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Energy Solutions for Decarbonization of Industrial Heat Processes

Danieli Veronezi [1,*], Marcel Soulier [2] and Tímea Kocsis [3,4]

1 Centre of Environmental Science, Faculty of Science, Eötvös Loránd University, 1117 Budapest, Hungary
2 Henkel AG & Co. KGaA, 40589 Düsseldorf, Germany
3 Department of Methodology for Business Analysis, Faculty of Commerce, Hospitality and Tourism, Budapest Business University, Alkotmány utca 9-11, 1054 Budapest, Hungary
4 Faculty of Science, Centre of Environmental Sciences, Eötvös Loránd University, Pázmány Péter Sétány 1/A, 1117 Budapest, Hungary
* Correspondence: danieliresearch3@gmail.com

Abstract: The global rise in population and advancement in civilization have led to a substantial increase in energy demand, particularly in the industrial sector. This sector accounts for a considerable proportion of total energy consumption, with approximately three-quarters of its energy consumption being used for heat processes. To meet the Paris Agreement goals, countries are aligning policies with international agreements, and companies are setting net-zero targets. Upstream emissions of the Scope 3 category refer to activities in the company's supply chain, being crucial for achieving its net-zero ambitions. This study analyzes heating solutions for the supply chain of certain globally operating companies, contributing to their 2030 carbon-neutral ambition. The objective is to identify current and emerging heating solutions from carbon dioxide equivalent (CO_2e) impact, economic, and technical perspectives, considering regional aspects. The methodology includes qualitative and quantitative surveys to identify heating solutions and gather regional CO_2e emission factors and energy prices. Calculations estimate the CO_2e emissions and energy costs for each technology or fuel, considering each solution's efficiency. The study focuses on Europe, the United States, Brazil, China, and Saudi Arabia, regions or countries representative of companies' global supply chain setups. Results indicate that heat pumps are the optimal solution for low temperatures, while biomass is the second most prevalent solution, except in Saudi Arabia where natural gas is more feasible. For medium and high temperatures, natural gas is viable in the short term for Saudi Arabia and China, while biomass and electrification are beneficial for other regions. The proportion of electricity in the energy mix is expected to increase, but achieving decarbonization targets requires cleaner energy mixes or competitive Power Purchase Agreement (PPA) projects. Brazil, with its high proportion of renewable energy sources, offers favorable conditions for using green electricity to reduce emissions. The utilization of biomethane is promising if costs and incentives align with those in the EU. Although not the objective of this study, a comprehensive analysis of CAPEX and lifecycle costs associated with equipment is necessary when migrating technologies. Policies and economic incentives can also make these solutions more or less favorable.

Keywords: industrial heating; greenhouse gas emissions; decarbonization; low-carbon solutions; regional analysis

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1. Introduction

The International Energy Agency [1] reported that the greatest sectoral increase in greenhouse gas (GHG) emissions in 2022 derived from electricity and heat generation, whose emissions were up by 1.8% or 261 Mt. The Intergovernmental Panel on Climate Change (IPCC) created five scenarios for the climate response based on scientific studies of greenhouse gas emissions (GHG), land use, and air pollutants. The most optimistic scenario involves cutting global carbon dioxide equivalent (CO_2e) emissions to net zero by 2050, which would meet the Paris Agreement [2] target of limiting global warming to 1.5 °C above preindustrial temperatures [3]. However, the most recent projections in the IPCC's Sixth Assessment Report [4] indicate that there is a high probability of exceeding the 1.5 °C limit between 2021 and 2040, particularly in scenarios with higher emissions. It emphasizes the urgent need for prompt and decisive action to tackle climate change and achieve the goals set out for mitigating global temperature rise, with the energy sector playing a significant role [5]. To achieve the goals of the Paris Agreement, countries are aligning their policies with international agreements and companies are setting targets and strategies to achieve net zero [6], (also defined as "climate neutrality" [7] supported by scientific initiatives such as the Science Based Targets initiative—SBTi [8]. In scholarly use, the word "decarbonization" means a reduction in greenhouse gas emissions [9]. The Greenhouse Gas Protocol [10] standard is widely used to account for CO_2e emissions, and it establishes three scopes to categorize the types of emissions (Figure 1). GHG accounting related to energy consumption for industrial heating is reported under Scope 1 as part of the company's control processes. It can also be heat that generates Scope 2 emissions if it is converted from electricity drawn from the grid and that electricity is not decarbonized [11]. Scope 3 of the inventory addresses the upstream and downstream activities within the product value chain. Schmidt et al. [12] presented a study showing the ratio of Scope 1, 2 and 3 emissions in different sectors in Germany, and demonstrated the importance of Scope 3, which emerged as the most significant in many sectors, often accounting for more than 70% of a company's total GHG emissions. Furthermore, the company in question disclosed in its 2023 sustainability report that 99% of its GHG emissions originate from Scope 3, with 26% attributed to upstream emissions associated with suppliers. The decarbonization of energy-intensive sectors, such as steel production, cement manufacturing, and the chemical industry, not only improves the sustainability performance of these industries but also affects the entire value chain, as these sectors' emissions are reflected in their customers' Scope 3 calculations. Therefore, the decarbonization of industrial heating in supply chains plays an important role in the realization of net-zero ambitions, where businesses are in a key position to influence the behavior, operations and investments of their suppliers.

