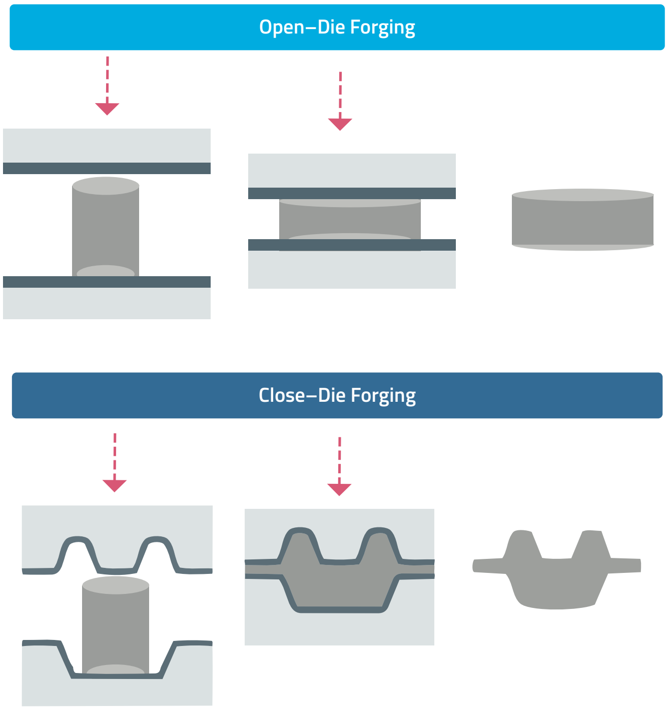


Figure 4: Comparison of open-die and closed-die forging.

2.3 Energy Flows

Large European steel forges have an annual hot-forming capacity of 50,000–60,000 tonnes. Sites typically include 20–30 furnaces, 1–5 hammers, and 1–3 presses. The average energy demand for each step is summarized in Table 1, which is based on measured consumption data from Ref.[13]. Under continuous operation, the average gas consumption rate for a large facility is around 15 MW. However, peak demand can reach 35–40 MW when multiple furnaces are operating simultaneously.

Table 1: Energy requirements for open-die steel forging processes (1200 °C) [13]. FCA analysis.

Process	Natural Gas Input (kWh/t)	Electricity Input (kWh/t)
Cutting	0	5–10
Heating	1000–1500	10–20
Forging		
Steam hammer	600–1000	0
Hydraulic press/ring	0	150–300
Heat treatment	400–600	5–15
Finishing	0	20–40
Total	**2000–3100**	**190–385**

A clear conclusion from this data is that the decarbonization of the forge hinges significantly on decarbonization of the furnaces, used for heating and heat treatment (70% of total energy input). The natural gas consumption of the steam hammer is also high; however, this can be more easily electrified (see electrohydraulic hammers in Ref. [17]), although the alternative technologies are likely more costly.

Note that these figures do not represent the theoretical minimum energy required for each process. For example, the natural gas demand is the gross input to the furnace, not all of which is efficiently transferred into the steel workpiece. The theoretical minimum energy required to heat steel from ambient (25 °C) to 1200 °C is approximately 230 kWh per tonne, given by the specific heat capacity of steel multiplied by a temperature lift of 1175 °C.

2.4 Decarbonization Options

Decarbonization of steel forging means decarbonization of the high-temperature heating furnaces. These furnaces are the largest source of emissions and energy use in the forge and pose a difficult decarbonization challenge because they require high temperatures for long durations. The remainder of this case study focuses on electrification of the furnace, which is likely the most promising route forward because: (i) it aligns with the rapid build-out of wind and solar electricity generation; (ii) it improves security of supply by reducing reliance on imported natural gas and avoiding the scarcity and scaling constraints of biofuels and hydrogen; and (iii) it can more easily be combined with flexible storage solutions.

Figure 5 compares the cost of heat transferred to the workpiece for alternative furnace options. Costs are shown for a large site in Germany with a constant 15 MW thermal load. Across all options, the dominant cost component is the energy supply itself (natural gas, biomethane, electricity, or hydrogen), while taxes, levies, and carbon costs play a secondary role. Furnace efficiency is also important, as it indicates how effectively the fuel is used. Efficiency terms are defined in the following section; however, for the purpose of this cost analysis an available heat efficiency of 50% is assumed (the true thermal efficiency of heat transfer to the workpiece is 15–20%). **This means policy costs applied per unit of fuel are effectively doubled when expressed per unit of useful heat delivered to the furnace. However, it also means that cost reductions enabled by increased flexibility (e.g., via energy storage) are similarly doubled on a per unit heat basis.**

Figure 5 shows that the incumbent natural gas-fired system is the lowest cost option at roughly 140 EUR/MWh of useful heat. Biomethane and electrified options without storage are roughly double this, at around 250 EUR/MWh. The inclusion of thermal storage can substantially narrow the gap, reducing the electrified case to approximately 190 EUR/MWh. In contrast, hydrogen-fired systems will always be too costly, with prices likely around 400 EUR/MWh (see Figure 8 in Ref. [1]. for a detailed cost analysis).

The use of carbon capture and storage (CCS) is another alternative technology to decarbonize the forge. The benefits include leaving the existing furnaces largely untouched, with only capture equipment attached to the flue gas. However, CCS is excluded from the present study for a number of reasons. First, transport and storage of the captured CO_2 is non-trivial, with costs now estimated at 120 EUR/tonne of CO_2 (thus, without considering the capital, this alone would add 24 EUR/MWh to the cost of gas) [18]. Regeneration of the sorbent material will require significant amounts of energy, which could otherwise be used to directly electrify the forge. CCS is dependent on a natural gas-dominated future which, as electrification of domestic heat occurs, may reduce natural gas demand below a minimum viable network threshold [19]. The forge would also continue being exposed to volatile gas prices.

