DECARBONIZING INDUSTRIAL THERMAL PROCESSES WITH MEDIUM VOLTAGE ELECTRIC RESISTANCE HEATING

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Abstract – This is an overview of the merits of electric process heating for decarbonizing fossil fuel-based industrial thermal processes. It discusses the advantages and disadvantages of common electric heating technologies in use today, including heat pumps, electrode boilers, and electric resistance heating. It also demonstrates how medium voltage electric resistance heating systems offer the versatility, adaptability, and efficiency to make electrification a cost-effective and technically feasible process heating option for a greater range of industrial applications.

Index terms — Electric process heating, Electric resistance heating, Medium voltage electric resistance heating, Process heating decarbonization

I. INTRODUCTION

A. The Critical Need To Decarbonize Industrial Thermal Processes

The European Union (EU) has set a goal to achieve carbon neutrality by 2050 [1]. The decarbonatization of heat production in light and heavy industry will play an important part in making progress toward this goal. Meeting the high-temperature heating requirements of industrial processes accounts for approximately one fifth of global energy demand; and burning fossil fuels to meet these needs generates around one third of the world's greenhouse gas emissions [2].

For example, the chemical, petrochemical, and pharmaceutical sector has the highest consumption of fossil fuel-based energy for heat production in European industry. The sector uses ~465 Terawatt hours (TWh) of fossil fuel-based energy to produce heat, equivalent to ~65% of the sector's total energy consumption [3].

B. Decarbonization Through Electrification

Despite the pressing need, decarbonizing industrial thermal processes remains challenging. While there are numerous technologies on the market that offer potential solutions, including hydrogen-, microwave-, and biomass-based heating systems, many emerging innovations are currently unproven for long-term operation in complex industrial processes.

Companies understand that they need to decarbonize; many have set ambitious goals to reduce Scope 1 and 2 emissions and created roadmaps to guide them toward carbon neutral operations. However, companies must be certain the process heating solutions they choose will not have a negative impact on productivity. With several technologies already in use in industrial thermal processes, in some cases for decades, electrification offers a way to decarbonize without compromising productivity by relying on unproven methods.

Electric heating technology has proven itself for more than a century in residential, commercial and industrial applications. The earliest forms of electric heating emerged in the mid-19th century with the development of the first heat pumps, followed in the 1880s by the introduction of tungsten lighting and heating systems that used carbon-based filaments to emit light and heat energy. The early 20th century saw the development of electrode boilers and new alloys such as nichrome that offer increased resistivity, allowing for more efficient heat production and more precise temperature control.

More recently, in the late 20th century, the development of more advanced controls increased precision and responsiveness, and medium voltage technology made electric heating a feasible option for higher-duty thermal processes. With an array of proven technologies already on the market, it is now theoretically possible that direct electrification could provide 62% of industrial process heat in the EU [4].

The challenge for those tasked with decarbonizing industrial processes is selecting the electrification technology, or combination of technologies, that will reliably meet process heating needs and be economically viable. The following sections of this paper outline the advantages and disadvantages of several common electrification technologies to provide an understanding of their potential impact and suitability for replacing fossil fuel-based heating systems in a variety of industrial processes. Later sections propose electric resistance heating, and particularly medium voltage systems, as the most viable electrification solution for the broadest range of industrial applications.

II. COMMON ELECTRIFICATION TECHNOLOGIES IN USE TODAY

A. Heat Pumps

A heat pump uses an electric motor to draw source heat and direct it to where it is required. By transferring heat rather than generating it, heat pumps can provide higher thermal energy outputs than they consume in electricity, allowing them to achieve high coefficients of performance (COPs), typically in the range of 2 – 3 COP. Higher COPs can be achieved in some conditions, for example if there is high-quality source or waste heat available.

The high efficiency of heat pumps can be a decisive factor in their implementation. However, there are other factors companies should consider as part of their section process.

Industrial heat pumps are large installations that must be supported by a complex infrastructure, which means they are not always suitable as direct replacements for existing fossil fuel systems. Geothermal systems, for example, require a very large footprint to extract source heat and transfer it to where it is needed in the process.

