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Alternative Thermal Technologies for Industrial Process Heat: Barriers and Opportunities

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Abstract

Energy scarcity and subsequent global fuel market shocks have become a significant concern for the United States. Process heating in industry accounts for over half of all industrial energy usage and is almost entirely (>95%) supplied by natural gas, coal, and byproduct fuels. Many existing alternatives, technologies, and strategies can reduce dependency on this fossil fuel usage to promote energy security and competitiveness. It is expected that adoption of alternatives is limited by capital investment. A working group exploratory exercise was performed to evaluate the current barriers to alternative process heat technology adoption for the manufacturing sector. Although the working group's findings emphasize electro-technologies due to their emergence as the central topic of discussion, we have contextualized these results by providing a fair and consistent comparison against several alternative thermal technology options. The most reported issue was the lack of financial incentives, with the second key issue for engineers and manufacturing sector decision-makers being the lack of awareness or understanding of available alternatives. This paper aims to provide an analysis of the levelized cost of heating for a variety of alternatives as part of addressing concerns from the emergent patterns reported in the exploratory exercise, as well as provide guidance on barriers to further adoption. Levelized cost of heating analysis considered the capital investment, operations and maintenance, lifespan, and fuel stream costs of various systems delivering heat to the product or process as a generalized cost per megawatt-hour delivered. The analysis indicates that biomass burners, industrial open-loop heat pumps, and central-receiver heliostat fields are at cost parity under average 2024 United States natural gas and electricity prices against well-optimized natural gas burners, though further cost reductions are necessary for consistent adoption.

Keywords: industrial process heating; levelized cost of heat; electro-technologies; energy security

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1. Introduction

One of the key issues faced by the United States' economy in the 21st century is energy security [1]. Not only does the United States' highly developed economy rely on the steady supply of fuel and electricity for everyday function, but there also exists a strong correlation between gross domestic product per capita—a key quality of life metric—and the average energy consumption per capita [2]. Energy costs and availability strongly drive the cost of material production and transportation, which compound throughout production and ultimately to the costs realized by consumers. Process heating alone accounts for more than 50% of US manufacturing energy usage (7.6 quads), and roughly one-third of this energy expenditure is lost as waste heat (2.5 quads). Nearly 95% of US industrial heat demands are met by just natural gas (55%), byproduct fuels (36%), and coal (5%) [3,4]. As such, reliance on these fuels exposes the US to significant fuel price and supply uncertainties, though fuel prices such as that of natural gas are expected to decrease slowly in the long term. Despite the US producing much of the fuel it consumes, global shocks still have a significant effect on the US manufacturing sector, such as the escalation of the Russo–Ukrainian War in 2022, which imposed a 1.4% retraction in total US economic output [5]. As such, demand exists for greater energy supply security, resiliency, and reliability within the industrial sector.

To that end, the US Department of Energy (DOE) put forward the Industrial Heat Shot initiative in 2022. This initiative is intended to mirror the leaps and bounds in technological development that occurred in NASA's Moonshot [6] during the Space Race; however, the Heat Shot is aimed at developing cost-effective alternate sources of industrial heat, thereby promoting energy security against fuel price volatility and cleaner industry [7,8]. A working group exploratory exercise was conducted by the DOE Better Plants Program team to identify the main barriers to adoption of alternative thermal technologies by industry.

This work aims to analyze the outcome of the working group exploratory exercise to address industry's perception of alternative thermal technology costs, to provide detail on practical engineering limitations and challenges of those technologies, and to inform research direction. Analysis of the levelized cost of heating (*LCOH*) of possible alternative process heat sources is performed while also elaborating on those sources and the state of process heat technology development. *LCOH* analysis itself is a well-established concept for comparing thermal technologies. Rather than an exhaustive assessment of Technology Readiness Levels (TRL) or adoption barriers, we have utilized information from real-world case studies to inform our cost and performance estimates where applicable. A detailed analysis of site-specific adoption dynamics falls outside the scope of our current economic framework. Gilbert et al. [9] provided a reasonable framework for approaching *LCOH* analysis and demonstrated it on case studies across four applications. Degelin et al. [10] demonstrated its usage in the comparison of heat pumps deployed in a district heating network, though this is naturally at much lower temperatures than heat pumps used within industrial applications. Bogoslavska et al. [11] performed *LCOH* analyses on various biomass fuels in Ukraine for a comparison against anthracite coal and natural gas whilst considering environmental taxes present at the time of their writing. Thiel et al. [12] provide an excellent comparison for thermal technology deployment costs, though less emphasis is placed on characteristics such as operative temperature range or engineering challenges to deployment. District heating *LCOH* analysis was also performed by Li et al. [13] regarding a case study in Sweden about combined heat and power, biomass boilers, and bio-oil boilers, focusing on dynamic heat demand. Beckers et al. [14] performed simulations using GEOPHIRES (GEOthermal energy for Production of Heat and electricity ("IR") Economically Simulated) to determine the *LCOH* and LCOE for enhanced geothermal compared to natural gas boilers. Though limited to that specific case, it does provide very detailed sensitivity analysis information on the simulations. Stanytsina et al. [15], like Degelin [10], performed an *LCOH* analysis on heat pumps, though their focus was largely on the residential and public sectors with brief reference to the industrial sector. An *LCOH* study on concentrating solar power central-receiver heliostat fields with thermal energy storage was conducted by Cruz-Robles et al. [16], which addresses the feasibility of concentrating solar power deployment in industry. *LCOH*'s use varies, with many focusing on cost comparisons for heating/ventilation and air conditioning (HVAC), district heating, and boiler applications. Much of the present analysis places additional focus on specific sources of heat, such as solar [16] or enhanced geothermal [14]. Similarly, some gaps are present in the comparison of available thermal technologies with respect to *LCOH*. In addressing industrial questions of alternative thermal technology financial feasibility as presented in the working group exercise, this gap in *LCOH* analysis is also addressed.

2. Background

2.1. Exploratory Exercise Methodology

During a working group on alternative process heating technologies with representatives from leading manufacturing firms with locations distributed across the US, an exploratory exercise to compare a wide range of thermal options was carried out during each of the 1 h working group sessions, from which electro-technologies emerged as the central topic of discussion. All alternative process heat options were evaluated during the exploratory exercise to ensure a fair and comprehensive comparative analysis. Seven monthly sessions were convened between August 2022 and March 2023. Attendance ranged from 17 to 26 participants in each session, but not all participants registered a response during the working group exercise. Although the sample sizes were limited, they were sufficient to present early interest patterns amongst the industry participants on energy efficiency topics.

The breakdown of working group participants is represented in Table S1 of the Supplementary Materials (SMs), and their responses to which systems are most difficult to fuel switch or replace are in Table S2 of the SMs. All the questions in the exploratory exercise allow participants to "select all that apply" as their answer except for one question about specific site experience. Figure 1e below details the exploratory exercise response regarding site experience, where "5" represents extensive experience, whereas "1" corresponds to minimal experience. It is relevant to note that not all working group participants responded during the working group exploration exercise.

Analysis of the results focuses primarily on the percentage of respondents who provided a response to a given question, such as the question "What are the primary barriers to energy efficiency?" As respondents can select all that apply, the sum of all percentage points is very likely to be higher than 100%. It is expected that there are multiple concurrent barriers that each working group participant is facing. It is notable that responses to the exercise are reflective of the participants' personal perceptions or fears and may be based on a lack of empirical evidence. The findings from the exploratory exercise may represent a range of priorities and challenges, occasionally lacking sufficient contextual details.

Energy efficiency represents technologies and operational practices that minimize thermal energy loss or improve the heat transfer effectiveness of existing processes. These measures reduce the total energy input required to reach and maintain target process temperatures (e.g., waste heat recovery, advanced thermal insulation, and process optimization) [17].

Alternative fuels comprise replacements like biomass, alternative hydrogen, or renewable natural gas (RNG) within combustion-based thermal systems. This approach maintains existing furnace or boiler infrastructure while altering the fuel source to reduce emissions [17].

Electro-technologies represent the direct conversion of electricity into thermal energy, replacing combustion-based heating entirely. These technologies utilize resistance heating, induction heating, electromagnetic waves, or heat pumps to deliver heat directly to the process [17,18].

2.2. Exploratory Exercise Results

Figure 1 below shows the results of the working group exploratory exercise. Participants were asked questions regarding the ease (or difficulty) of implementing a variety of solutions to process heating, including energy efficiency, alternative fuels, and electro-technology implementation at their organizations. The numbers in Figure 1 represent the total number of working group participants who provided responses for each specific category/sub-section during the exploratory exercise. The total sample size for energy efficiency- and electro-technology-related questions was 17, and the total sample size for alternative fuel-related questions was 13.