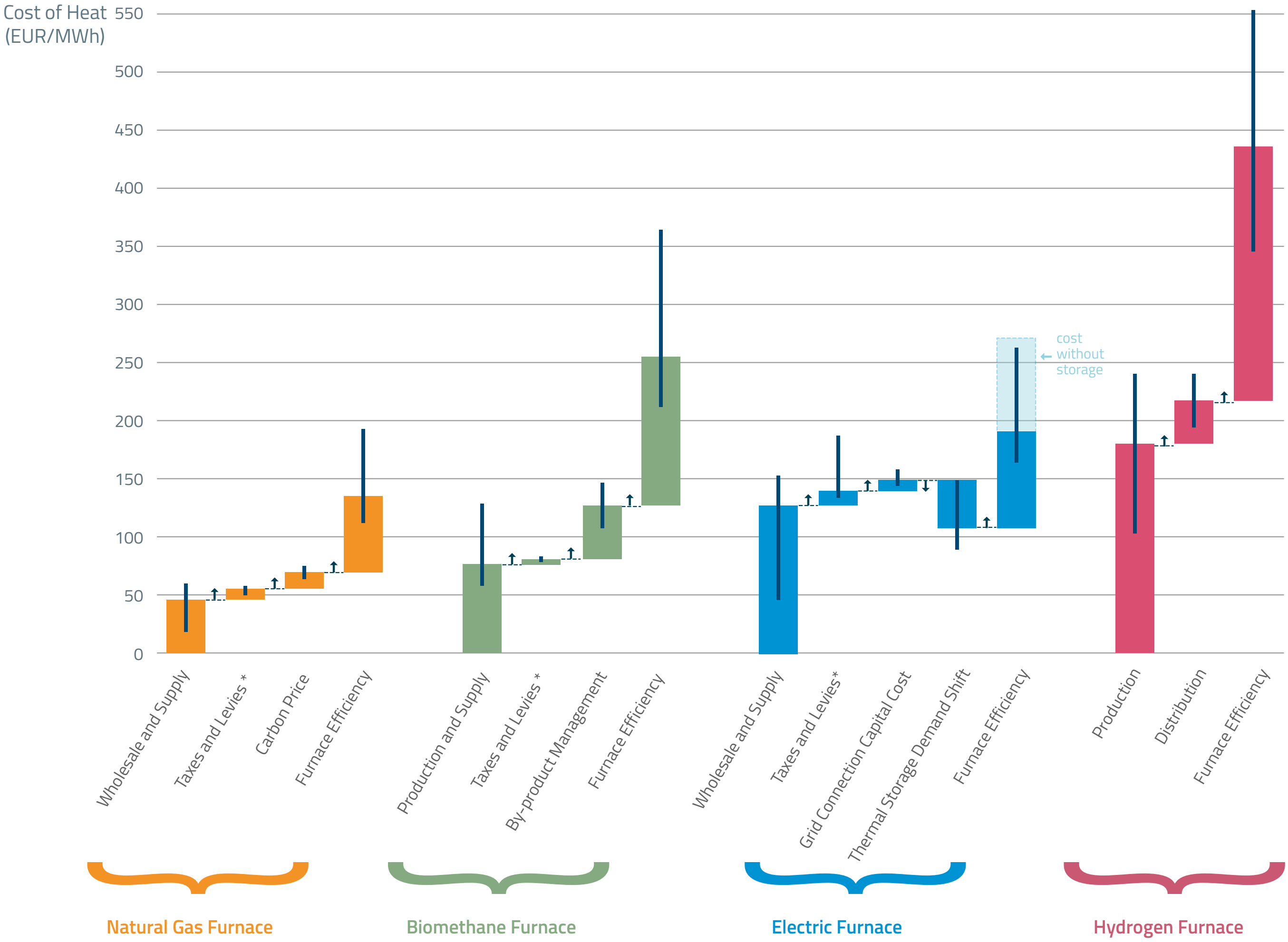


Figure 5: Cost of heat comparison for alternative furnace options for steel forges located in Germany, with a current annual gas consumption of 100–150 GWh (50,000–60,000 tonnes of steel products). The cost for each option is broken into components, with error bars indicating likely cost ranges. Natural gas prices correspond to the I4 consumption band in 2023 [20]; the low and high price ranges are based on 2020 and 2023, respectively. A carbon price of 75 EUR/tonne is assumed, consistent with current EU ETS values. A mean furnace efficiency of 50% is assumed, with a likely range of 35–60% [13]; note this is the available heat efficiency, not the true thermal efficiency. Biomethane production and supply, and by-product management costs are taken from [21], with the same efficiency assumptions as the natural-gas case. For electric furnaces, wholesale and supply electricity costs and taxes and levies are taken from the IF consumption band in [22]. Thermal storage is estimated to reduce costs by 40 EUR/MWh, with a low cost of capital; the light-blue shaded region indicates the cost when storage is not used. Electric furnaces typically use more heat recovery, so the assumed efficiency range is increased by 5% relative to the gas-fired case. Hydrogen production costs are taken from [23], assuming a mean value of 6 EUR/kg (representative of SMR with CCS, or renewable hydrogen produced from low CAPEX electrolyzers). Hydrogen distribution costs are from [24], and the hydrogen furnace efficiency is assumed equal to the natural gas system.
* = excludes taxes and levies which are recoverable.

BioMethane

The effectiveness of biomethane as a means to decarbonize high-temperature heat is a complex topic. It depends heavily on the feedstock from which it is produced (e.g. crop residues, manure), where it is produced, how it is transported, and where it is consumed.

The general pathway is as follows [25]: biological material is used to produce biogas, which is "upgraded" via the removal of CO_2 and other impurities into biomethane. The producer injects this biomethane into the natural gas grid and is entitled to sell certificates based on the "quality" of the biomethane (i.e., biomethane derived from manure has a negative carbon intensity, and its certificates can therefore be sold at a higher price) [21]. Consumers of natural gas can then purchase these certificates and claim the natural gas they are using is carbon neutral. The regulatory and accounting framework is complex, as many certification schemes exist for different member states.

Notably, the current cost of these certificates is quite cheap at approximately 9–15 EUR/MWh [26], [27]. Thus, as carbon prices gradually increase under the EU's ETS, biomethane certificates offer a slightly cheaper compliance route; i.e. a carbon price of 75 EUR/tonne CO_2 increases the cost of natural gas by 15 EUR/MWh. Biomethane also benefits from being a drop-in fuel option which does not require equipment upgrade, albeit at a higher price than unabated natural gas. However, the role of biomethane beyond being a near-term transitional fuel is uncertain for a number of reasons.