Heat pumps offer lower temperature limits than other systems, typically around 200°C, and their performance can vary depending on the quality of the source heat. To provide the consistent temperatures required by industrial processes, heat pump systems may need to incorporate waste heat recovery, which can present startup challenges. Additionally, heat pumps are complex systems with numerous components, so maintenance costs can be higher than alternative solutions.

B. Electrode Boilers

Electrode boilers are often used to meet large load demands, typically for steam and hot water applications, as they are capable of operating at high voltages to produce high-megawatt (MW) outputs while reducing transformer requirements.

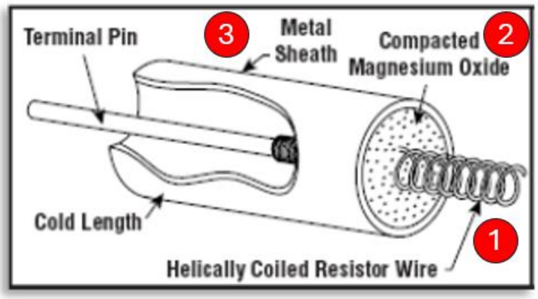
While electrode boilers offer advantages in applications with large load demands, their suitability for specific sites and processes must be assessed against additional criteria. These systems have a large vertical footprint typically upward of 6 meters, which typically makes a direct boiler room replacement challenging. This means infrastructure must be re-routed to an external boiler location, increasing the time and cost of installation. Maintenance and operation costs are also often high due to the presence of sensitive components such as electrodes and sensors and the additional electricity demand of numerous pumps and hydraulic systems. The cost-efficiencies gained from operating at higher voltages can be counteracted by the additional energy consumption of auxiliary electrical systems.

Finally, it should be noted that electrode boilers are not suitable for applications with stringent requirements for water quality or feedwater treatment. These systems rely on the conductivity of water to generate heat, so the poor conductivity of deionized, demineralized, or reverse osmosis (RO) water makes them unsuitable for use in electrode boilers.

C. Electric Resistance Heating

Electric resistance heating (ERH) is based on the premise of Ohm's law, which defines the proportional relationship between current, voltage, and resistance. Of all the electric heating technologies described in this paper, ERH has the simplest design:

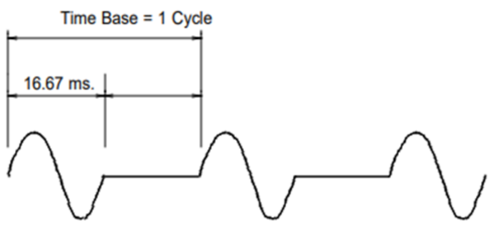
1. Current is passed through a resistance coil to generate heat.
2. A dielectric material protects the coil and transmits the heat.
3. A metal sheath emits the heat into the process.



Unlike the electrification technologies described above, ERH systems have no moving parts, offering lower costs for installation, maintenance, and operation. ERH also provides high efficiency, with 100% thermal conversion of electrical power that reaches the heating element. I^2R losses are low in ERH systems, with some small upstream losses in power wiring and heat dissipation through power consumption; in medium voltage systems, such losses are typically under 1%.

ERH systems are often used to simplify the management of dynamic loads and avoid energy wastage. Power to the heating elements can be trimmed and fired based on the needs of the process at any given point in time. This responsiveness is enabled by silicone-controlled rectifiers (SCRs), which can offer firing cycle times as short as 16.67 milliseconds, helping eliminate energy wastage in dynamic processes with large thermal swings.

Chart: Firing Precision Enabled by SCRs



The chart above demonstrates high precision DOT firing model which can reduce firing as short as 1 cycle. 1 cycle on 50 or 60Hz signal is 20ms / 16.67ms respectively

It's simple, adaptable design, small footprint, and ability to address heating applications up to 800°C make ERH an extremely versatile technology. ERH systems are currently in use across numerous industrial thermal processes, from relatively benign water and steam applications to more aggressive oil, gas, and caustics processes.

While it is the most versatile of the technologies considered in this paper, the main limitation of ERH is that it cannot be applied to the very high-temperature (>800 C) processes that are common in hard-to-abate industries.