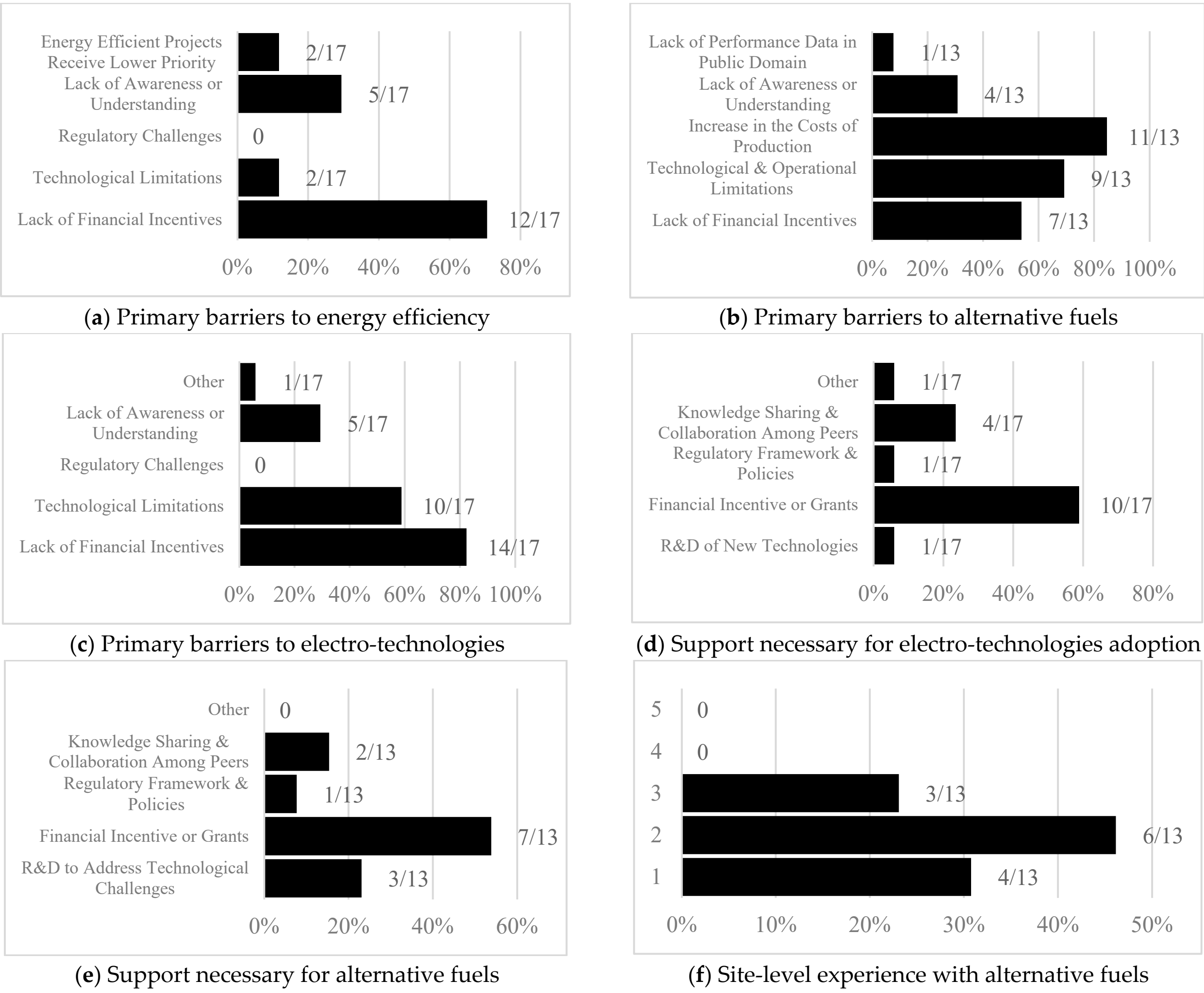

Figure 1. Working group exploratory exercise results: Primary barriers were identified for adopting different technologies categorized under (**a**) energy efficiency, (**b**) alternative fuels, and (**c**) electro-technologies. The necessary support required for adopting (**d**) electro-technologies and (**e**) alternative fuels was also identified, along with (**f**) site-level experience with alternative fuels. Note: Numbers represent the number of participants who responded to each category. The total sample size (N) for sub-sections 1 (**a**,**c**,**d**) is 17; the total sample size (N) for sub-sections 1 (**b**,**e**,**f**) is 13.

Three themes appear most consistently within the exercise. First is the perception of financial unviability; next is the perception of technological immaturity (that alternative methods are operationally or technologically limited in their capacity to perform the required tasks); and last is a stated lack of awareness or understanding. The first two perceptions could possibly be the result of the lack of awareness or understanding, whether stated or unstated. Examples such as boilers, steam generation, and sterilization somewhat bear out this possibility. Both boilers and steam generators have a wide range of alternative technologies capable of providing process heat from 100 °C to 400 °C [19]. Also, sterilization often employs relatively low-temperature steam (~130 °C) [19] under pressure when process heat-avoidant means (e.g., UV and X-Ray) are not being used.

3. Methods

3.1. Levelized Cost of Heating Methodology

To determine how grounded concerns of financial viability are, *LCOH* analysis [20] can be performed to capture the cost per delivered megawatt-hour of energy into the charge material, which enables an objective, apples-to-apples comparison across diverse technologies by capturing total lifecycle costs, including capital investment, operating expenses, energy price volatility, maintenance, and carbon risks. *LCOH* can be calculated via Equation (1), and the capital recovery factor can be calculated by Equation (2):

$$LCOH = \frac{T_{CI} \times C_{rf} + M + ACE}{Q_D} \quad (1)$$

where

T_{CI} is the total capital investment ($);
C_{rf} is the capital recovery factor (1/year);
M is the operations and maintenance costs ($/year);
ACE is the annual cost of source energy ($/year);
Q_D is the thermal energy demand (MWh_{th}/year).

$$C_{rf} = \frac{I(1+I)^N}{(1+I)^N - 1} \quad (2)$$

where

I is the interest rate (%);
N is the lifespan of investment (years).

3.2. Technology Characterization Methodology

In the following sections, a variety of technologies for process heating and their capabilities, as well as key research pathways, are discussed, with the associated costs addressed later. Needs relating to each technology are also noted, such as fuel logistics, cost, or deployment complexity. Technologies characterized include natural gas (NG) burners, hydrogen (H_2) gas burners, typical electrified sources, biomass burning, small modular nuclear reactors, heat pumps, geothermal, and solar capture sources. These technologies and their respective potential operating temperature ranges for practical purposes are compared in Figure 2. Per McMillan and Ruth's heat demand estimation analysis [21], approximately 45% of US process heat demand falls at or below 250 °C, and ~85% falls below 600 °C. Notably, several options are available for handling such heat demands (e.g., solar thermal, nuclear, geothermal, and heat pumps). The higher-temperature breakpoints in McMillan and Ruth's analysis are 1100 °C and 1500 °C, which account for 20% of process heat demand [21]. Additionally, 1100 °C primarily encompasses the temperature needs for iron and steel. The 1500 °C breakpoint largely represents clinker manufacturing and poses a uniquely difficult challenge for process heating in general. As with all types of process heating, lower-temperature requirements can be managed by much higher supply temperatures, though often wastefully.

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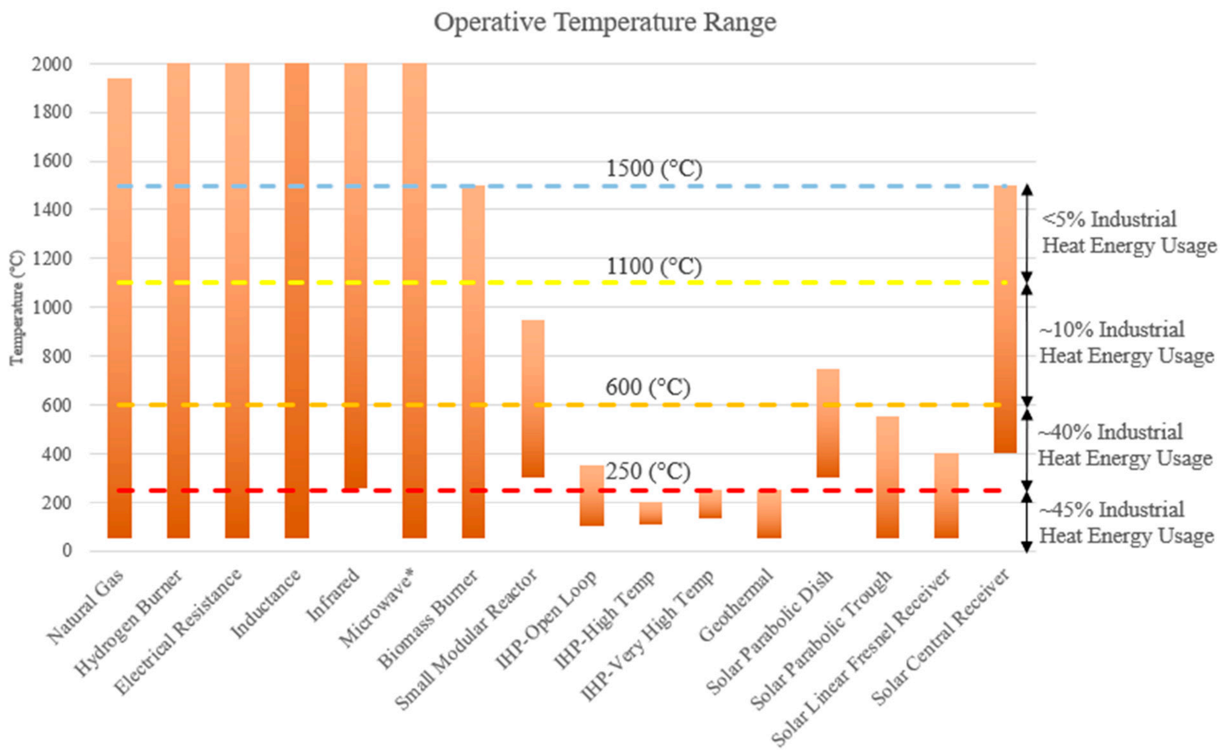

Figure 2. Operative temperature ranges for selected thermal technologies. * Microwave heating maximum temperature is not hard limited, unlike hydrogen burners [limited by flame temperature] or infrared [limited by emitter maximum temperature].

4. Results

4.1. Technology Characterization Results

4.1.1. Natural Gas Burners

Natural gas is a ubiquitous utility found in industry. Because NG is energy dense both gravimetrically (45–55 MJ/kg; [22,23]) and volumetrically (35.9 MJ/m^3; [18]), NG combustion provides a simple way to effect large amounts of heat into a product; however, its nature as a fossil fuel lends itself to many logistical and economic challenges. To use NG as fuel, transportation must occur with enclosed containers, ranging from human-portable compressed gas cylinders to large tanker containers that cryogenically store NG in a liquid form, or in a dedicated network of NG pipelines [24,25]. Its usefulness in energy-intensive industries like steelmaking comes from its high adiabatic flame temperature of 1937 °C [26]. This high flame temperature has the drawback that N_2 molecules dissociate into monoatomic nitrogen and can bond with oxygen. These form nitrogen oxides or NO_x emissions, which can form nitric and nitrous acids. This high flame temperature and NG's consumption at the point of use contribute to NG being generally favorable on an exergy basis. Exergy, or the availability of energy, is highly dependent on the conditions of the reference frame. The higher the temperature of the heat source relative to the temperature of the heat sink, such as ambient air, the higher quality the exergy is said to be. Accounting for energy consumption in fuel distribution is a necessary component in describing a technology's energy availability. Site-to-source multipliers, also called site-to-primary conversion factors, account for inherent energy losses present in converting fuel to electricity, if applicable, as well as transmission or distribution losses [27]. Typical grid electricity possesses a site-to-source multiplier of 3, which means the power plant that generated that electricity consumed 3 units of fuel to produce 1 unit of electricity, or that the power plant, voltage transformation, and power transmission in total are approximately one-third efficient at delivering electricity to the end user [27]. NG, pumped through pipelines via compressor stations, typically consumes 0.025 MWh of fuel for every 1 MWh of fuel delivered to the end user, thus NG possesses a site-to-source multiplier of 1.025 [27]. Discussion on the exergy efficiency of the alternative thermal technologies examined is provided in Section S2 in the SMs.