The supply of biomethane is insufficient to decarbonize industrial heat at scale. Currently, Germany produces 11 TWh of biomethane each year [26] – from approximately 10,000 biogas plants [28], of which only 250 are able to upgrade biogas to biomethane[26]) – against an industrial gas demand of 220 TWh [29]. This cannot be easily scaled, as biomethane production is ultimately constrained by the availability of biological feedstocks, which also must be managed with land-use and biodiversity considerations.

The certificates do not capture the true cost of production and producers are heavily subsidized through national support schemes. Without these subsidies, biomethane is produced at 60–130 EUR/MWh [21], meaning the current certificates are cheap simply because they are a surplus margin on a subsidized operation .

From an emissions perspective, biomethane is "less-green" than often claimed, with biomethane production facilities leaking 2–5.5% of total output [25]. Additionally, as gas usages in domestic heating systems is replaced with electrified solutions, there is concern that the minimum viable throughput for the gas network will no longer be met [19]. Studies specific to Germany estimate that 90% of the gas distribution grid will become obsolete under net zero [30]. This means it will likely be unable to transport biomethane to end users at reasonable cost.

In summary, while biomethane is a relatively cheap and cleaner alternative to unabated natural gas for high-temperature heat in the near term, it risks delaying investment in longer-term decarbonization solutions.

3. Electric Furnaces and Thermal Storage

3.1 Conventional Furnace

Figure 6 shows a simplified layout of a 5 MW natural gas-fired furnace. As is typical for an open-die forging facility, the furnace is operated in batch mode. The main heat-transfer mechanisms are listed and discussed in detail in the following subsection.

The furnace comprises several key components: a door for rapid access to the workpieces while minimizing heat losses; a refractory brick lining (firebrick) which provides insulation and acts as a radiative surface; burners, where natural gas combustion produces high-temperature jets that drive internal gas circulation as well as radiation from flat-flame structures which initially heat the refractory walls; and a recuperative heat exchanger, which preheats incoming combustion air using the thermal energy in the flue gas that would otherwise be wasted.

Recuperation is an important aspect of furnace design because it preheats the incoming air, thereby reducing overall fuel consumption by up to a factor of two. In some furnaces, more advanced regenerative heat-exchange systems are used [13]. In these systems, for example, hot flue gas is passed through a packed bed of ceramic media (a regenerator), which stores heat as its temperature rises. The flow is then periodically switched so that cold combustion air passes through the hot ceramic bed and is preheated before entering the burners. Multiple regenerators are typically used so that one can be charged while another is discharged. In effect, this is a form of small-scale thermal energy storage that is already deployed in industrial furnaces (albeit to increase process efficiency and not to provide flexibility by heating with electricity).

Although Figure 6 shows only a single burner, in practice multiple burners are distributed along the side walls to ensure more uniform temperature and more homogeneous and controllable heating rates. Combustion also determines the furnace's internal atmosphere, which consists primarily of combustion products (CO_2 and H_2O) and nitrogen (N_2) and, depending on combustion parameters (lean/rich), residual oxygen, and trace species (e.g. CO) [15], [31]. This is discussed in a later section in relation to workpiece oxidation and other practical operating considerations.

Figure 7(a) shows the interior of a furnace with a refractory brick lining and burner ports. Note the black oxidized material at the base of the furnace, known as "scale". Figure 7(b) shows an electrically driven handling machine (manipulator) being used to access workpieces inside the furnace. The bright glow is thermal radiation from the hot refractory lining in the visible spectrum.

3.2 Furnace efficiency

Furnace efficiency can be defined in two main ways. First, the thermal efficiency, η_t, is defined as the minimum possible heat input to the workpiece divided by the heat input from the fuel, as given by,

$$\eta_t = \frac{m \quad c_p \quad \Delta T}{Q_{fuel}}$$

Where m is the mass of steel, c_p is the specific heat of steel, ΔT is the required temperature lift, and Q_{fuel} is the total fuel heat input. Recall to reach 1200°C the minimum heat is 230 kWh/t and from Table 1 that a typical furnace is 1250 kWh/t; thus, the thermal efficiency is approximately 18%.

Another definition is known as the available heat efficiency, η_{av}, which quantifies how much heat is lost via the flue gas. It is given by the fuel heat input minus the flue gas heat output, divided by the fuel heat input:

$$\eta_a = \frac{Q_{fuel} \quad - \quad Q_{flue}}{Q_{fuel}}$$

This available heat is used to heat the workpiece but can also be lost through leaks through the walls or furnace door. It is a useful metric for comparing fuel sources, as the leak losses are broadly similar regardless of how the heat is generated.