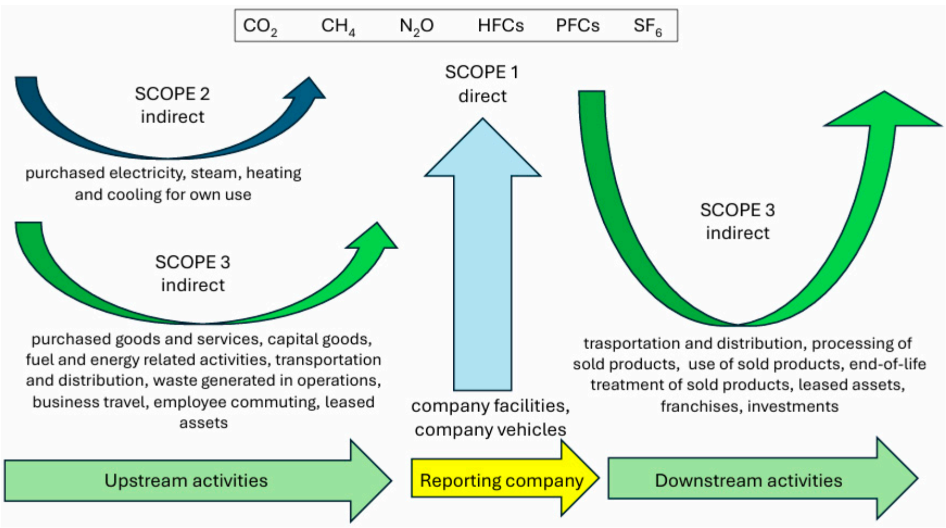

Figure 1. Overview of GHG Protocol scopes and emissions across the value chain [13].

Decarbonizing industrial heating requires innovation and presents challenges, including meeting a variety of process requirements such as heating temperature range, and regional specifications related to resource availability and prices. Among energy solutions, electrification is a promising path forward, with various technologies at different stages of development, including heat pumps, electric boilers and thermal energy storage (TES) systems. Furthermore, alternative fuels such as hydrogen, biomass and biomethane are also in advanced stages of use or development and gaining widespread attention. Selecting any of these technologies raises concerns about their reliability in meeting demand, flexibility in different scenarios (such as weather conditions and grid requirements), and feasibility from an investment and operational perspective [14]. It is important to consider varying conditions that differ from one region to another.

1.1. Industrial Heating Processes

Heating applications are important in almost all industries and domestic processes, and most of the materials that we use and the food and drinks that we consume have been heated at some stage. For industrial processes, heating is used for different purposes, including the generation of steam, the carrying out of chemical reactions, the drying of materials, the melting of metals and the heating of installations. In addition, there are different techniques for heating, including fuel combustion, electrical and radiant heating [15]. A fundamental distinction can be drawn between direct and indirect heating processes. In direct processes, heat is brought into direct contact with the material without the use of a heat exchanger. In contrast, indirect processes involve the transfer of heat through the surface of the material with the assistance of a heat transfer medium (air, steam, liquid baths) by conduction and convection or by heat radiation (infrared) [16].

Due to the wide variety of applications, industrial heat generally requires different temperature levels, depending on the specific needs of each process. In terms of temperature, high ranges above 400 °C are required to produce metals and non-metallic minerals such as cement, ceramic, and glass. Low and medium temperatures below 400 °C provide most of the heat required for food manufacturers, sterilization, textiles, paper, oil refining, chemical and wood products [17].

Figure 2 contrasts the overall world energy consumption with the specific energy needs of the industrial sector, highlighting the latter's significant dependence on heat energy. The industry accounts for 32% of total energy usage (in 2019), with a staggering 74% of its consumption dedicated to generating heat. High-temperature processes constitute nearly half of the heat demand while the remainder is split between low- and medium-temperature applications. Notably, only a small fraction of industrial energy comes from renewables, pointing to a substantial opportunity for reducing carbon emissions in the sector [11].