NG is economically volatile, with its cost being highly dependent on global production and geopolitical conditions. During years of high production, prices are lower, but any kind of shock to global trade can increase prices, even for locally produced fuel [28]. Thus, use of NG burners limits a manufacturer's autonomy and stability. System efficiency is highly dictated by maintenance, with efficiency falling heavily if seals are damaged or insulation is degraded [29,30]. The burners themselves are inexpensive relative to their annual energy costs [29]. Typical NG burners are simple, effective, well documented, and reliable. Temperature within a furnace, oven, or boiler can be adjusted simply by valve control on an active burner. Its expected lifespan is 10–15 years, which depends on the operating conditions. Due to NG's industrial ubiquity, high exergy efficiency, and well-documented range of energy efficiencies, NG burners make for an effective baseline by which alternatives can be judged [29].

4.1.2. Hydrogen Gas Burners

Hydrogen is a combustible gas with technical requirements similar to those of NG but with a carbon-free structure. Its adiabatic flame temperature is higher than that of NG at approximately 2182 °C [26]; however, it possesses several other key property differences. H_2 has a higher gravimetric energy density (120–142 MJ/kg) [23] with much lower volumetric energy density (10.8 MJ/m^3) [18]. In other words, to achieve the same amount of energy as that of NG, approximately three times the volume of H_2 is required. The alternative is to pressurize H_2 so that more molecules are packed together within a given volume. The ability to change fuels in burners is compared via the Wobbe Index, in which H_2 (48 MJ/m^3 [24]) possesses a lower value than that of NG (40–60 MJ/m^3 [31]). H_2's flame speed is about 10× higher than that of methane [32]. Its high flame speed increases the risk of flashback, flame instability, and higher NO_x emissions. It also requires careful burner design and control to manage the higher combustion temperatures in industrial settings. The high flame speed combined with H_2's lower density necessitates a modified burner design for safe use [24] and higher flow speeds [32]. NG pipelines can theoretically transport H_2, with a 30% H_2/70% NG mixture by volume called "Hythane" being a practical balance that requires little difference in safety and performance considerations [33]. Because of the small size of diatomic H_2, it can infiltrate the structure of materials; it is not considered porous, such as steel or aluminum, and can exacerbate leakages in the lines. This leads to embrittlement in such materials [34], which is largely limited to the surfaces exposed to H_2 flows [35].

Implementation of H_2 burning for an end-use is complex, as H_2 flames possess a small quenching distance allowing for flames to propagate past small openings into the fuel–air mix [36]. Much of the natural gas piping can still be used in conjunction with modified burner heads, although care must be taken to ensure either (a) long-length laminar flow (>4000× pipe diameter) [37] or (b) turbulent flow conditions [37]. This is necessary because of the potential for gas stratification where the two gases in the pipe do not remain mixed and instead separate into layers, yielding inconsistent—at best—end-use control behavior. Additionally, the fuel–air ratio requires adjustment if retrofitted from NG. Supply and storage of H_2 are significantly more complex questions that tie in heavily to the environmental aspects of H_2. Owing to H_2's low density and molecular size, storage is difficult, requiring large, specialized high-pressure (~700 bar) tanks for storage and a low volumetric energy density (~5.6 MJ/L) [34].

H_2 can be supplied from many sources, with individual sources denoted by color, as depicted in Table 1. Green H_2, for example, is H_2 sourced via renewably driven electrolysis, whereas gray H_2 is sourced from steam reformation of NG. Solar heating, discussed in Section 4.1.8, can be used to thermochemically split water into hydrogen and oxygen. The sources listed are by no means exhaustive [34]. Table 2 illustrates that the colors assigned to H_2 can be depicted as a spectrum, though there is little agreement on the terminology (i.e., yellow H_2 may refer to H_2 produced from grid electricity or from solar power, depending upon the publication). Just as the temperature of NG burning produces NO_x, H_2 also does so in slightly higher quantities because of an even higher flame temperature.

Table 1. Various colors of hydrogen.

Hydrogen Color	Source
Green	Renewable electricity/electrolysis [38]
Yellow	Grid electricity/electrolysis [39]
Gray	Steam methane reformation [38,40]
Blue	Steam methane reformation w/CCUS [38,40]
Aqua	Oxygen-induced oil field thermolysis [38,41]
Turquoise	Methane pyrolysis [39]
Brown	Biomass/lignite pyrolysis [38–40]
Black	Coal pyrolysis [38,39]
Purple/pink	Nuclear/electrolysis [38]
Red	Thermolysis/thermochemical [39]
White	Naturally occurring deposits, byproduct [42]

Many avenues exist for research in H_2 procurement and deployment. On the production front, aqua, white, and green hydrogen are the strongest emission reduction avenues, with aqua H_2 possessing both great potential for national impact and many development challenges [38,41]. Aqua H_2 is a recent innovation still in the pilot production scale, which focuses on injecting oxygen deep into oil sands to combust and thereby raise the temperature in the oil sands enough so as to split the heavy oil and water, leaving the CO_2 entrained in geologic storage while pure H_2 is extracted [41]. This would effectively allow H_2 production to infrastructurally mirror NG extraction if successful. Proton H_2's "Project Apollo" entails an industrial pilot plant targeting the production of 500 tons of aqua H_2 per day [43]. Similarly, white H_2 formation is naturally occurring underground H_2. The core challenges surrounding white H_2 relate to the exploration of economically viable sources: natural geologic H_2 production is not well understood [41], and drilling, especially for exploration, is fiscally risky [43]. Enhancement of green H_2 production largely relates to the cost of electrolytic cells and improving electrolytic cell efficiency because these are about twice as expensive as a blue H_2 system (i.e., a gray hydrogen system with carbon capture, utilization, and storage [CCUS] installed) [44]. Green H_2's availability in the US is limited, with the combined total of proposed projects in 2024 amounting to 0.72 million metric tons of green H_2 per annum [44]. Nearly all H_2 in the US is currently produced by steam methane reformation. For deployment, issues of flashback [45] and heat release rate [46] persist. Both must be balanced by a H_2 flame's small quenching distance, leading to smaller burner openings, lower volumetric energy, and density requiring higher volumetric flow to achieve the same delivered energy as that of NG. Autoignition flashbacks can occur within laminar flow premixed burner arrangements, as evidenced by Pers et al. [45].

Research must first focus on a reduction in H_2 production costs and adaptation of existing infrastructure to improve general deployment. High-temperature processes possess viability with current hydrogen deployment; however, H_2-fired sintering requires further investigation to ensure product material properties are preserved when compared with the properties of NG burners. Additionally, modifying current regenerative burner concepts to compensate for the lower flue gas mass flow present in H_2 burning in an oxyfuel arrangement may be possible, while still benefiting from the characteristically high heat recovery of regenerative burners. Development of cost-effective barriers to H_2 embrittlement or leakage and strong safety regulation measures, such as how NG has methanethiol added for smell identification of leaks, are required for long-term deployment and storage. In chemical reaction heating, development of tighter flow control methods for hydrogen is necessary for the stability of process temperatures. H_2 currently is cost-viable for metal smelting, calcining, heat treatment, melting, and coking. However, fuel availability for these processes is limited, and though H_2 fuel and burner costs are low enough for viability, it is not currently strongly cost competitive.

4.1.3. Electro-Technologies

Electro-technologies shift energy consumption away from onsite fuel burning toward centralized grid power [47]. Electro-technologies can help improve energy security by dispersing supply problems that arise within individual fuel supply chains to a variety of sources. Manufacturers that electrify therefore become more resistant to fuel price shocks. Additionally, the implementation of electro-technologies in highly concentrated industrial areas is beneficial from a public health perspective due to reductions in local pollution or smog.

A core point of research and investment to enable electro-technologies is found in power infrastructure, such as transmission lines and transformers [48]. Though strategic-level publications on this topic are few, significant research is ongoing for individual component systems of grid infrastructure, such as improving the heat transfer capabilities of transformers to improve lifespan and capacity. Unfortunately, drastic supply and cost bottlenecks exist for large distribution transformers; prices were reported to have increased by 400–900% over the past 3 years (as of 2024); and lead times exceed 2 years, a 300% increase over pre-2022 levels. Material shortages in electrical steel, both typical and amorphous, are contributing to rising costs and limiting the growth of transformer production vital for implementing electro-technologies. Leaner methods of production or alternative materials represent a potential avenue for further research. Transmission line research largely focuses on the optimization of grid scheduling and delivery [49,50], though some novel solutions have been developed for low-cost integration, such as how to connect rural communities into extra high voltage lines without the need for a traditional distribution substation [51]. Research in various electro-technologies required to improve deployment of varying technologies is discussed in Sections Resistance–Microwave. Note that researchers are evaluating thermal electrical processes to replace typical process heating where possible, such as for sterilization. Work is also underway in pulsed electrical fields [52] or cold plasma techniques [53], which would obviate the need for low-temperature steam in such applications.

Each technology discussed in this section derives heat from electricity in some way. Despite meeting this criterion, industrial heat pump systems are excluded from this discussion for two reasons: (a) the scope of that topic and (b) the unique energy consumption and efficiency behavior of heat pumps compared with the behaviors of other technologies being discussed here.