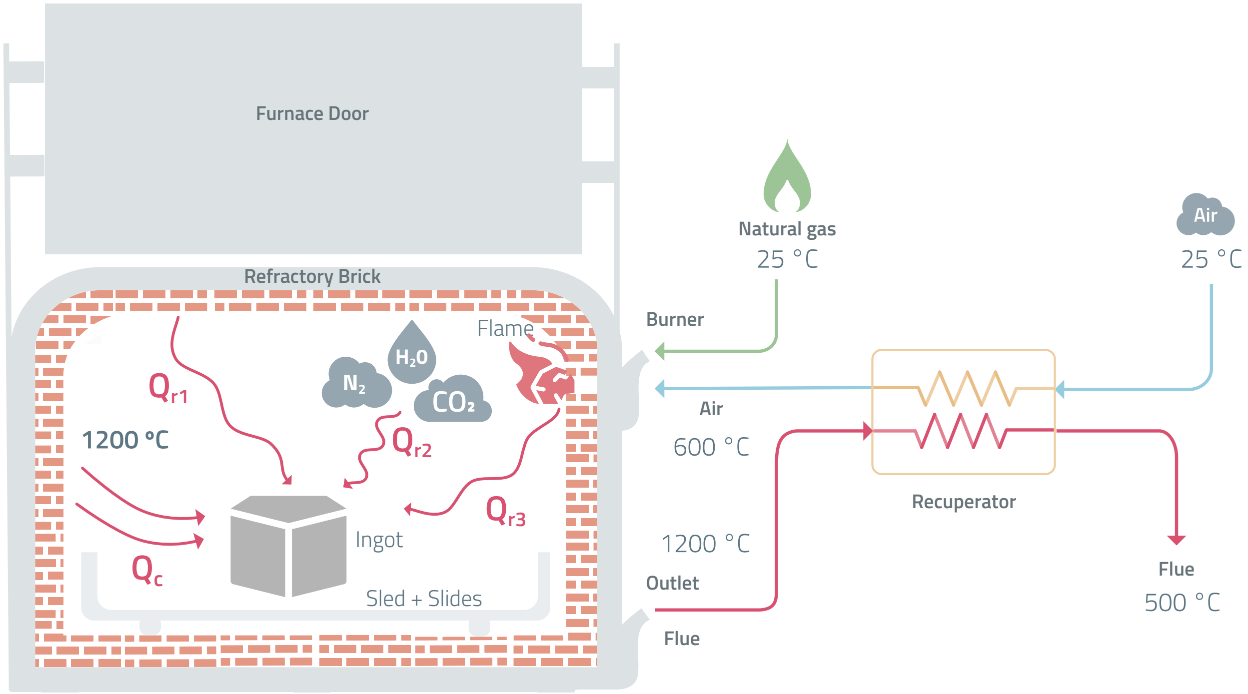


Figure 6: Conventional natural gas-fired furnace. Q_{r1} = radiation from refractory walls; Q_{r2} = radiation from internal atmosphere; Q_{r3} = radiation from flame (luminous soot particles); Q_c = convection.

Figure 7: (a) Inside of a car-bottom furnace; notice eight burner holes in the refractory lining and significant scale on the floor. (b) Electric manipulator removing steel workpiece from furnace.

3.3 Heat Transfer in Furnaces

The purpose of the furnace is to heat the workpiece uniformly from ambient temperature to approximately 1200 °C. Figure 6 shows the principal heat-transfer mechanisms by which this is achieved. **In steel forging furnaces, the dominant heat-transfer mechanism is thermal radiation [15].** Thermal radiation (often shortened to just radiation) is the transfer of heat by electromagnetic waves. All bodies at temperatures above 0 K emit radiation; however, at elevated temperatures, radiation becomes increasingly important, and above roughly 1000 °C it typically dominates over convection and conduction [15].

The radiative heat-transfer rate between a hot surface and a cold surface can be expressed (in simplified form) as:

$$\dot{Q}_r = \varepsilon \sigma A \left(T_h^4 - T_c^4\right)$$

where ε the emissivity, σ the Stefan-Boltzmann constant *(*$5.67\times 10^{-8}\ Wm^{-2}K^{-4}$*)*, A is the surface area of the workpiece, and T_h and T_c are the hot and cold temperatures (in Kelvin, not °C). Note that the temperature terms are raised to the fourth power. As temperature increases the T_h^4 term grows rapidly and overcomes the small magnitude of the Stefan-Boltzmann constant. This explains why radiation becomes so dominant at high temperatures. For example, increasing the absolute temperature from 500 K to 1000 K increases the T_h^4 term by a factor of 16. In steady-state furnace operation, there are three main sources that provide net radiative heat transfer to the workpiece:

- **Refractory lining: 80–95% of all heat transfer**: The refractory surfaces are large radiators and provide the majority of radiative heat input to the steel [15], [16], [31], [32].

- **Furnace atmosphere: 5–10% of all heat transfer:** The combustion products (CO_2 and H_2O) surround the workpiece and the inside of the furnace. These gases are active in the infrared region and radiatively transfer heat to the workpiece [15], [16], [31], [32].

- **Burner flame: 5–10% of all heat transfer:** The flames at the exits of the burners transfer heat via radiation to the workpiece. The magnitude of radiation from the flame depends on its "luminosity" (soot particles combusting) and design of the fuel system (e.g., pre-mixed) [31].

Note, unlike solids, which emit radiation over a continuous spectrum, combustion gases primarily emit and absorb radiation in discrete infrared bands. However, diatomic molecules such as N_2 and O_2 are largely "infrared-transparent", meaning they do not participate significantly in radiative heat transfer [15].

During furnace start-up, the burner's flame is very important as it is the primary heat-transfer mechanism for heating the refractory lining to its operating temperature. Once the lining is hot, it becomes the main radiative emitter, and the furnace approaches steady-state.

Aside from radiation, the remaining 5–10% of heat transfer to the workpiece is provided by convection from the furnace atmosphere and is given by,

$$\dot{Q}_C = hA(T_h - T_c)$$

where h is the convective heat-transfer coefficient. In contrast to radiation, the temperatures are only raised to the first power, which is why convection becomes less dominant as furnace temperatures rise. However, convection is important as it ensures a more uniform temperature distribution throughout the furnace and reduces local hot/cold spots.

Even though the radiative and convective heat fluxes are high at the surface of the workpiece, the overall heating process takes hours because the thermal energy transferred to the surface slowly conducts into the center of the steel piece; recall, this occurs at a rate of approximately 100 mm per hour, which is why large billets and ingots require long times to reach a uniform forging temperature throughout.

3.4 Electrification Technologies for Furnaces

In conventional furnaces, 80–95% of the total heat transfer to the workpiece is provided via radiation from the hot refractory surfaces. **Thus, the main objective of furnace electrification is to use electricity to raise the temperature of the refractory walls and roof to 1200–1250 °C.** This section outlines the main electrification technologies and discusses the extent to which they can be integrated with thermal energy storage systems or, instead, are better paired with electrochemical batteries for flexibility.

3.4.1 Indirect Resistive Heating

Indirect resistive heating is a widely used electrification method for many industrial processes. In its simplest implementation, resistance elements are installed within the furnace chamber. When current passes through the elements, the unit heats to a high temperature and radiates directly into the workpiece and refractory lining. **Such systems are already deployed in high-temperature industrial furnaces and are reported to offer improved temperature control and higher efficiency.** See, for example, Kanthal's electric car bottom furnace and rolling mill in Hallstahammar, Sweden [33], [34]. Notably, since the elements radiate directly to the workpiece, there is no intermediate medium which pairs well with thermal storage. In this case, electrochemical batteries are better suited for load shifting purposes.