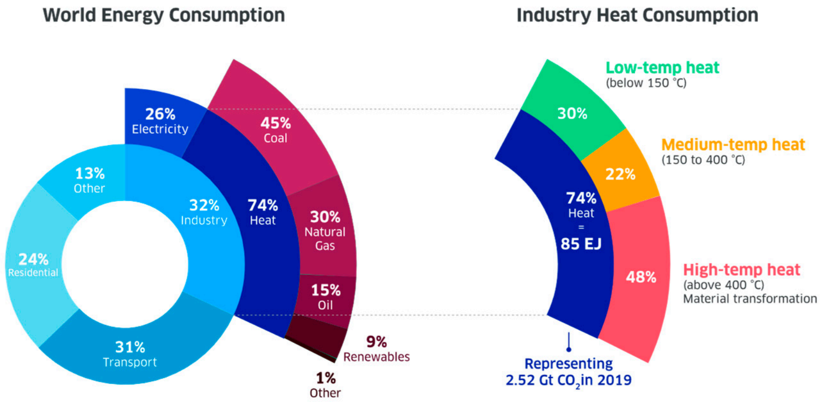

Figure 2. Industry drives global energy consumption [11].

1.2. Technological Developments for Heating Process Decarbonization

The quest for decarbonization in industrial heating processes has led to significant technological advancements aimed at reducing the reliance on fossil fuels. These innovations encompass the implementation of electrically powered solutions, as well as the exploration of low-carbon fuel alternatives. Additionally, advancements in material science have led to the development of high-efficiency insulation and heat exchange materials, which further reduce energy waste. Bellos et al. [18] investigated the efficiency of three different solar collector types coupled to an absorption heat transformer for industrial process heat production in the low-temperature range (80–160 °C). They found that a simple flat plate collector is the best choice for the range 95–120 °C, an advanced flat plate collector is the best solution for higher temperatures up to 140 °C, and for higher temperatures, an evacuated tube collector beats the others. Walden et al. [19] states that heat pumps present a highly efficient component to decarbonize process heating. For any zero-carbon heating technology to be viable, it must complete the end user's heat requirement at an affordable cost [20]. Pisciotta et al. [21] investigated the cement, lime, glass, and steelmaking industries in the US for low-carbon solutions (e.g., carbon capture and storage, fuel switching, etc.) in industrial heating processes.

Among the low- and medium-temperature industrial heating solutions, there are established technologies, including biomass, electric boilers, concentrate solar thermal systems (CST), and heat pumps. Kumar R. et al. [22] describes the diverse processes in which solar thermal or concentrate solar thermal (CST) systems can be utilized to supply renewable energy, while addressing key challenges such as climate conditions, space requirements, and energy intermittency. In the context of the decarbonization of energy-intensive industries, such as steel production, there are already established solutions that utilize electricity, with electric arc furnaces and cases using bioenergy, which employs charcoal as a fuel source and reduction agent within a blast furnace, used as an option where the fuel is available. In cement production, the integration of alternative energy sources instead of fossil fuels, known as coprocessing, is already established, and the use of biogas or biomethane requires only a modest retrofit to kilns [23]. Furthermore, there is considerable potential for the utilization of hydrogen (H_2) as a fuel for both sectors. However, the price of this fuel may be a limiting factor in certain applications. In this context, the term 'green hydrogen' is employed to describe hydrogen produced from renewable sources [24]. Furthermore, the development of Thermal Energy Storage (TES) systems has increased their potential as a solution to the challenges of energy management and distribution at high temperatures. These systems are capable of releasing and storing heat, offering a versatile solution to these challenges [25]. Carbon Capture and Storage (CCS) [26,27] is emerging as a compelling option for decarbonizing high-energy-intensity industries, serving as a critical measure in instances where the transition away from fossil fuels is not currently viable due to technical or economic constraints. While geothermal energy has been raised as a sustainable solution for residential and district heating, especially associated with heat pumps, its application in industrial heating is constrained by its temperature output and geographical availability. However, its contribution to a mix of renewable electricity generation is noteworthy [28].

The purpose of this study is to provide an analysis of heating solutions for the supply chain of companies with a global presence to contribute to their carbon neutrality ambitions. The evaluation will focus on existing and emerging technologies, considering their CO_2 emissions, required operating temperature ranges, and estimates of operational expenditures. The aim of this comprehensive analysis is to identify solutions that are well-suited for different global regions and evaluate the most beneficial in terms of defined criteria.

2. Material and Methods

Five regions (Brazil, China, US, EU, Saudi Arabia) were selected to analyze possible solutions for decarbonizing heating processes based on source energy consumption and technology to find the best low-carbon solution for each region. These regions were selected based on the supply chains of a specific globally operating company, but at the same time they represent the most powerful economic regions of almost all continents.

2.1. Data Collection

This study included both qualitative and quantitative surveys to identify industrial heating solutions and collect regional data on CO_2e emission factors and energy prices. The data collection focused on prioritizing the main sources, which included government websites, environmental agencies, scientific articles, and research institutions. Official organizations and governmental environmental agencies were instrumental in providing accurate data on energy emission factors and prices.

However, the availability of data was limited in certain regions, notably China and Saudi Arabia, where transparency in reporting is less consistent. In these cases, estimations were made based on literature reviews. Despite these challenges, the study aimed to maintain a high level of reliability by providing justifications for all assumptions and prioritizing official data sources. These efforts ensured that the conclusions drawn were robust and based on the best available information.