Resistance

Resistance heating utilizes Joule's Law of Heating to convert electrical energy to thermal energy, whether by a dedicated heating element or by passing the current directly through the material to be heated. Heating via resistance can be considered as having a coefficient of performance (COP) of 1, where every 1 MMBtu of electrical energy input yields 1 MMBtu of thermal energy. Resistance heating can be applied either directly (via passing current through the item to be heated) or indirectly (via a heating element), though delivered temperatures are naturally limited by the operating temperature of the element (1200 °C for CrNi alloys with >2000 °C possible for graphite or tungsten in inert atmosphere) [54]. More typical uses are for lower-temperature requirements where a spark is potentially dangerous, such as heating in oil-well work [55]. Studies have been performed on usage for much higher temperature processes (>1100 °C) where current is passed through the workpiece, such as sintering [56] or hot rolling [56]. When current is passed directly through the workpiece, the maximum temperature is largely limited by the electrodes. As with furnaces, efficiency of resistance heating is highly dependent on insulation effectiveness. The primary barrier to resistance heating adoption is the cost of the delivered heating because of the cost of electrical energy compared with that of fossil fuels despite the technology's maturity. Resistance heating is already perceived as effective publicly, with stovetops and space heaters as prime examples. Efforts to lower the costs of delivered electricity will improve resistance heating competitiveness, so efficient energy storage methods that could take advantage of low off-peak hours usage rates could increase rates of adoption. Any ability to shift from time-of-use to time-of-purchase would be beneficial to resistance heating adoption.

Research in resistance heating deployment should focus on high-temperature processes such as metal smelting, nonmetal melting, heat treatment, and sintering. Short electrode lifespans limit resistance heat viability in metal processing despite high efficiency compared with that of NG burners. The aluminum industry is currently developing and implementing pilot-test-level plasma arc torches as a drop-in replacement for NG burners [57]. These systems would require relatively high-purity nitrogen as the working gas, though they do possess great potential to limit not only CO_2 emissions but also NO_x. Resistance heating has high potential in sintering; processes such as flash sintering [58] pass both current and an electric field through the product to achieve densification faster and at higher energy efficiency than that of sintering via direct resistance heating alone. Currently, resistance heating can be effectively employed in fluid boiling, distillation, drying, curing/forming, and chemical reaction heating. Low-cost thermal energy storage (TES) would enable economical load-shifting of resistance-based process heat; for example, electrical resistance heat from solar PVs can be stored and then provided across the evening and night.

Inductance

Inductance heating uses magnetic flux to develop currents in the workpiece that then resistively heat the workpiece. This method possesses many similarities with direct resistance heating, except that this method is noncontact capable. Inductance heating is most seen in domestic cooking [59], though it is used in industry for processes such as gear teeth tempering, billet heating [60], and injection mold heating [61]. These are less sensitive to insulation concerns because heat is directly imparted into the workpiece, with typical systems imparting 50–60% of the input energy into the piece; more recent superconductor-based experiments have achieved 80–90% efficiency [60]. Inductance heating adoption, being electrical, shares electrical cost concerns; however, inductance heating is particularly of interest in heat treatment because the heat penetration depth can be adjusted by electrical frequency. This strategy is primarily limited by the geometry of the heater itself compared to the application.

Induction heating is currently limited to metal smelting, melting and heat treatment, and some nonmetal melting. However, these are all limited primarily by the range of applicable materials, as well as the electricity cost in conjunction with its currently modest efficiency. Research in induction heating should largely focus on exploring applicable target materials, which have a limited range. Since current designs depend highly on product and heater geometry compatibility, adoption rates could be increased by either devising a method to rapidly develop appropriate heating element geometry that can be produced promptly—akin to programs that produce the g-codes used by Computer Numerical Control (CNC) machines—or even developing a largely adjustable configuration. Similarly, superconductor investigation yields great potential to lower the operating cost of this method as nearly all of the process heat generated would be passed into the workpiece.

Infrared Heating

Infrared (IR) heating involves the emission of 0.7 to 1000 μm [62,63] wavelength electromagnetic radiation at a workpiece. Although natural gas-fired IR heating is prevalent, this section will focus on electrically driven IR heating. IR heater radiation temperature strongly depends on wavelength, with shortwave systems such as tungsten coil incandescent lamps yielding temperatures that exceed 2000 °C. These shortwave systems are also notably more efficient in converting electricity to IR radiation. Describing the efficiency of delivering IR power into a workpiece is currently not possible with multiple present methods [64]. Although it requires line-of-sight, IR heating presently serves many industries [65], such as textiles, paint curing, composites, and heat treatment. One significant barrier to adoption is the working lifespan of IR emitters/lamps; often <10,000 h, which is a limitation for industries in which shutdowns occur less than annually. A natural avenue for improvement is enhancing conversion efficiency, which some researchers have investigated by using graphene IR emitters for grain drying [66].

Research into increasing IR heating deployment requires higher-lifespan emitters. Specific applications such as sintering require creative solutions such as IR laser emitters deployed in additive manufacturing strategies [67] to compensate for a limited penetration depth. Optimizing IR emitter efficiency and power output density is necessary to improve deployment in processes such as fluid heating and boiling. Vertical-cavity surface-emitting lasers potentially could be used in melting and smelting processes with sufficient development of power density because emitter power densities of 4.9 kW/cm^2 have been reported [68]. At this power density, 60 cm^2 of emitters would be required to achieve a power output equivalent to a 1 MMBtu/hr rated NG burner.

Microwave

Microwave heating involves firing 1 mm to 1 m wavelength electromagnetic radiation at a workpiece. Microwaves are particularly dependent on the workpiece both materially and geometrically. Metals can readily achieve melting temperatures when exposed to microwaves of sufficient power, as the associated plasma discharges range from 2000 K to 6000 K [69]. Pyrolysis of plastic waste [70] and sintering of ceramics [71] are some examples of other implemented use cases. Despite a system efficiency of 50–70%, microwaves were able to achieve ~80% energy usage savings in the example of ceramic sintering. Regarding geometry, microwaves penetrate poorly and often provide surface-level heating, so they can reasonably be used only where surface heating is ideal or in the instance of a high specific area in the workpiece. Lower-frequency emitters are notably more efficient than higher-frequency emitters [72]. Semiconductor-based microwave generators pose a very effective and flexible development, capable of highly directed heating [73] and very narrow-band emission (±0.1%). These semiconductor generators also largely solve the very short lifespan problems present in magnetrons; however, the current issues for them revolve around their high cost, limited emitter power, and weakness to high-temperature exposure. It may be possible to increase both directed power and the concentration of the applied heat using a phased array configuration.

Research into increasing microwave heating deployment largely focuses on emitter lifespan and efficiency. Nonuniform heating and selective heating (material-dependent efficacy of heating) necessitate the development of dedicated control systems for microwave heating for applications such as fluid heating, boiling, and distillation. Potential exists for possibly exploiting selective heating in processes such as calcining, particularly of spodumene for lithium refining [74], and in chemical reaction heating, such as energizing only the necessary reactants. Extensive cataloging of applicable materials is necessary, such as induction heating.

4.1.4. Biomass

Biomass burning possesses the unique distinction of being the oldest method of heating. Modern burners with the appropriate kinds of biomass can achieve heating of 1500 °C [75], which meets most industrial thermal needs, though potassium-laden ash typically limits use at this temperature due to corrosion and deposition. Additionally, the cost of heating is reasonably competitive [76,77]. Although these systems may seem ideal, the solid fuel nature of biomass poses a significant, yet similarly old, logistical hurdle also seen in coal-fired heating. Transport over great distances must be completed by vehicle (e.g., trains, ships, or automotives). The cost of transport severely reduces economic competitiveness with respect to distance, so biomass fuel sources ideally should be relatively local to the use. Additionally, solid waste must also be handled similarly. Additionally, sourcing must be consistent, as loss of biomass yield in sourcing may starve the burner system of fuel.

Biomass fuels possess high sulfur and chlorine contents, generally much higher than that of natural gas or coal. This presents a challenge for retrofit because, at present, alloys are unlikely to handle the higher corrosion in the long term [78,79]. To handle this, several spray-coating strategies exist, such as high-velocity oxy-fuel spraying [80] and plasma spraying [81]. Current work to solve corrosion issues in retrofits largely focuses on the alloys and methods used for spray coating, such as the use of pseudo-alloys in thin-wire arc spray [82].

Research to increase biomass deployment should largely focus on easing logistics and supply constraints [83]. Consistent biomass fuel supply sourcing and transportation cost challenges both limit potential deployment in general. Biomass fueling is viable if locally sourced in most industrial use cases, except for processes where the product is chemically or compositionally sensitive, such as sintering or metal smelting. Current logistics research mostly focuses on the use of biomass in fluidized bed reactors or gasifiers [84,85]. If biomass were instead regarded as a carbon source, producing liquid hydrocarbon fuels from it in conjunction with hydrogen [86] would be possible. If biomass is instead used as a hydrogen source, steam reforming may be another angle to approach for converting such solid fuel to a logistically simpler fluid in the form of hydrogen or syngas [87]. Issues regarding tar and polycyclic aromatic hydrocarbon buildup persist in typical direct biomass burners.

4.1.5. Small Modular Reactors

Small modular reactors (SMRs)—also called small and medium reactors by the International Atomic Energy Agency—are nuclear reactors with a core power per unit below

600 MW [88]. Nuclear fuels possess thus far unparalleled energy density. At a burnup rate of 50,000 MWd/t_m, 1 metric ton of uranium fuel will release more energy than 140,000 tons of coal [89]. This results in highly simplified logistics where the system, fueled at construction, may require refueling only thirty to forty times in the reactor's lifetime—potentially as long as 60 years. Currently, the limitation of reactor lifespan estimation beyond 60 years is a lack of research confirmation of examples operating past 60 years [90]. The cost of nuclear power generation is almost entirely front-loaded, with installation being the single highest cost, whereas fueling comprises only 10% of generation costs. By comparison, fueling in natural gas plants occupies 70–80% of generation costs [91]. The magnitude of available power and the self-contained nature of SMRs indicate a great capability for providing district heating via cogeneration in areas with less developed infrastructure [92,93] and for SMRs to reach economic viability in regions where natural gas rates exceed $10/MMBtu [94,95].