Alternatively, resistance elements can be placed outside the furnace and coupled to a blower system. In this configuration, air (or another working gas) is heated as it passes over the elements and is then delivered to the furnace through the burner slots in the refractory lining. This can be implemented as a relatively "drop-in" solution where the natural gas burners are simply replaced with electric burners (e-burners); see, for example, the system being developed by HyperHeat, which uses radiative elements to heat air up to 2000 °C [31]. Note, electric burners for large-scale forging furnaces are not yet commercially proven and remain at a moderate technology readiness level. **External resistive heaters also integrate well with thermal energy storage.** In a typical arrangement, a resistance element can heat a solid storage medium inside an insulated container. When heat is required, a working fluid such as air is passed over the hot storage medium and then into the furnace. Figure 8 shows a generic example of such a system. Several commercial and emerging high-temperature TES concepts operate in this space, including systems based on refractory brick (Rondo, Electrified Thermal Solutions, Calectra), carbon blocks (Antora, Fourth Power), or other solid media (Kraftblock). A broader overview of high-temperature TES developers has been previously provided in Figure 4 in Ref.[2].

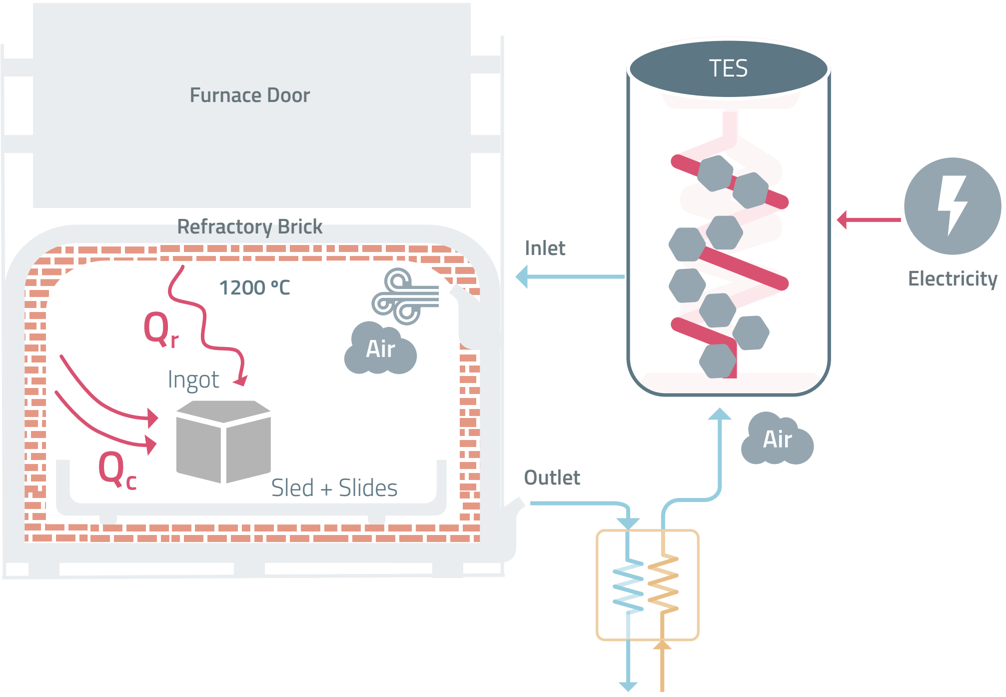


Figure 8: Electrified furnace with integrated TES system. Electricity is converted to thermal energy via electric resistive elements in the TES unit. Heat is then transferred to the furnace using air. Qr = radiation from refractory walls; Qc = convection.

3.4.2. Direct Resistive Heating

In direct resistive heating, electrodes are attached to the workpiece and a voltage is applied so current flows through the steel. By a phenomenon known as Joule heating, the electrical energy is converted directly into thermal energy within the material. However, because steel is highly electrically conductive, achieving substantial resistive heating requires very high current levels or long workpieces to provide enough electrical resistance [16]. Implementation is also challenging for large forgings since electrical contact is difficult to maintain reliably on hot, oxidizing surfaces, and "current crowding" near the electrodes can produce very high local heat fluxes. This can lead to local overheating and melting at the contact points. These issues generally make direct resistive heating likely unsuitable for large open-die workpieces, due to insufficient quality of the final workpiece, however it is used for long and thin steel sections.

3.4.3. Induction Heating

In induction heating, the workpiece is placed within an alternating magnetic field, which is generated by running alternating current through a surrounding coil. Because steel is electrically conductive, the changing magnetic field induces "eddy currents" (swirling loops of electrical current) within the workpiece, which raise the temperature. However, the induced currents are concentrated near the surface due to the "skin effect", so heating is most intense on the surface of the workpiece and must conduct inward [35]. As a result, induction is best suited to smaller cross-sections or applications where rapid surface heating is acceptable. In the last decade, research on the use of large direct-current magnetic fields to mitigate the skin effect for large slabs has been undertaken, but this work has not yet progressed beyond modeling [36].

Induction heating is already widely used in closed-die forging, where large numbers of small billets can be heated rapidly and repeatedly [17]. For the large workpieces typical of open-die forging, induction heating is physically beyond its limits. As there is no intermediate thermal storage medium, operational flexibility can only be provided by electrochemical batteries or by timing the batch operation schedule with some losses in output efficiency.

3.4.4. Plasma Heating

Plasma torches generate high temperatures by using electrical energy to ionize a working gas. Plasma temperatures can reach several thousand degrees Celsius, far exceeding those required for steel reheating and forging. Plasma-based furnace heating is an active area of research, with pilot-scale trials showing promising results, including uniform heating and greater than 80% emissions reduction from the natural gas baseline [37]. The choice of plasma gas significantly influences performance and NOx production, with initial results indicating CO_2 as a promising option. However, retrofitting existing furnaces with plasma-based heating will be challenging due to the large local heat fluxes and practical integration of torches into the furnaces.

3.4.5. Combined Systems

Hybrid approaches, which combine multiple electrification technologies, have been proposed. For example, Berger et al. describe a concept for an electrified walking-beam furnace in which indirect resistive heating is used to initially raise the workpieces to 850 °C. Induction heating is then used to reach 1200 °C [35]. Since the workpiece's core has already been preheated, the skin effect is less limiting, than if the whole workpiece was heated solely by induction.