It is also important to note that emission factors and energy prices are subject to time variation and can be influenced by a range of factors, including climatic conditions and geopolitical aspects.

2.2. Identification of Industrial Heating Solutions

A comprehensive literature review was carried out to identify current and emerging industrial energy solutions for low- (<100 °C), medium- (100 °C to 400 °C) and high- (above 400 °C) temperature processes. The solutions were categorized according to these temperature ranges to provide a broader understanding of industrial heating, rather than focusing on a single productive process. The criterion used to select solutions was the technology's stage of development. To meet the CO_2 emissions targets as soon as possible, it is crucial to consider technologies that are at least in the pre-commercial demonstration stage, meaning they could be in use within five years. Therefore, the identified solutions meeting these definitions are listed according to Table 1.

Table 1. Identified solutions by temperature range/green color signs existing technologies for the given temperature range.

Technology	**Temperature Range**			**Stage of Development**
	<100 °C	**>100 °C <400 °C**	**>400 °C**	
Heat pump [11]		-	-	Commercial
Electric boiler [11]			-	Commercial
Biomethane fuel [23]				Commercial
Biomass fuel [23]				Commercial
Thermal energy storage [25]				Pre-commercial
Electric arc furnace [23]				Commercial

2.3. Definition of Regional Approach

The use of a regional approach was crucial for considering the unique circumstances of each area, which may yield different outcomes. The emission factors for CO_2e in relation to electricity grids and fuels vary between countries. This study focuses on regions that are the most significant global sourcing areas or countries for the company under investigation. The selected regions or countries were Europe, the United States, Brazil, China, and Saudi Arabia.

2.4. Survey of CO_2e Emission Factors

To determine the CO_2e emissions and estimate the operational costs, a survey was conducted. The survey collected quantitative data on the CO_2e emission factors of the electricity grids and fuels and their respective prices for each defined region. For Europe, the figures represent the countries of the European Union, and it is important to note that an average is used, which may vary for each constituent country. The CO_2e factor of the grid, i.e., the emissions per unit of electricity generated, is determined by the different power sources of the grid. This can vary significantly from country to country, depending on the main source of power generation. For example, a country whose main resource is coal-fired thermoelectric power will have a correspondingly higher emission factor than a country that relies on hydropower. This specific case can be visualized by comparing China and Brazil, which make greater use of coal and hydropower, respectively. In some countries that are continental in size and do not have an entirely connected grid, such as the US, the CO_2e emission factor can vary widely by region. However, for the purposes of this study, the average value provided by the US Environmental Protection Agency (EPA) was used. The values for the grids can be found in Table 2.

Table 2. Average grid CO_2e emission factor by region or country.

Region/Country	Year	kgCO_2e/kWh
Brazil [29]	2022	0.043
China [30]	2021	0.557
European Union [31]	2021	0.360
Saudi Arabia [30]	2021	0.614
United States [32]	2022	0.389

The emission factors for fuel can also vary from region to region, depending on their composition and the proportion of renewable fuel, as in the case of diesel and gasoline, or on the feedstock in the case of biomass. Based on that, emission factors were collected using a regional approach, and non-renewable fuels also considered for the purpose of comparison. For fuels such as diesel, coal or natural gas, this CO_2e may not vary significantly, and a default value is used (Table 3). For the biomass emission factor, a survey of the main materials used in the regions was conducted and used as the emission factor, and the values are shown in Table 4. In both cases, the emission factor was converted from kgCO_2e/GJ to kgCO_2e/kWh by setting 1 GJ as equal to 277.77 kWh.

Table 3. Fuel emission factors [32].

Fuel	kg CO_2e/GJ	kgCO_2e/kWh
Coal	99.20	0.357
Diesel	74.07	0.266
Natural Gas	55.713	0.186

Table 4. Average biomass CO_2e emission factor by region or country.

Region/Country	Biomass Type	kg CO_2e/GJ	kgCO_2e/kWh
Brazil [29]	Sugarcane bagasse	1.94	0.006
China [29–32]	Crop Straw	-	0.007
European Union [33]	Woody biomass/forest biomass	-	0.027
Saudi Arabia	-	-	-
United States [32]	Wood and Wood Residuals	1.25	0.004

In Brazil, biomass accounts for 8.8% of the energy matrix, with sugar cane bagasse and straw being the principal sources of biomass electricity generation in the country, accounting for 71% [34]. China's biomass resources mainly come from the agricultural sector, such as straw [35]. Within the EU's bioenergy usage, solid biofuels accounted for 70.3% in 2021, with approximately three-quarters of the biomass supply coming from Germany [36]. The main biomass source for heating processes in the country is woody/forest biomass [37], which was taken into account in this study for the EU biomass reference values for CO_2e emissions. In Saudi Arabia, renewables account for less than 1% of the total energy mix in 2021 [38] and therefore, they are not included in the overview of emission factors in Table 4. In the US in 2022, wood and wood waste—bark, sawdust, wood chips, wood scrap and paper mill residues—accounted for 2.1% of total annual US energy consumption. The industrial sector consumed 61% of the wood and wood waste share of energy consumption [39].