Adoption of SMRs, however, is beset by difficulties not necessarily inherent to the reactors. Nonproliferation of the isotopes necessary for nuclear weapons development and construction imposes limits on countries that can maintain nuclear fuel processing facilities and requires heavy protections beyond typical safety measures against access to the fuel rods of the SMR [96]. However, this arguably ties in with the second issue SMRs face: economies of scale. Although SMRs potentially have greater economic viability than that of typical large-scale reactors [97], achieving that level of viability requires enough deployment that the costs decrease as systems and implementations are standardized. However, standardization is also limited by licensing constraints and national legal framework differences [98]. This required deployment scale also creates a type of paradox presented in some technoeconomic analyses [99]: the potentially strongest source of energy economically should scale its production, but costs are currently too high to achieve the necessary level of adoption to drive the production scale. SMR adoption in industry also faces a combination of regulatory and insurance issues. Nuclear power plant operators are liable for damage resulting from the plants, regardless of fault, which necessitates insurance for reactor operation [100,101]. For reference, American Nuclear Insurers' average single-reactor site premium was approximately $1 million per year in 2019 [100]. On the regulatory side, only one SMR design has been certified by the US Nuclear Regulatory Commission as of 2024: the NuScale US600 pressurized water reactor assembly, a building that will house 12 SMRs rated at 50 MW_e each and totaling 600 MW_e [102]. Certification and approval for this specific SMR in this configuration required about 33 months.

Exergy efficiency in SMRs is largely limited by reactor core temperature, which itself is limited materially. Additionally, the core heats a working fluid rather than applying its heat directly, an extra heat transfer step that contributes significantly to irreversibility. Between lower temperatures and additional heat exchange, SMRs can be expected to possess less exergy efficiency than that of the typical natural gas burner despite great potential to the contrary and a site-to-source multiplier of 1.

Research on increasing SMR deployment should largely focus on miniaturization; however, this would need to occur in conjunction with development of a streamlined regulatory pathway for industry to implement them within typical project construction time frames and some form of insurance premium adjustment for reactor size. Miniaturization is necessary to facilitate deployment in small- to medium-sized manufacturing because even relatively small SMRs are still large enough that only the largest manufacturers could both afford and fully use them. Additionally, reduced construction costs would be a key driver in making SMRs cost-effective because of the previously stated low cost of energy generation. Significant technical development is required for SMR use in high-temperature processes such as smelting or calcining, not only in the form of achievable working fluid temperatures, but also must overcome material limits in gas-cooled reactor designs, while ensuring maintaining safety requirements at those heightened temperatures.

4.1.6. Industrial Heat Pumps

In the case of industrial heat pumps (IHPs), a low or moderate temperature heat source is elevated to a higher temperature and provided to an end-use, most commonly referred to as a heat sink. IHPs exhibit higher thermodynamic efficiency than that of conventional systems because they transfer thermal energy from a lower temperature source such as water, air, or waste heat to a higher temperature sink or end-use rather than generating heat through direct combustion or electrical heating. This enables IHPs to achieve heating efficiency significantly greater than 100% or a COP greater than 1, where COP is the amount of heating energy provided per input energy. IHPs commonly possess COPs above 2.5, providing 2.5 joules of thermal energy into products per joule of electrical energy. Heat pump COPs are highly dependent on the lift, the differential in temperature of the heat sink from the temperature of the heat source. The larger the difference in these temperatures, the lower the COP. IHPs are best used with waste heat recovery [103,104] and even geothermal heat sources [105]. Additionally, much higher COPs can be achieved by simultaneous heating and cooling, though analysis on this scenario is outside the scope of this paper.

IHPs have been heavily researched and analyzed because of their exceptional potential for cost and energy efficiency. Much research relates to the choice of refrigerant [106–110] or focuses on component configuration [107,111–113]. Naturally, these are most attractive where electrical costs are low, and the steadily increasing maximum operating temperatures yield increasing access to larger markets [114,115]. To provide 90 °C for district heating water that returns at 40 °C, the IHP cost of operation could be as low as $\$13.2/\text{MWh}_{th}$ [116]. Most well-established commercial models provide process heat at or below 80 °C; however, IHP technology is at the functional model stage and offered by manufacturers.

- High-Temperature Heat Pumps: High-temperature heat pumps (HTHPs) are commonly defined as those exceeding 100 °C heat sink temperatures [107,110], or heat pumps that are theoretically capable of generating steam from closed-cycle action.
- Very-High-Temperature, or Advanced, Heat Pumps: Very-high-temperature heat pumps (VHTHPs), sometimes also referred to as advanced heat pumps (AHPs), are not as readily defined. The International Renewable Energy Agency provides the basic characteristic that VHTHPs maintain heat sink temperatures of 140 °C or above from closed-cycle actions [117].
- Open-Loop Heat Pumps: Open-loop heat pumps (OLHPs) operate using a vapor-compression evaporation process. This limits the use of typical heat pump refrigerants, so process water (R718) is instead used as the refrigerant that is heated into steam. The open-loop nature and potential for fewer moving parts result in much higher maximum supply temperatures, with 350 °C steam being offered by Baelz [118] via thermal recompression and 280 °C offered by Spilling [119] via mechanical recompression [120].

IHPs, despite having a relatively high implementation cost, have achieved cost viability through high efficiency, and the nature of COPs means there is a far greater capacity to reduce operating costs than for most electrified systems. However, implementation and operating-cost competitiveness are highly region-dependent: although high-temperature heat pumps exist commercially, adoption in the United States is often hindered by competing policies and by less favorable electricity-to-gas price ratios (i.e., higher spark ratios), which can erode the operating-cost advantage relative to gas-fired heat [112]. Relatively low-temperature processes such as sterilization, boiling, and drying can be readily achieved with current technology; however, maximum temperatures achievable with current IHPs are far too low for applicability in the most energy-intensive industrial heating processes. Recent studies in food, pulp and paper, textile, and automotive manufacturing in the United States all found evidence of energy reductions but were contrasted by additional costs rather than operating-cost savings [121–123]. Research into general reductions in cost, such as by development of plug-and-play models like chillers, would yield the greatest impact on deployment. Refrigerant research is extensive, so collation of refrigerant characteristics and effects on heat pump performance into a database may provide a machine learning opportunity for refrigerant prediction like AlphaFold in protein folding prediction [124]. The broader view remains that industrial heat pump technology implementation remains contingent on the electricity-to-gas price ratios [112].

4.1.7. Geothermal

Below the ground's surface, a tremendous—nearly inexhaustible—amount of thermal energy is available. Per the *2013 World Energy Resources* report on geothermal resources [125], the total heat content of the Earth is approximately 3.5×10^{21} MWh, or 11,942,000,000,000 quads. The heat content at crust level is approximately 1.5×10^{18} MWh, or 5,118,200,000 quads. By comparison, the US total energy consumption, including transportation, in 2023, was 93.6 quads [126]. Use of even 1% of the heat content of the Earth's crust could supply the US total energy demands for over 500,000 years, assuming no increase in demand and that the energy was used efficiently in each US demand. Theoretically, temperatures within the crust can reach >1000 °C, but the levels practically accessible are significantly lower at around 200–300 °C [105,125,127].

Process water is pumped into the ground to a desired depth, heated on its passage through porous underground rocks, and pumped back up for usage. Direct use for heating is possible, and about 852 MW_{th} of direct geothermal heat was installed worldwide as of 2020 [128]. By comparison, heat pump integration with geothermal supply for heating is far more common at 77,547 MW_{th} worldwide as of 2020 [128]. Resourcing geothermal heat requires significant upfront capital investment that also possesses greater-than-typical financial risk because of the intensive drilling operations required for initial deployment. Drilling must be far deeper than that which would be performed by oil and gas drilling, though much of the gas drilling strategy is adapted to geothermal drilling. Extensive testing is also necessary to ensure the financial viability of the geothermal well site. Drilling and injection operations account for around 50% of the total project cost, and such operations can fail because of unforeseen problems downwell [129]. The rate of penetration —the speed at which drilling occurs—heavily drives the cost of operation because most costs are time-dependent.

Nearly all geothermal systems are subject to corrosion from hydrogen sulfide (H_2S), which is also exacerbated by elevated temperatures. Additionally, H_2S forces the use of lower-strength steels to avoid cracking from hydrogen embrittlement. Similar problems also occur in geothermal reservoirs that are naturally rich in CO_2, with the Southern California Imperial Valley site experiencing nearly 3 mm per year of corrosion in basic carbon steels [129]. This is a major divergence from the oil and gas industries, which need to be accounted for if geothermal systems are to be adopted en masse, especially for industrial process heating deployment. Lower-temperature processes, such as food processing, may find direct use of geothermal heat or the integration of HTHPs viable by using the geothermal reservoir as the heat source, thereby lowering the necessary temperature rise.

Enhanced geothermal systems (EGS) require effort to expand the availability of geothermal resources into areas with low-permeability rock [130]. These systems currently have questions regarding consistency of thermal output over the lifespan of an EGS, issues of induced seismicity, and mineral dissolution/precipitation within the working loop. Dispatchable, or flexible, geothermal systems that vary output to meet electrical or heating demand pose a potential solution to issues of variability from some renewables [131]. Similarly to dispatchable geothermal, underground water reservoirs, whether natural or artificial, can behave as a form of stable thermal energy storage. The Flooded Springhill coal mines in Nova Scotia are a prime example of this [132].

Research for increasing the deployment of geothermal heating for industrial processes should largely focus on EGS and materials science, which are necessary both for long lifespans of geothermal installations in particularly corrosive regions and for minimizing downwell trouble in drilling via greater drill bit durability. The initial drilling procedure itself is the prime driver of geothermal deployment costs and is entirely capable of encountering unforeseen difficulties that turn an otherwise effective project into a financially unrecoverable one. Enhancing the speed and reliability of this step is paramount. Limited testing has been performed previously on alternative methods for drilling, such as laser cutting [133]. Minimizing induced seismicity in EGS is necessary for widespread, safe deployment. Similarly to IHPs, geothermal systems is currently capable of providing for low-temperature processes such as sterilization, boiling, and drying; however, this comes at a greater financial cost and risk by comparison because of the aforementioned drilling costs and difficulties. Further comparisons to IHPs show that geothermal systems are likely to be far less limited in potentially achievable temperatures because the limits are principally materials and drilling depth.