Other hybrid concepts focus on the furnace structure itself. For instance, the refractory lining can be designed with multiple layers of refractory brick or embedded thermal-storage media. This effectively increases the thermal inertia of the furnace by providing integrated thermal energy storage.

3.5. Practical considerations

The shift from natural gas-fired burners to electric heating introduces several practical considerations, which are discussed below.

3.5.1. Internal furnace atmosphere

In a conventional furnace, the internal atmosphere consists primarily of hot combustion products (mainly CO_2 and H_2O) together with N_2 from the air. Depending on the completeness of the combustion process, small amounts of CO and residual O_2 may also be present. Opening the furnace door also allows air to enter, although due to internal circulation, the atmosphere stabilizes quickly. **The combustion gases are advantageous for furnace heating because they are strong radiators and fully surround the workpiece, which helps promote uniform heating.**

This is not the case for electrified furnaces, where there is no combustion to continuously generate CO_2 and H_2O. **If an electric furnace is operated with a simple air atmosphere, the gas is mostly composed of N_2 and O_2 which are highly transparent in the infrared wavelength region.** This means even more radiative heat transfer must come from the refractory bricks and heating elements.

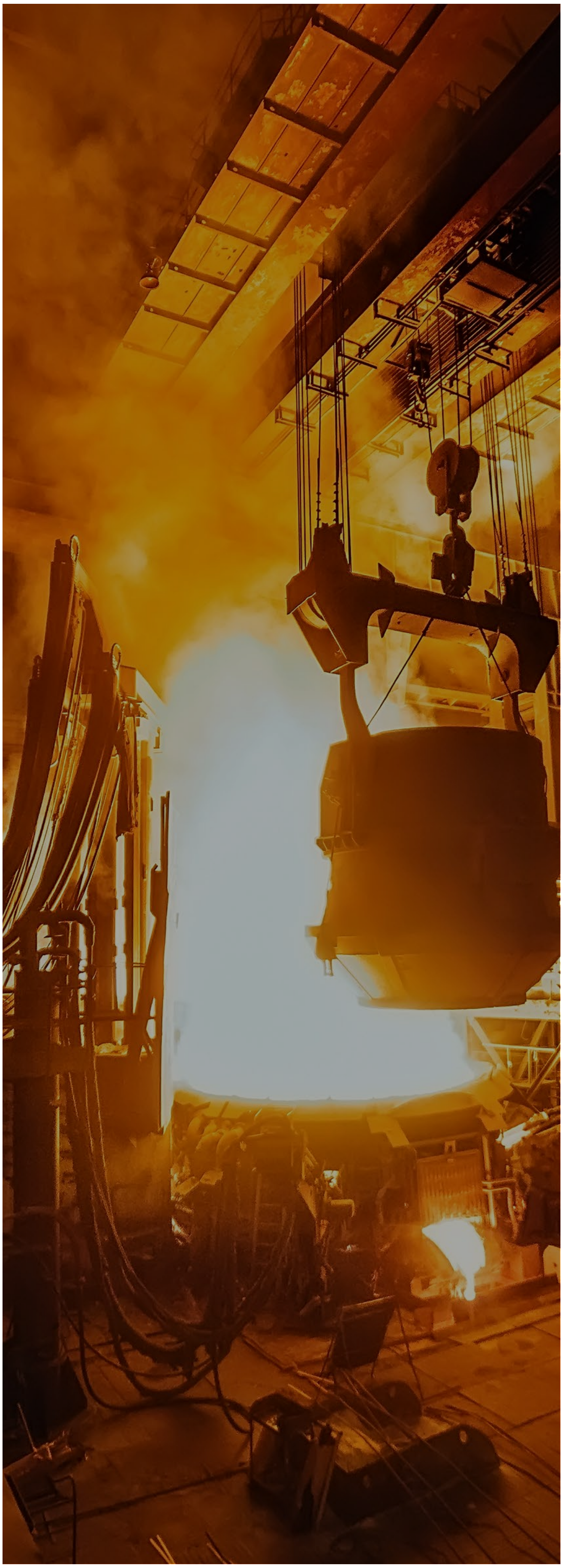
Aside from radiation effects, another important consideration of the internal atmosphere is its effect on workpiece oxidation (scale formation). Oxidation is governed mainly by oxygen partial pressure, temperature, and time at temperature, so long heating periods can cause substantial scaling. In gas-fired furnaces, CO_2 and H_2O dilute the O_2 concentration relative to normal air, but the atmosphere is still typically oxidizing, and door openings can create temporary furnace-wide spikes in O_2 concentration. Thus, for electrified systems it is important to monitor and assess the atmosphere, as continually bringing in hot air will increase oxidation. Suggested methods to limit oxidation include recirculating the airflow (so that it becomes predominantly N_2) or using an engineered atmosphere.

3.5.2. Circulation

In gas-fired furnaces, circulation is largely driven by the momentum of the combustion products when they exit the burners. This promotes circulation and helps avoid stagnation zones. For electrified systems, this flow mechanism is removed. For example, indirect resistive heating elements placed inside the furnace will provide less circulation than replacement with air-based electric burners. In all cases, natural convection plays only a smaller role than with gas-fired burners [31].

3.5.3. Retrofit

Steel forging furnaces typically operate for many decades. Therefore, decarbonization will often need to be delivered through retrofit, unless a furnace is near end of life [13]. In many cases, the furnace structure and mechanical handling equipment can remain largely unchanged, and electrification options should seek to make use of this existing capital. However, retrofit feasibility will be site-specific and depends on the available electrical grid connection capacity, which is discussed shortly.



4. Size of Storage and Resulting Cost Reductions

The difference in cost between gas and electricity means electrification requires 35–85% higher energy costs than unabated gas options. However, electrification of steel heating furnaces can be made more cost-effective by including thermal energy storage. The storage system acts as a buffer, which charges using electricity during low-price periods and discharges heat "on demand" when required by the furnace. This strategy enables electricity price arbitrage on the day-ahead market and is the main source of cost savings for the plant. Additionally, TES may provide ancillary grid services (e.g. frequency regulation) for extra revenue, although these are secondary in cost-saving magnitude.