D. ERH And Other Electrification Technologies

1) *Using ERH With Heat Pumps:* ERH systems can work in conjunction with heat pumps in a variety of ways. For example, in suboptimal startup conditions, ERH can initiate the heating process and then hand over to a heat pump when the process is running effectively. ERH can also provide preheating for heat pump systems with unreliable source heat, stabilizing the source temperature so that heat pumps can operate at high COPs. In addition, ERH systems can boost heat in locations where thermal output from centralized heat pumps cannot meet process demands as shown in the figure below.

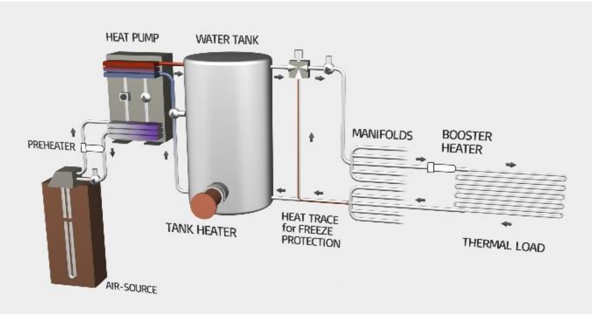


Figure 1: process flow diagram showing how ERH systems can boost heat in locations where thermal output from centralized heat pumps cannot meet process demands.

2) *Using ERH In Lieu Of Electrode Boilers:* ERH systems can replace fossil fuel-fired boilers without the limitations of electrode technology. ERH is well suited for applications that require deionized, demineralized, or reverse osmosis water, as the resistor wire has no contact with the water supply. ERH systems are also typically smaller than existing boilers and have no moving parts to maintain, offering lower installation and maintenance costs than electrode boilers. This smaller footprint also means facilities can have more open space and larger clearances, increasing the safety and accessibility of the working environment.

E. Key Considerations For Electrification Technology Selection

1) *Infrastructure Changes:* One of the primary factors in selecting viable electric heating solutions is the impact of addressing the infrastructure requirements of the new system. Infrastructure considerations may be site-specific, for example assessing the footprint of a new system compared to the available space. Considerations may also be process-specific, such as determining the comparative cost and efficiency of installing multiple heat exchanges or applying heat directly to the process.

2) *Process Criticality:* For processes that require consistent temperatures and on-demand availability, systems that offer

redundancy in case of failure should be considered. Many facilities install backup heat pumps or electrode boilers in case the primary system fails. ERH, however, offers built-in redundancy; these systems typically contain hundreds of heating elements, and a single element failure has little to no impact on system performance.

III. LOW VOLTAGE AND MEDIUM VOLTAGE ELECTRIC RESISTANCE HEATING

A. The Emergence Of Medium Voltage ERH

Low voltage (<1 000 V) ERH systems have been used for industrial process heating for many decades. Medium voltage (1 000 V to 7 200 V) ERH systems, while a more recent development, were introduced over a decade ago and have been successfully applied to a broad range of industrial thermal processes globally.

Elevating the voltage level significantly reduces the amount of current required to operate systems, as shown in the figure below.

Low voltage systems	Medium voltage systems
Up to 1 000 V Average efficiency ~96% **1 MW at 480 V = 1 204 A**	1 000 V to 7 200 V Average efficiency ~99% **1 MW at 4.16 kV = 139 A**

Figure 1: Comparison of low voltage and medium voltage ERH

B. Efficiency Gains And Cost Reductions With Medium Voltage Systems

In processes with multi-megawatt loads operating year-round, lower amperage and small increases in efficiency can lead to significant cost reductions. Directly applying medium voltage supply to the heating elements removes the need for transformers to step down voltage and reduces the amount of wiring and other infrastructure required. This combination of reduced complexity and increased efficiency has a positive impact on the cost of installation, maintenance, and operations.

For more information on efficiency gains and cost reductions with medium voltage systems please click here to view a 2014 PCIC White Paper on the subject.