4.1.8. Concentrating Solar

Solar power is tremendously plentiful, so much so that it drives nearly all of the natural processes we take for granted: the currents in the oceans, the winds in the skies, the water cycle that brings fresh water inland with its rains, and photosynthesis within plant life, which itself, by degrees, powers animal and human life. For comparison, the sun delivers approximately 1.13×10^{22} joules to the Earth every day, or ~10,743 quads [134], and as mentioned earlier, the US total energy consumption in 2023 was 93.59 quads. In only 13 min, the sun delivers energy that is equivalent to what the US consumes in a year. Solar power is measured by the power delivered per unit area, or insolation. As solar energy is bound up in photons of light, this energy can be concentrated to a point to achieve higher temperatures than those of the surroundings. This concentration is characterized by a concentration ratio, which represents the comparison of reflector area to receiver area. Most decisions related to concentrating solar power (CSP) installation are focused on a balance of simplicity, capacity, and efficiency. A lack of solar tracking simplifies installation and potentially allows for a large capacity of heat to be delivered for the cost, but this heat is time-of-day dependent and inefficient with both the solar power available and the temperatures deliverable.

Numerous working fluids are used in solar thermal systems, such as water, compressed gases like air or helium, as well as molten salts [135,136], thermal oils, and even nano-additive enhanced mixtures [137]. The choice of working fluid largely depends on the operating temperature range and potential for TES to handle off-solar hours. Compressed gases such as air or helium can currently achieve the highest temperatures—with design temperatures reaching 1150 °C [138] with molten salts despite theoretically being capable of higher temperatures—and top out around 550–600 °C owing to receiver material limitations [139,140]. Compressed gas use, however, is limited by the pressure drop over long lengths of travel. Various CSP configurations are pictured in Figure 3, and the characteristics are presented in Table 2 below. Details about the configurations follow.

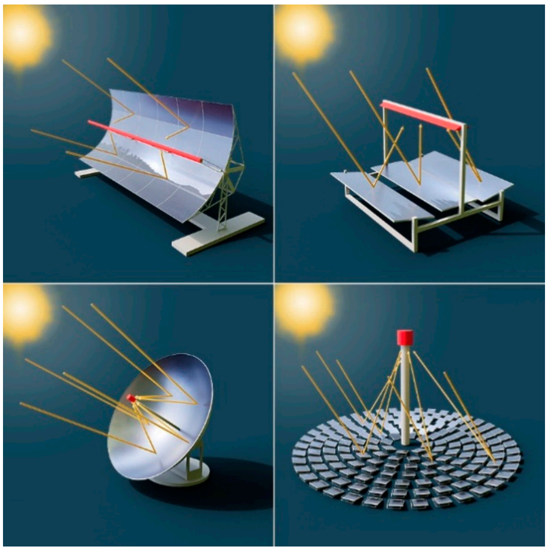

Figure 3. CSP configurations: (top, left to right) parabolic trough collector and linear Fresnel receiver; and (bottom, left to right) parabolic dish receiver and centralized receiver heliostat field.

Table 2. CSP configuration characteristics.

	PDRs	PTCs	LFRs	CRHFs
Practical max temperature range (°C)	300–750 °C [141]	400–800 °C [142,143]	~400 °C [144]	1150–1500 °C [138,145]
Concentration ratio and focus type	~1500×, two-axis/point focus	~80×, one-axis/line focus	~30×, one-axis/line focus	~1000× [139], two-axis/point focus
Circulation media	Mineral oils, steam, pressurized gases, ionic liquids, molten salts	Mineral oils, steam, pressurized gases, molten salts, liquid metals	Mineral oils, steam, pressurized gases, ionic liquids	Mineral oils, steam, pressurized gases, molten salts, liquid metals
Current limiting factors	Cost per kW_{th}, lack of adaptation for supply of heating	Cost per kW_{th}, receiver materials limit both length (friction in flow) and maximum potential temperature	Cost per kW_{th} (largely driven by Fresnel lens cost)	System size (which imposes a harsh minimum scale for cost-effective deployment)
Design advantages	Well suited to low-power, high-temperature requirements	Readily scalable for power and, to an extent, temperature	Akin to PTCs, more compatible with pressurized gas working fluid because of larger typical pipe diameter	Currently capable of achieving temperatures required by the most intensive industries, such as cement production

- Parabolic dish receiver

Parabolic dish receivers (PDRs) consist of a reflector dish with a receiver mounted at or near the dish's focal point. The entire array rotates in a two-axis fashion to track the sun, aiming directly toward it to maximize capture efficiency. PDRs are generally configured for electrical generation, such as via a Stirling engine [146], with process heat generation being unconventional. PDRs operate around 300–750 °C [141].

- Parabolic trough collector

Parabolic trough collectors (PTCs) are a far more common method for developing process heat from solar power. Parabolic trough collectors consist of a receiver tube suspended in the focal point of a reflective trough—a long semi-circular mirror. This receiver is rotated on one axis to track the sun. PTCs are well documented, with large amounts of fundamental analysis being available [142,147–149]. Increasing capacity is straightforward, only requiring more PTCs in parallel. Operating temperatures currently peak around 400–550 °C [143], though research has been performed on pressurized gas PTCs that can achieve 800 °C by using ceramic receivers [142].

- Linear Fresnel receiver

Linear Fresnel receivers (LFRs) are like PTCs except that the receiver tube is mounted separately above several flat one-axis tracking reflectors. This field of flat reflectors approximates a parabolic curve needed to focus incoming light onto the receiver tube. LFRs offer performance similar to that of PTCs but are hindered by the expense of Fresnel lenses [139]. These may, however, be more compatible with pressurized gas usage on larger scales than PTCs because the receiver tube is stationary and can therefore more easily be made larger in diameter to reduce the effect of pressure drop.

- Centralized receiver

Centralized receiver heliostat fields (CRHFs), also known as power towers, use a central receiver atop a tall tower in the center of a field of two-axis tracking reflector lenses. Power towers are often used for electrical generation, process heating, or both in the form of cogeneration. As with PTCs, a wide array of analyses, designs, and empirical studies has been performed on CRHFs [150–153]. Because these systems are generally quite large installations, the National Laboratory of the Rockies, formerly the National Renewable Energy Laboratory, has developed a free, open-source tool—SolarPILOT—for heliostat field configuration and characterization [154]. With concentration ratios over 1000×, power towers achieve very high temperatures, as high as in designed plants, up to 1150 °C [138]. Further increased temperatures are largely a matter of material capability limitations. One design from Synhelion, intended to produce syngas using solar heat, achieves 1500 °C [145]. Synhelion, in conjunction with CEMEX, successfully completed a pilot test of solar clinker brick production [155].

Thermal energy storage is a potentially important integration in solar thermal systems so as to provide continuous supply throughout the day and across adverse weather conditions. Molten salts, which are capable of TES behavior, require start-up heating to run initially, and a potential "boost" from external heat sources should the molten salt begin to freeze. About 10 h of TES capacity is sufficient to eliminate this need for boost [156]. TES also has application for providing heat from electrical resistance driven by photovoltaics and wind, smoothing out the intermittent nature of those electrical generation methods into a continuous supply. Materials for standalone TES vary, with lower-temperature applications using PCMs like paraffin and higher temperatures using low-cost brickwork. Brick-based TES maintains a relatively long lifespan of around 40 years and potential delivery temperatures of 1100 °C, such as per examples like RONDO Energy [157].

Research regarding increasing deployment of CSP should focus on mitigating weather dependency of thermal output. Solar thermal strategies currently see deployment incidentally in drying and curing processes, though little elsewhere to any significant degree. Low-cost TES systems pose a strong strategy for riding out adverse weather conditions; however, integration of TES naturally implies a higher cost of CSP deployment, which also means CSP requires further cost reductions to maintain cost-effectiveness. High reliability and temperature stability from TES would also introduce the possibility of CSP use in chemical reaction heating. Current designs are largely capable of handling lower-temperature processes (e.g., providing steam for sterilization), though potential exists for the use of centralized receiver CSP in much higher-temperature processes such as calcining.

4.2. Levelized Cost of Heating Results

Over 95% of industrial process heat is currently reliant on fossil fuels. Electro-technologies, alternative fuels, and process heat avoidance offer promising alternatives, yet industry surveys reveal a widespread lack of awareness and understanding of these options. The transformative technologies discussed in this paper all have different capital costs, operating costs, lifespans, efficiencies, and fuel price sensitivities. To distill the differences in alternative process heat technologies to a few numbers, an *LCOH* [20] is performed. Table 3 provides the costs of source energy and fiscal rates. Yearly operations and maintenance are assumed to occupy about 3% of the total capital investment of the chosen system. This assumption is in line with literature where O&M costs of different thermal technologies are assumed to range from 1 to 5% of the capital costs [158–160].

Table 3. Costs of source energy and fiscal rates.

Cost	Rate
Interest rate (%)	5%
Cost of electricity ($/MWh)	$80.80 [161]
Cost of natural gas ($/MWh)	$15.66 [162]
Cost of hydrogen ($/MWh)	$23.27 [163]
Cost of biomass ($/MWh)	$12.87 [76]
Cost of nuclear fuel ($/MWh)	$9.60 [95]
Operations and maintenance rate (%)	3%

In each case, systems are sized to produce 1 MW of thermal power, assumed to run for 8760 hr/year. This leads to an annual thermal energy demand, Q_D, of 8760 MWh_{th}/year in each example. Capital costs and performance parameters were either extracted directly from the referenced literature or derived by the authors. In cases where data were not provided for our specific baseline, values were back-calculated to reflect a standard 1 MWth/h capacity, ensuring consistency across the compared technologies. Table 4 presents an analysis of the *LCOH*. For lifespan terms, 20 years is assumed unless another value was otherwise found.

Table 4. Levelized cost of heating analysis.