As China's biomass emission factor was not identified, the average of crop straw or vegetal waste in US and Brazil was used, as these are both large agricultural countries. However, it is worth mentioning that the crop emissions may vary for each region depending on agricultural practices. Another important aspect is that emissions from biomass are classified as biogenic, meaning they are associated with the natural carbon cycle of biologically based material. From this perspective of the life cycle, most carbon accounting methodologies consider the net balance of CO_2 to be zero, considering its sequestration during plant growth. The biomass emissions considered in this study relate to CH_4 and N_2O. The emission factor for biomethane as a replacement for natural gas can be considered neutral due to its closed life cycle and production from sources such as organic material or ethanol production.

2.5. Survey of Energy Prices

A survey was conducted to find the energy prices for electricity and fuels in each of the determined regions. To ensure data harmonization, the costs presented in this survey are in USD/kWh. For certain fuels, such as coal and biomass, prices are found in USD per ton and in these cases, it was necessary to find the mass required to supply 1 kWh and calculate its cost. To make this calculation, the heat content of the fuels had to be collected, and the conversions can be found in Appendices A and B. The energy price survey is presented in Table 5. The prices of biomass and biomethane for the EU were based on German prices. This is because this information is not compiled for the EU, unlike electricity and natural gas, and the country is the largest producer and consumer of these fuels among EU countries. The price of EU biomass was calculated based on the average price between wood pellets (506.81 EUR/t) and wood chips (187.34 EUR/t). The price of sugarcane bagasse in Brazil can vary regionally, ranging from 30 USD/t to 80 USD/t, and the average value was taken into consideration (55 USD/ton). For biomethane, no more recent prices were found for the US and China, and they may not reflect the current situation. For the US and China, data from the International Energy Agency were taken, which give world prices from 50 USD/MWh to 190 USD/MWh, and the higher figure was taken. The average price of electricity in the EU was taken from the last quarter of 2023. However, it should be noted that this figure has fluctuated considerably.

Table 5. Values for energy prices by region.

Region/Country	Energy Price (USD/kWh)					
	Electricity	Natural Gas	Biomass	Biomethane	Coal	Diesel
Brazil	0.170 [40]	0.111 [41]	0.027 [42]	0.250 [43]	0.019 [44]	-
China	0.093 [45]	0.049 [46]	0.062 [35]	0.190 [47]	0.014 [48]	-
European Union	0.200 [49]	0.079 [49]	0.070 [50]	0.190 [50]	0.024 [51]	-
Saudi Arabia	0.059 [52]	0.005 [53]	-	-	0.024 [51]	0.008 [54]
United States	0.078 [55]	0.048 [56]	0.044 [39]	0.190 [47]	0.019 [44]	-

2.6. Calculation Method

Electricity emission factors were collected for each grid and fuel, along with their regional prices. These data provided the basic context for assessing the energy efficiency of different heating systems and solutions through the Coefficient of Performance (COP). The COP is an indicator of a system's efficiency as it measures the amount of heat produced per unit of energy consumed (Equation (1)) [57]. For example, a gas boiler with a COP of 0.8 effectively delivers 0.8 kWh of heat energy for every 1 kWh of energy consumed.

$$COP = \frac{\text{Useful output energy}}{Inputed\ energy} \times 100 \quad (1)$$

It is important to mention that for combustion systems, the term Annual Fuel Utilization Efficiency (AFUE) can also be found, expressing the same conception as the COP. Using efficiency, the energy consumption of each appliance was calculated to determine the amount of energy required to provide 1 kWh of heat. This approach allows a comparative analysis of the energy costs and emissions associated with each system. It is important to note that the efficiency of each system has a direct impact on its energy consumption; less efficient systems require more energy to produce the same amount of heat. Therefore, both the operating costs and the environmental impact of each system vary with their respective COP values. This methodological approach enables an understanding of the trade-offs between equipment efficiency, cost effectiveness and environmental impact, and provides a comprehensive basis for evaluating energy solutions in the context of regional variations in fuel costs and electricity emission factors. By rearranging Equation (1), it is possible to calculate the energy required to supply 1 kWh.

Applying the COP for each technology and taking 1 kWh of output energy as a baseline, Table 6. shows the results of emissions and energy prices for each technology evaluated. For comparison with current use, fossil fuel-based equipment was also included in the calculations and is presented in Table 6. The efficiency of equipment can vary depending on factors such as the design and technology used. The values presented here represent an average of the theoretical efficiency ranges. It is also important to highlight that for equipment that utilizes combustible fuels, such as biomethane and natural gas, the same efficiency value was considered for boilers and furnaces. Although the values may be similar for both, it is important to emphasize that the operating systems are quite different and here, the focus is more on the fuel used. Furthermore, it is important to note that the CO_2e emissions resulting from electricity consumption can be further reduced or even completely offset by choosing green electricity.