C. Increased Feasibility Of Applying Electrification To More Processes

Low voltage ERH systems are widely used at industrial facilities for small, decentralized loads or providing startup, preheating, and heat boosting. Over the last decade, medium voltage systems have increased the range of applications for ERH systems, providing the ability to electrify larger heat loads (over 2 MW) cost-effectively. With a technical readiness level (TRL) of nine (NASA TRL scale), medium voltage ERH increases the feasibility of applying electrification to decarbonize centralized fossil fuel-based systems.

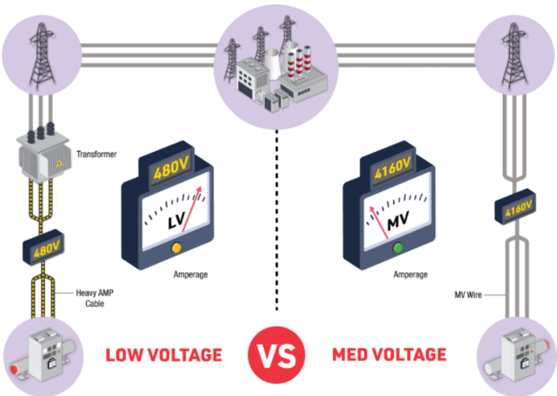
Medium voltage systems have been deployed at industrial facilities for more than a decade and utilize the core design principles used in ERH for over a century. The long-term performance of such systems is well understood, in contrast to emerging electrification technologies that are yet to prove themselves across multiyear lifecycles.

IV. MEDIUM VOLTAGE ELECTRIC RESISTANCE HEATING USE CASE EXAMPLES

A. Minimizing Heat Loss Over Long Distances At A Chemical Manufacturing Facility

Faced with ambitious carbon reduction targets, a chemical manufacturer sought a solution to address the heat requirements of its new octane production plant. This process demands a reliable heat supply to maintain continuous production output and meet the growing demand for octane in plastic resin production.

Given the 350-meter distance between the heater and the control panel, a 3 MW 6 300 V electric process heater was implemented. Over such a long distance, lower voltage systems can experience significant losses through the connecting cables, reducing overall efficiency. By utilizing a medium voltage solution, these losses are minimized, ensuring a highly efficient and reliable installation. Electrifying the process heating has also provided a reduction of approximately 6,000 tonnes of CO_2 annually compared to fossil fuel-based alternatives.



B: Integrating With Existing Electrical Supply Infrastructure At A Fuel Refinery

As part of its drive to increase biodiesel production, a fuel company wanted to expand and decarbonize its vacuum distillation unit, including the process heater for preheating the green feed. The company identified ERH as a potential solution, but wanted to avoid the need to install low voltage switchgear and cabling infrastructure. Two 3.85 MW medium voltage heaters were installed and are now part of a conversion process that is estimated to reduce emissions throughout the company's value chain by 1.2 to 1.7 million tonnes of CO_2 annually.

V. CONCLUSION

With decarbonization targets to achieve, companies that depend on high-duty thermal processes must identify ways to reduce the use of fossil fuel-based heating systems. This paper has shown how electric heating in general, and ERH in particular, offer viable and proven alternatives for industrial thermal processes, including higher-temperature processes beyond water and steam that cannot be addressed by heat pumps and electrode boilers.

It has further shown that medium voltage ERH has broadened the range of processes to which ERH systems can be applied, providing the versatility, adaptability, and efficiency to make electrification feasible for large, centralized thermal loads without the limitations of heat pumps and electrode boilers.

VI. REFERENCES

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VII. VITA

Ali Aboosi has a bachelor's degree in chemical engineering from the University of Surrey in the United Kingdom. Through his career he has focused on the thermal design of bespoke process heating solutions and leveraging his strong technical background to provide consultative advice for some of the largest industrial companies around the world.

Ashaleigh Robinson has a master's in chemical engineering from University of Manchester, in the UK. Ashaleigh completed a year in industry and graduate programme at Spirax Group, predominantly focusing on steam and electric thermal process solutions in Spirax's focus industries. After the graduate programme, Ashaleigh moved into a Business Development role for Chromalox, with a focus on synergy projects between some of the Spirax Group companies.