Method	Total Capital Investment (TCI) ($/$MW_{th}$)	Expected Device Lifespan	Source Energy	Heating COP/Heating Efficiency	LCOH ($/MWh)	References
NG burner (obsolete/ill-maintained) or NG burner (O/IL)	$224,000	15 [30]	Natural gas	15% **	$107.63	[29,30]
NG burner (typical) or NG burner (T)	$224,000	15 [30]	Natural gas	35%	$47.97	[29,30]
NG burner (modernized/optimized) or NG burner (M/O)	$224,000	15 [30]	Natural gas	55%	$31.70	[29,30]
H_2 Burner	$373,000	15 [30]	Hydrogen	55%	$47.69	[30]
E-Resistance	$50,000 ****	20	Electricity	98% ****	$83.08	

Table 4. *Cont.*

Method	Total Capital Investment (TCI) ($/$MW_{th}$)	Expected Device Lifespan	Source Energy	Heating COP/Heating Efficiency	LCOH ($/MWh)	References
E-Inductance	$1,138,000	20	Electricity	60%	$149.00	[29]
Infrared or IR	$1,259,000	10 [62]	Electricity	70%	$138.35	[62,164]
E-Microwave	$2,168,000	10 [73]	Electricity	70%	$ 154.90	[71,73]
Biomass burner	$235,000	10 [76]	Biomass	55%	$27.68	[76]
SMR	$5,350,000	60 [90]	Nuclear fuel	60%	$66.59	[90,95]
IHP-OLHP	$580,000	20 [20]	Electricity	3.93	$27.86	[20,107]
IHP-HTHP	$580,000	20 [20]	Electricity	2.96	$34.60	[20,107]
IHP-VHTHP	$580,000	20 [20]	Electricity	1.83	$51.45	[20,107]
Geothermal	~$569,400 *	20	Geothermal	–	$65.00 *	[105]
CSP-PDR	$4,111,000	20	Solar	65%	$51.74	[165]
CSP-PTC	$4,585,000	20	Solar	46% ***	$57.70	[139]
CSP-IFR	$5,499,000	20	Solar	43% ***	$69.20	[139]
CSP-CRHF	$3,712,000	20	Solar	52% ***	$46.71	[139]

Note: TCI values are based on literature data or author calculations. All calculations assume a consistent system load of 8760 MWh_{th}/year delivered. * Manzella et al. [105] directly provide an *LCOH* range for geothermal power; TCI is estimated from back-calculation. ** Unver et al. [29] present the case study of an NG furnace that is both older technology and ill-maintained, leading to an efficiency of ~15.74%. *** Rough back-calculation from Weinstein et al.'s [139] efficiencies in electrical generation, assuming the same electrical conversion efficiency across all four against the heating efficiency provided in Subramaniam et al. [166] **** Estimated engineering assumption for resistance heaters; the heating element is one of the least expensive components of an industrial electric heating system. Assumed to have 2% losses.

In comparison with a typical natural gas burner, modernized hydrogen burners, biomass burners, most IHPs, and central-receiver CSPs each possess equivalent or more favorable *LCOH*s. Certain technologies such as microwave heating and inductance heating appear to require improvements to both efficiency and capital investment costs to become more attractive for implementation. The most favorable option currently appears to be biomass burning at ~$27.68/$MWh_{th}$, although this assumes consistent local sourcing of fuel, which is not always possible.

Figure 4 presents a graphical comparison of the *LCOH* for the technologies examined, with the reference line being the *LCOH* of a typical NG burner. To glean the impact of the type of technology and their respective efficiencies, the technologies were split into different groups and then compared with the COP/efficiency factors, as shown in Figure 5a. In general, it is seen that as the COP/efficiency factor decreases, the *LCOH* increases. It is also seen that certain technologies, such as the biomass burner, geothermal, H2 burner, and certain IHP and CSP technologies, perform better than the typical NG burner in terms of the *LCOH*. The group average *LCOH*, shown in Figure 5a, provides a general idea of the economic performance across the technology group, but inter-group variation can be high, as seen in the electricity-powered technologies. The conditions for this analysis are ultimately not exhaustive, and individual use cases must be considered for accurate results.

A sensitivity analysis was carried out to understand the impact of select factors, such as TCI, lifetime of the equipment, and O&M costs, as presented in Figure 5b, and the fuel price, as presented in Figure 5c. The analysis evaluates the sensitivity of each technology to four key parameters by varying each parameter independently to twice and half its baseline value. Together with the baseline case, this results in nine scenarios per technology. Even with the factors doubled or halved, the biomass burner and the IHP-OLHP have lower *LCOH*s compared to the typical NG burner.

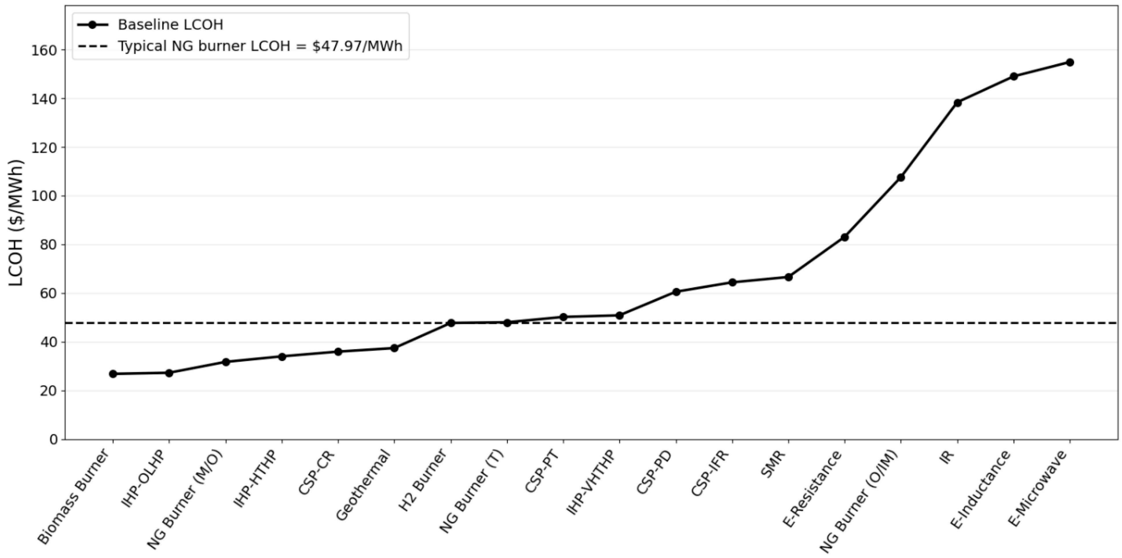

Figure 4. *LCOH* comparison of the technologies examined.

Figure 5b shows that technologies with TCI tend to experience larger increases in *LCOH* when TCI, equipment lifetime, and O&M costs are varied. As TCI increases, the effect of a shorter equipment lifetime becomes more pronounced because capital costs must be recovered over a shorter period, increasing the annualized replacement or capital recovery burden. Similarly, because the O&M costs are assumed to scale with TCI, higher-capital technologies also show a greater *LCOH* sensitivity to O&M cost changes. Overall, the results indicate that capital-intensive technologies are more vulnerable to cost increases associated with higher upfront investment, reduced lifetime, and elevated O&M expenses. It was also noted that the change in *LCOH* due to varying the O&M costs was lower than the impact from TCI, equipment lifetime (Figure 5b), as well as fuel price (Figure 5c). The impact of the fuel price on *LCOH* is also influenced by the COP or efficiency factor of the technology. Technologies with higher COPs or efficiency require less input energy to deliver the same amount of useful heat, which reduces the contribution of fuel or electricity price to the overall *LCOH*. As a result, higher-efficiency technologies are less sensitive to fuel price fluctuations, while lower-efficiency technologies show larger changes in the *LCOH* when fuel prices vary.

The comparison of the characteristics of each technology with typical natural gas burners is summarized in Table 5. Costs for which TCI dominates over ACE in the *LCOH* term are considered front-loaded, whereas ACE being greater than TCI is considered back-loaded. Considering these different metrics and their comparison provides end users with sufficient information to scope out the applicability of a technology for a specific use case.

Naturally, this analysis does have limitations. First and foremost is the fuel pricing sensitivity, which varies widely by state in the US. US average prices are used where attainable, such as for electricity, natural gas, and hydrogen. Similarly, CSP systems are very dependent on local insolation and usage of TES to provide for heat outside daylight hours, which was not calculated here. Additionally, it should be noted that several of these technologies can be implemented in tandem such that their complementarity is maximized. For instance, a synergistic integration of technologies, such as solar, wind, and geothermal energy, can effectively mitigate their potential drawbacks, such as the temporal variation and load-generation mismatch. However, including such analysis would need regional or local resolution, which is out of the scope of this work, which focused on a harmonized comparison of the different alternative thermal technologies that are available to provide industrial process heat. This work aimed to provide comparisons of the lifetime costs of the systems in relation to one another. Through that lens, we can see that there are technologies that are competitive or are nearly competitive with an average NG furnace. It should be recognized that many facilities operate NG furnaces that are less efficient than the average, and so are functionally paying a higher *LCOH*, which then means a greater number of alternatives are cost competitive in such a case and that the most reported issue of the exploratory exercise—lack of financial incentive—is not entirely firmly grounded.