Table 6. CO_2e emissions and energy costs by region considering the COP of the technologies.

Technology	COP	kgCO_2e and USD/kWh Energy Output	Region/Country				
			Brazil	China	European Union	Saudi Arabia	United States
Heat pump	3	CO_2e	0.014	0.186	0.120	0.205	0.130
		Energy cost	0.057	0.031	0.067	0.020	0.026
Electric boiler	1	CO_2e	0.043	0.557	0.360	0.614	0.389
		Energy cost	0.170	0.093	0.200	0.059	0.078
Biomethane boiler/furnace	0.8	CO_2e	0.000	0.000	0.000	-	0.000
		Energy cost	0.313	0.238	0.238	-	0.238
Biomass boiler/furnace	0.7	CO_2e	0.009	0.010	0.039	-	0.006
		Energy cost	0.039	0.089	0.099	-	0.063
Thermal energy storage	0.85	CO_2e	0.051	0.655	0,424	0.722	0.458
		Energy cost	0.200	0.109	0.235	0.069	0.092
Electric air furnace	1	CO_2e	0.043	0.557	0.360	0.614	0.389
		Energy cost	0.170	0.093	0.200	0.059	0.078
Diesel boiler/furnace	0.7	CO_2e	-	-	-	0.380	-
		Energy cost	-	-	-	0.008	-
Natural gas boiler/furnace	0.8	CO_2e	0.233	0.233	0.233	0.233	0.233
		Energy cost	0.139	0.061	0.099	0.006	0.060
Coal boiler/furnace	0.6	CO_2e	0.595	0.595	0.595	0.595	0.595
		Energy cost	0.032	0.023	0.040	0.040	0.032

3. Results and Discussion

The upcoming sections will conduct a comprehensive analysis to identify the most beneficial solutions tailored to the specifics of each region. To achieve this, an analysis will be conducted of the technologies or fuels that are most utilized in each region for a specific temperature range. This will then be compared with solutions that can reduce greenhouse gas emissions. These will serve as reference points for comparative analysis to determine the most suitable solutions. The analysis will rank solutions based on the estimated cost per ton of saved CO_2e. This quantifies the environmental impact in economic terms, providing a tangible measure of sustainability and cost-effectiveness. Identifying prevailing solutions and constraints within each region will optimize energy utilization and facilitate a transition towards more sustainable alternatives, and aligns with global efforts to mitigate climate change and reduce greenhouse gas emissions.

3.1. Ranking of the Solutions by Regions

3.1.1. Brazil

In 2021, approximately 47% of Brazil's energy matrix consisted of renewable sources. The largest contributor was oil at 34%, followed by sugar cane-based products (18%), natural gas (12%), and electricity (12%) [58]. Brazil predominantly relies on renewable sources (84%), such as hydroelectric, biomass, solar, and wind power, for electricity production. The projection for 2031 indicates an increase in natural gas supply and a decrease in oil and its products. Sugarcane biomass is expected to play a larger role in the national energy matrix during the study period [58]. In Brazil, natural gas and electricity have the biggest representation as energy sources for industrial heating processes, while coal usage remains minimal despite its use in thermal power plants for energy generation. Natural gas served as the reference for comparing low, medium, and high temperature ranges with other solutions. The comparative results across low, medium and high temperature ranges are presented in Appendix C. For both analyses, comparison was made with the use of green electricity for electrical equipment (Appendix C). It is important to note that both $kgCO_2e$ and USD/kWh consider the efficiency of the listed equipment. Therefore, electric equipment such as heat pumps and electric boilers may perform differently despite using the same source of energy.

In the context of low and medium temperatures, biomass represented the most beneficial solution for decarbonization efforts. This is due to the almost neutral value of CO_2e emissions, as well as the low price, which can be attributed to it using processed waste and Brazil being a major grower of sugar cane for ethanol and other derived products. The utilization of sugarcane bagasse is viable in regions where its production is concentrated, such as in the southeast of the country. Longer distances make the cost of the material higher, as well as increasing the emissions associated with transportation. Another crucial factor is the influence of the agricultural scenario on the price. Heat pumps come in second place, while also reducing energy costs. This is also because Brazil has a very significant sustainable electricity matrix in addition to the heat pump efficiency. It is important to reinforce that current technologies for heat pumps can reach up to 150 °C. Both heat pumps and electric boilers can perform even better if they use sustainable sources with lower or zero CO_2 emissions. Conversely, biomethane presented the most expensive alternative in comparison to natural gas, an anticipated outcome given its emerging technology landscape. Brazil already has incentives and policies for including a percentage of biomethane in the natural gas pipeline; however, it has not been economically feasible in some regions and improvements are still necessary in terms of legislative frameworks and incentives. In comparison to the utilization of renewable electricity considering zero CO_2 emissions (Appendix C), both heat pumps and electric boilers demonstrate considerable potential for cost savings, with reductions of 559.50 USD and 485.95 USD per $tonCO_2e$ saved, respectively. These savings exceed those associated with the use of biomass. The cost of renewable electricity, in this case solar energy, was based on 0.026 USD/kWh [59], and the same approach was employed to consider the efficiency of each type of equipment given the output values (Appendix C). The utilization of this type of energy typically involves the purchase of energy through power purchase agreements (PPAs), which are typically structured as longer-term contracts. These contracts can be beneficial for companies from an economic perspective, but more challenging in terms of long duration and specific terms and risks associated. In Brazil, until 2024, there was a tax deduction for the supply of solar energy. However, this ceased to apply to new installations after this period, which should result in a reduction in the rate of increase in installed capacity in the country and a reduction in its economic attractiveness [60]. Nevertheless, the solar energy market is anticipated to expand from 34.20 GW at the end of 2023 to 97.46 GW by 2028; it is attractive for Brazil because it has some of the highest solar irradiation in the world [61].