As was discussed in the previous section, certain electrification technologies are naturally suited to thermal storage. For example, if the furnace uses an intermediate heat-transfer fluid (e.g. hot air), it can incorporate a TES system at relatively low cost. **Thermal energy storage tends to be much cheaper on a per-unit energy basis when compared to electrochemical batteries; on the order of 20% of the capital cost of a Li-ion battery system for equivalent capacity [1].** However, other methods (such as induction heating) convert electrical power directly to heat in the workpiece and cannot be integrated with an external thermal store. For these technologies, electrochemical batteries are better suited to buffer electricity.

An important question when including storage is how to optimally size the storage capacity and quantify the extent to which this can reduce the plant's average electricity cost over a year. This was analyzed by implementing a linear optimization model with hourly 2024 electricity prices from the German market [38]. The model assumes the thermal storage is ideal (100% efficiency) and minimizes the total annual electricity cost for a representative forging plant with a constant process heat demand (denoted as "d"). This provides a theoretical limit on cost savings from load-shifting using storage.

Figure 9 shows the resulting average electricity cost as a function of storage size, for two different charging scenarios. (Note, the storage was modeled agnostically, so the results can be applied for either thermal or battery.) In the figure, the red dashed line indicates the average 2024 electricity price in Germany, and the yellow dashed line indicates the average gas price for the same year. The two solid curves correspond to the scenarios with a storage system. The blue curve indicates a system with "nominal" charging power – i.e., the storage charges at the rate of the forge's nominal heat rate, "d". The green curve indicates a system which can charge at a higher rate than the forge's thermal load (an "overpowered" storage system). For example, if the forge has a load of d = 30 MW, the blue line assumes the storage can be charged at a rate of 30 MW, and the green line assumes it can charge at 60 MW. In practice, this means the grid connection must be larger than the process's demand, so the storage can absorb much more power during cheap-price periods. For example, during midday hours when electricity is increasingly inexpensive, the overpowered system can quickly absorb low-cost electricity well above the furnace's instantaneous needs and store it as thermal energy. A clear obstacle for electrification will be access to large grid connections. In Germany the so-called Baukostenzuschuss fee would require the forge to pay at a connection cost of 300,000 EUR/MW.

The results highlight an important trade-off between storage capacity and charging power (grid connection size). Key observations from the analysis include:

- **Normal charging power (blue):** Even with a very large storage capacity (on the order of 1000 hours of heat supply), the nominal-charge scenario cannot bring the average electricity cost below the average wholesale gas price. However, a moderately sized storage system (about 10 hours of capacity) does yield significant savings from the no-storage case – reducing the average electricity cost from roughly 80 EUR/MWh down to 55 EUR/MWh.
- **Oversized charging power (green):** In the overpowered charging scenario, the storage is much more effective at cutting costs. Because the system can capture cheap energy quickly, the average electricity cost drops more steeply with increasing storage size. Once the storage exceeds roughly 30 hours of capacity in this scenario, the plant's average electricity cost falls below the average gas price.
- **Trade-off between storage capacity and grid connection**: As an example, to achieve an average wholesale electricity cost of approximately 50 EUR/MWh, the forging plant could either invest in an over-sized charging system with roughly 10 hours of storage or stick with a nominal-sized charging system but then require approximately 30 hours of storage capacity**. In other words, a smaller grid connection (lower charging power) can be offset by additional storage capacity to maintain the same cost target, and vice versa.**

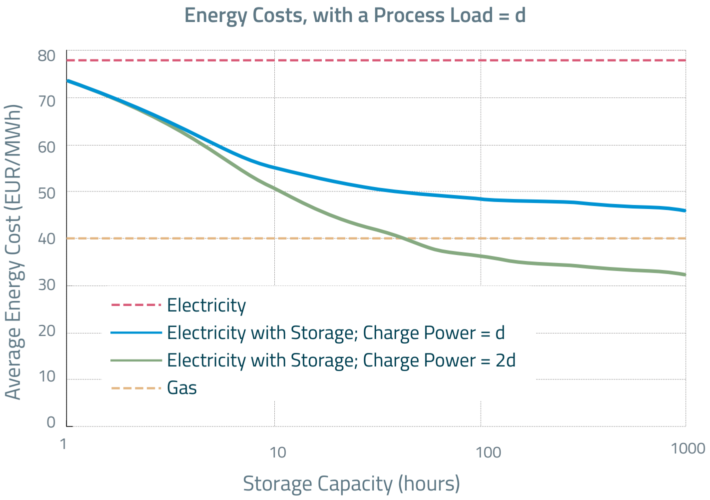


Figure 9: Energy storage capacity (i.e., size in MWh) and its effect on the average energy cost of the forge. The analysis uses hourly German wholesale electricity prices for 2024. "d" is the storage charging power, which for a large forge would be at least 30 MW. FCA analysis.

5. Conclusion

Open-die steel forging is an energy- and emissions-intensive manufacturing process. In the EU, downstream processing steps such as forging, rolling, and finishing account for 80% of total employment in the steel sector. The largest and most challenging decarbonization step is the replacement of natural gas-fired furnaces. A case study exploring electrification options and the role of thermal energy storage has been presented, to better understand decarbonization pathways for metal forging and other high-temperature manufacturing industries in the EU. The analysis is based on a large steel forge with a layout similar to the Dirostahl plant in Remscheid, Germany.

Analysis of furnace heat transfer, electrification options, and storage capacity highlights several key points:

- Heat transfer to the workpiece is dominated by radiation from the refractory walls, and electrification options should seek to replicate this radiative heating environment.
- The most mature and likely electrification method for open-die forging is indirect resistive heating. This is delivered either by electric heating elements placed directly in the furnace, resistive elements integrated within an e-burner assembly, or external electric heaters coupled to a thermal energy storage (TES) system.
- In closed-die forging, where workpieces are smaller, additional electrification options become viable, such as induction heating (and are already widely used).
- The internal furnace atmosphere matters for both radiative heat transfer and the extent of workpiece oxidation (which leads to material losses), and must be considered during electrification.

Analysis of 2024 hourly wholesale electricity price data highlights the trade-off between grid connection size and thermal storage capacity when seeking to minimize operating costs

Ultimately, the choice of decarbonization pathway, whether fuel switching or electrification, is primarily an economic one. While hydrogen and biomethane are likely to remain costly and constrained by supply, flexible electricity consumption is becoming increasingly cost-effective. Additionally, prioritizing electrification enables multiple technological solutions, reducing risk of locking in to a single technology.