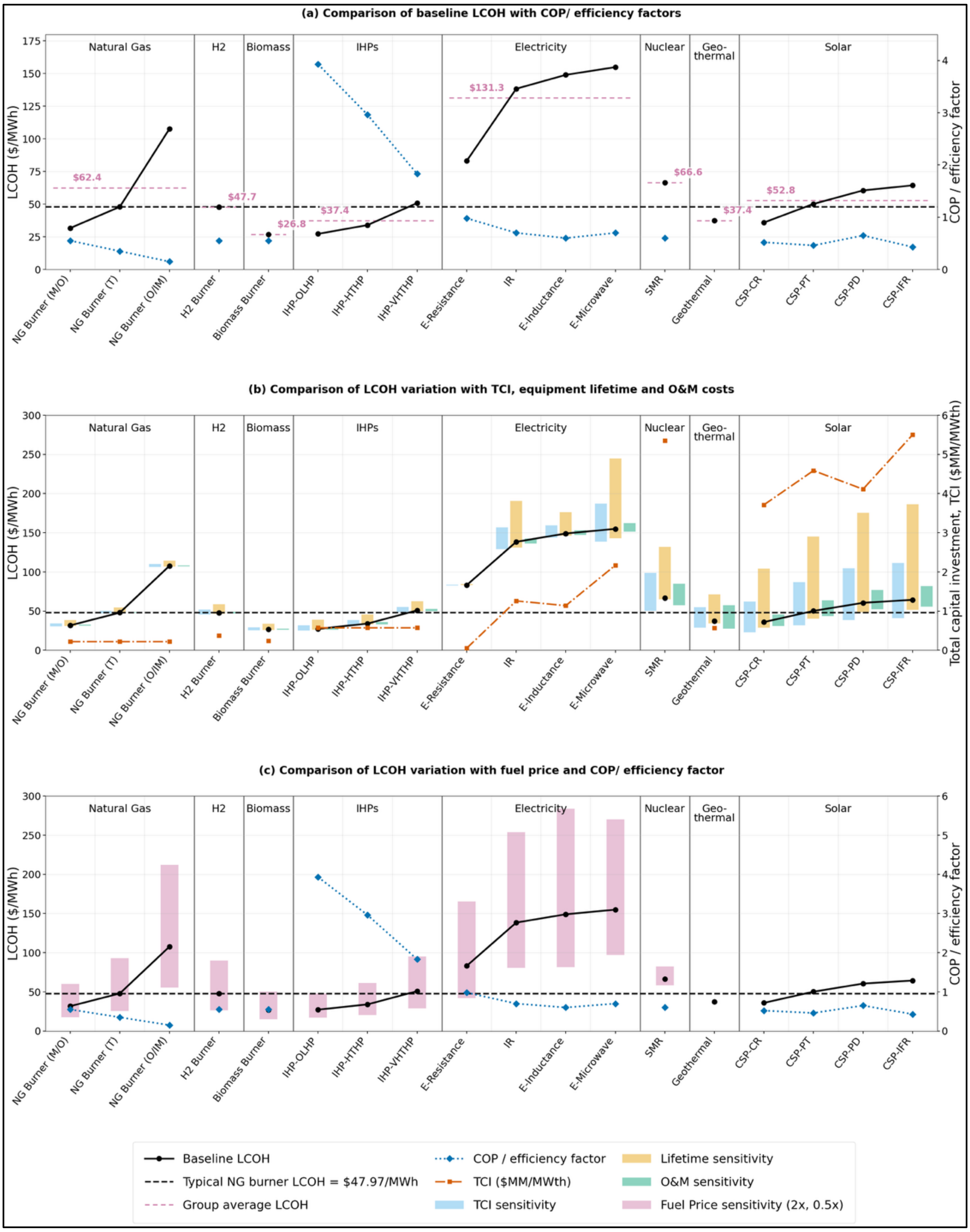

Figure 5. Comparison of (**a**) baseline LCOH with COP/ efficiency factors, (**b**) LCOH variations with TCI, equipment lifetime, and O&M costs, and (**c**) LCOH variations with fuel price and COP/ efficiency factor.

Table 5. Summary of characteristics of thermal energy technologies.

Technology	LCOH ($/MWh$_{th}$)	Maximum Temperature (°C)	Pros	Cons	Deployment Complexity	Cost Profile
NG burner (obsolete ill-maintained)	$107.63	1937 [26]	Likely an already available, in-place, and operational system.	Severe inefficiency, poor reliability.	Low	Back
NG burner (typical)	$47.97	1937 [26]	Baseline.	Baseline.	Low	Back
NG burner (optimized)	$31.70	1937 [26]	Excellent efficiency.	Scope 1 remains, few mitigation options.	Low	Back
H_2 burner	$47.69	2182 [26]	Logistically similar to natural gas. Strong maximum temperature.	Difficult sourcing, high price variability.	Low	Back
Resistance	$83.08	>2000 [54]	Simple installation with precise control.	As with all electrified methods, highly dependent on electrical costs.	Low	Back
Inductance	$149.00	1500 [167]	Rapid and precise heating. Heat imparted directly to workpiece.	Limited penetration depth.	Moderate	Back
Infrared	$138.35	2200 [62]	Very effective for thin workpieces, coating curing from surface heating.	Requires line-of-sight. Low element lifespan. Limited workpiece depth.	Low	Back
Microwave	$154.90	>2200 [70]	Selectively heats workpiece directly. Possible temperatures meet and exceed current industrial needs.	Limited penetration depth and low conversion efficiency.	Moderate	Back
Biomass burner	$27.68	1500 [75]	Potential for very low fuel cost and for zero to negative carbon emissions.	Solid fuel logistics challenges and presence of particulate emissions.	Moderate	Back
SMR	$66.59	950 [90]	Operational costs are a smaller fraction than typical. Largely front-loaded cost.	Regulatory issues slow adoption. *LCOH*s reduce with economies of scale.	High	Front
IHP-OLHP	$27.86	350 [118]	High COPs reduce energy needed to provide required process heat.	Need significant waste heat quantities. COP dependent on waste heat grade.	Moderate	Back
IHP-HTHP	$34.60	200 [107]	High COPs reduce energy needed to provide required process heat.	Highly heterogeneous in design and installation.	Low/Moderate	Back
IHP-VHTHP	$51.45	250 [107]	High COPs reduce energy needed to provide required process heat.	Highly heterogeneous in design and installation.	Low/Moderate	Back
Geothermal	$65.00	250 [105]	Near entirely front-loaded costs. Supply is effectively inexhaustible.	Drilling/injection: risky, expensive, with high-cost variability. Corrosion issues.	High	Front
CSP-PDR	$60.52	750 [141]	Very high concentration ratio yields high temperatures from little array area.	Little adaptation present for heating supply. Output is time-of-day and geographically dependent.	Moderate	Front
CSP-PTC	$50.18	550 [142,143]	Easily power scalable. Mechanically simple.	Large land area required owing to low concentration ratio.	Moderate	Front
CSP-LFR	$64.38	400 [144]	Easily power scalable. More complex than CSP-PTCs, but generally simpler.	Large land area required owing to low concentration ratio.	High	Front
CSP-CRHF	$35.93	1500 [138,145]	Very high temperatures possible, e.g., clinker brick production needs.	Needs very large land area. Cost-effective only with economies of scale	High	Front

Note: No systems in this summary are equipped with CCUS, and hydrogen is assumed to be green hydrogen.

5. Conclusions

This study is intended to both compile reference information to help address a lack of knowledge, as detailed by an industrial exploration exercise, and to provide some direction for research into alternate process heat technologies to help bridge the knowledge and need gaps between research and industry. Current temperature ranges and *LCOH*s were compiled or calculated; pathways for research were discussed, in general, and each method was addressed regarding its unique associated challenges.

From this study, the following conclusions are presented:

1. The study's conclusions regarding lack of financial incentives are reasonably founded for standard natural gas burners alongside biomass burners and industrial heat pumps, as they are the only strong financial competitors, with both retaining significant caveats to their competitiveness.
2. Technologies with front-loaded costs, such as SMRs, geothermal, or CSP, could then become competitive through grants or discounts, as fueling costs over their lifetimes are either low or near-zero, or by significant development in reducing deployed system costs.
3. Nearly all other technologies require significantly reduced fuel stream pricing to attain strong competitiveness. Electro-technologies are most sensitive to this, as resistance heating, which is inexpensive to install, possesses an *LCOH* that is much higher than even inefficient natural gas burners on a national average.
4. Though technological limitation/readiness concerns are not as strongly founded, challenges do persist in deployment, which hinder further adoption. Hydrogen handling and infrastructure are a strong example of this.

While this study focuses on comparing individual process heating alternatives, we recognize that the integration of multiple technologies, such as coupling geothermal with intermittent solar thermal, could yield higher economic performance and system-level optimization. However, we note that the design of hybrid systems with multiple technologies is highly dependent on specific geographical and operational contexts, presenting a compelling opportunity for future research.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en19153474/s1, Figure S1: Exergy efficiency analysis of examined technologies. Figure S2: Typical emissions from examined technologies, assuming no carbon capture strategy. Table S1: Working group responses indicating the industrial sectors represented by the participants. Table S2: Equipment that is difficult to transform into alternatives. Table S3: Summary of characteristics of thermal energy technologies. Reference [168] is cited in the supplementary materials.

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Data Availability Statement: The *LCOH* data presented in this study are available on request from the corresponding author. The exploratory exercise data are not publicly available due to privacy restrictions.

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Nomenclature/Abbreviations

Symbol	Definition	Units
quad	Unit of energy equal to (10^{15}) British thermal units (Btu)	$\approx 1.055 \times 10^{18}$ J (1.055 EJ)
MW	Megawatt	W
MWh	Megawatt-hour	Wh
MW_{th}	Megawatt thermal	W_{th}
°C	Degree Celsius	°C
K	Kelvin	K
COP	Coefficient of performance	–
LCOH	Levelized cost of heat	USD/MWh_{th}
SR	Spark ratio (defined in this study)	–
Abbreviation	Definition	
DOE	Department of Energy	
NASA	National Aeronautics and Space Administration	
GEOPHIRES	GEOthermal energy for Production of Heat and Electricity Economically Simulated	
HVAC	Heating, ventilation, and air conditioning	
RNG	Renewable natural gas	
NG	Natural gas	
H_2	Hydrogen	
CO_2	Carbon dioxide	
NO_x	Nitrogen oxides	
TES	Thermal energy storage	
PV	Photovoltaic	
IR	Infrared	
SMR	Small modular reactor	
IHP	Industrial heat pump	
VHTHP	Very-high-temperature heat pump	
AHP	Advanced heat pump	
OLHP	Open-loop heat pump	
EGS	Enhanced geothermal system	
CSP	Concentrating solar power	
PDR	Parabolic dish receiver	
PTC	Parabolic trough collector	
LFR	Linear Fresnel receiver	
CRHF	Central receiver heliostat field	
TCI	Total capital investment	
O&M	Operations and maintenance	

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