In the context of high temperatures, the utilization of electrical energy for equipment such as electric arc furnaces with high-efficiency performance has been demonstrated to be the most beneficial. However, an increase in cost is to be expected. The use of thermal energy storage (TES) systems has typically been considered in conjunction with other systems, which has the effect of enhancing the overall benefits of their use. For both technologies, the use of renewable sources will result in enhanced performance in the decarbonization process, as can be seen in Appendix C, becoming more affordable due to the lower price of solar energy in the case of PPAs.

3.1.2. China

Over the past decade, China has primarily relied on coal as a source of energy, along with notable representation in global oil and natural gas consumption. Nevertheless, even Chinese leaders have come to recognize that the country's economy is on the brink of significant change [62]. The Chinese electrical sector is currently undergoing a significant transition. Given that thermal plants currently account for over 70% of the world's electricity, it is of utmost importance to decarbonize this industry to address concerns surrounding climate change 18. As Maguire [63] identifies, coal is currently the most prevalent fuel for industrial heating in China.

In the context of low-temperature ranges, natural gas usage is employed as a benchmark for comparison with alternative solutions. In the context of medium- and high-temperature scenarios, coal is employed as a reference point. The results of the analysis are presented in Appendix D, which covers the low-temperature range and addresses medium- and high-temperature scenarios. In addition, a comparison was made with the use of green electricity for electrical equipment. Based on the comprehensive analysis conducted, heat pumps represent the optimal choice for low-temperature processes due to their remarkable efficiency, which exceeds that of gas or coal by a factor of three to four. Industrial heat pumps are still emerging, but initial implementations can be found, especially within light industries [62]. As China's power sector accelerates its transition to decarbonization, the environmental performance of heat pumps will be even more impressive using grid electricity, or when powered by renewable energy sources acquired by contracts or self-generated electricity. Although biomass and biomethane may have higher costs, they offer significant potential for future advancements. This is because biomass usage has been incentivized, as highlighted by Guo et al. [35]. On the other hand, electric boilers may appear impractical for reducing CO_2 emissions due to the high coal share in the electrical grid, but it shows promise as a viable solution when powered by green electricity alternatives.

When utilizing green electricity, specifically solar energy, the price is comparable to that of grid electricity, typically around 0.91 USD/kWh [64]. After conducting output energy calculations, Appendix D presents the performance of heat pumps, while also highlighting electric boilers as an environmentally and economically viable solution. Heat pumps show notable cost savings, with negative numbers indicating these savings. Nevertheless, when green energy is employed, the cost reduction is less pronounced, as it aligns more closely with the reduction in CO_2 emissions. Coal remains the dominant energy source for Chinese industries due to its cost-effectiveness compared to alternatives. When evaluating solutions for medium and high temperatures, gas boilers present a viable option, although they incur a fuel cost increase of approximately 104.60 USD/ton CO_2e saved. This makes gas boilers a feasible short- to medium-term solution, despite their reliance on fossil fuels. Biomethane and biomass rank second and third, respectively, due to their low or neutral CO_2 emissions. Electrification, on the other hand, remains a less affordable solution in the current Chinese context, partly due to the emission factor of the grid and because its cost is three times higher than that of coal. Nevertheless, when compared with green electricity usage, the cost of decarbonization can be reduced by over 10 times due to the lack of emissions, going from 1833.33 USD/ton CO_2e saved to 113.78 USD/ton CO_2e saved in the cases of electric boiler and TES, making it more affordable than biomethane and approaching the cost of biomass.

Decarbonizing high-temperature processes in industries poses significant challenges in China, as these sectors are major contributors to the country's CO_2 emissions. Potential solutions include natural gas, biomass, or electrification, while hydrogen may become viable in the medium to long term as prices decrease. Carbon capture and storage (CCS) technologies can address industrial process emissions and those from residual fossil fuel use.