5.1. Recommendations

At EU-level, the fastest route to scale is to make electrified high-temperature heat investable: align de-risking instruments with retrofit needs, reform network charges to reward flexibility, and fast-track grid connections and permitting. Thermal energy storage should be treated as a system asset that reduces operating costs and supports renewable integration [2].

- Explicitly recognize high-temperature industrial heat (including forging furnaces) as a priority category in EU industrial policy, rather than concentrating policy attention solely on primary steelmaking upstream. Electrified forging is a downstream anchor where most steel jobs and value are located. It is a segment that is highly mobile internationally and therefore strategically important to keep in Europe.
- Recognize electrification combined with thermal energy storage as a robust, low-risk decarbonization and resilience pathway. This combination is compatible with multiple high-temperature heating technologies and protects companies against energy price shocks and volatility.
- Ensure high-temperature thermal energy storage linked to industrial electrification is recognized in EU and national system planning and flexibility assessments. This would improve visibility of multi-hour and multi-day flexibility needs, justify targeted procurement, and enable storage-based industrial loads to be treated as system assets rather than isolated behind-the-meter solutions.
- Reduce the electricity-to-gas price ratio through targeted policy and the increasing build-out of renewables. Prioritize measures that increase the supply of clean firm power to industrial sites and enable flexible demand. Rising EU ETS prices and the associated cost of carbon emissions are likely to increase the risk of carbon leakage and relocation of this industry outside Europe.
- Provide CAPEX support and OPEX incentives to de-risk early projects (e.g., contracts for difference schemes such as SDE++ in the Netherlands [39]) and build on the EU industrial heat electrification pilot auction logic that blends CAPEX grants and OPEX support for early movers. This can be complemented with EU financial guarantees to reduce lender risk and unlock higher debt ratios for early commercial electrification and storage projects.
- Prioritize grid connection planning and permitting. **Electrical grid connections are highly likely to be a major constraint for retrofit projects.**
- Avoid grid network tariffs that are based on the plant's maximum rated power. In practice, the plant is likely to draw at its maximum rated power only during low-price periods (often high-renewables hours), when the grid is typically not stressed.
- Encourage member states to integrate industrial electrification into network development plans with explicit allocation for industrial clusters and high-temperature heat users (not only households and transport).
- Use the upcoming Electrification Action Plan to provide clear guidance, explicitly supporting the retrofit of existing furnaces (not only greenfield), hybrid transition solutions, and integrated thermal energy storage as a decarbonization and flexibility enabler. Starting the transition with a hybrid approach can help validate technologies and de-risk subsequent scale-up. For example, electrifying smaller furnaces and initially operating during low-price periods will validate and de-risk future projects.
- Create lead markets for low-carbon forged steel components through green public procurement, product standards, and embodied carbon reporting. This would improve revenue certainty for electrified forging facilities and complement supply-side support.

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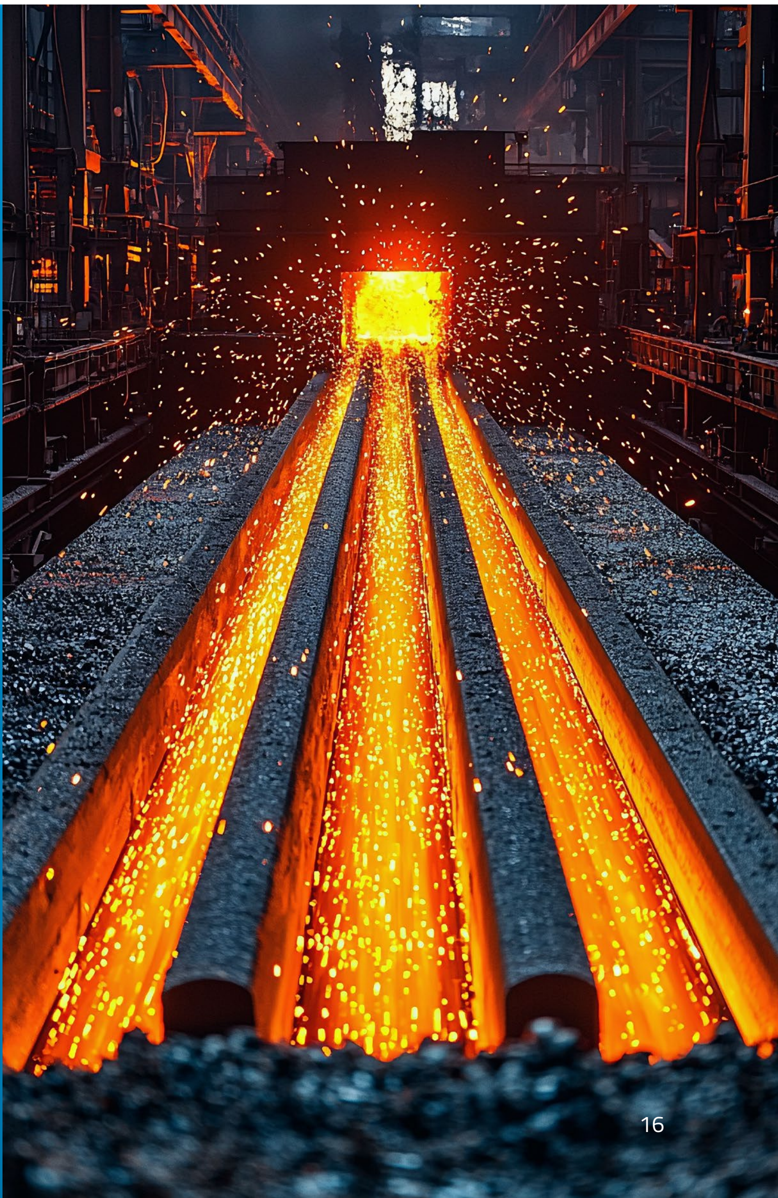

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We are a climate innovation think tank. We exist to close the remaining innovation gaps to reach net-zero emissions by 2050. To reach this objective, we accelerate innovation in critical industries where sustainable solutions are still in very early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

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