Regarding the analysis of energy costs, coal remains the most cost-effective energy source in China, while also being the second highest in terms of emissions. The country's electricity generation sector heavily relies on fossil fuels, primarily coal, making it a major contributor to China's high CO_2 emissions when considering the grid context.

3.1.3. European Union (EU)

In recent decades, the EU-27 has made significant progress in reducing GHG emissions while promoting economic growth. Three-quarters of GHG emissions stem from energy-related activities. Although the share of renewable energy in the energy mix increased from 21.8% in 2021 to 22.5% in 2022, fossil fuels still dominate. The European Union's (EU) target of 42.5% renewable energy by 2030 will accelerate the decarbonization of the EU's electricity supply in the coming decade. This will require a significant increase in renewable energy capacity in the member states. In contrast, the industrial sector, which was responsible for 21% of EU GHG emissions in 2021, has consistently reduced its emissions over time, achieving a 35% decrease by 2021 compared to 1990 levels. This decline in emissions is attributed to economic changes, emissions reduction measures, and improved energy efficiency. Fluctuations in emissions are closely tied to production volumes, notably during economic downturns such as those in 2008–2009 and 2020 [65].

In the EU scenario, fossil fuels play a significant role in heating. Natural gas serves as a base for comparing technologies in the low- and medium-temperature range, while coal is used as a reference for high-temperature applications, particularly in energy-intensive industries. Appendix E presents the analysis of low- and medium-temperature applications and provides the ranking of high-temperature applications. An analysis of green electricity usage was also added.

According to the results shown in Appendix E, heat pumps prove to be the optimal solution for low-temperature applications, offering superior performance in reducing costs and emissions. However, it is important to note that this solution is limited to temperatures up to 150 °C and its efficiency decreases above 100 °C, resulting in variable performance. Biomass boilers offer a compelling alternative with energy cost investments of 3.83 USD/ton CO_2e saved. Biomass contributed 40% to the EU's renewable gross final energy consumption in 2022, highlighting its key role [66]. The cost-effectiveness of biomass varies depending on factors such as regional differences in wood pellet and chip prices, availability, and geographical distribution, also applicable for different types of biomasses. Electric boilers appear impractical for reducing CO_2 emissions due to the grid emission factor; however, it is important to consider that they can perform differently in countries with a bigger share of renewable energy sources for electricity production. Alternatively, choosing green energy or self-production can significantly change the scenario and achieve CO_2 reduction goals. According to LevelTen Energy [67], the average cost of green electricity from wind and solar energy in the EU for PPAs was 0.062 USD/kWh in 2022. This cost makes heat pumps an even more affordable and environmentally friendly option, with electric boilers being the second most optimal choice, surpassing biomass. High-intensity energy industries play a crucial role in decarbonization, and while natural gas offers one of the better solutions, industry still relies heavily on fossil fuels. Biomethane offers a superior solution to electrification, unless green electricity is used, due to its lower emissions and comparable costs. According to the [68], biomethane production has doubled since 2018, highlighting its growing potential for future use.

In the context of electrification, as the electricity grid incorporates more renewable energy, the scenario will improve for equipment such as electric boilers, electric furnaces, and TES, which will also impact hydrogen production. This shift is attributed to the CO_2e reduction potential of these solutions compared to high-emission fuels like coal. Appendix E presents an analysis of green energy usage, and the findings indicate that in this scenario electrification represents the most advantageous solution from both an environmental and an economic perspective.

The EU has introduced significant legislation, such as the Energy Efficiency Directive (EED, EU/2023/1791) and the Renewable Energy Directive (RED, 2009/28/EC), alongside the Net Zero Industry Act (NZIA, COM (2023) 161), creating a robust policy framework to support the electrification of various sectors.

3.1.4. Saudi Arabia

Currently, Saudi Arabia's energy landscape is dominated by conventional sources, with solar contributing just 0.1%, natural gas 59.6% and oil 40.3% to the primary energy mix [69]. However, recognizing the need for sustainable development and environmental protection, the country has set targets, outlined in the Saudi Green Initiative, to increase the share of renewable energy to 50% by 2030. This shift towards renewable resources is mainly driven by wind and photovoltaic (PV) solar [70]. Appendix F presents the ranking of solutions for low temperatures, and for the medium and high temperature ranges compared with diesel usage. A comparison with green electricity was also performed.

For low temperatures, the most beneficial solution compared to the commonly used diesel in terms of carbon abatement and cost is the use of natural gas. The cost of fossil fuels, i.e., diesel and natural gas, in the country is very low compared to electricity, for instance. A second option is heat pumps. Given the projected increase in energy demand and the goal of carbon neutrality by 2060, investments in technologies like heat pumps could be strategically beneficial for Saudi Arabia. For the use of green electricity, heat pumps emerge as the most environmentally and economically advantageous solution, followed by electric boilers. The country is investing in solar installations, which may result in low supply costs. In this analysis, a projection of 0.032 USD/kWh for PPAswas used, according to studies by Bellini [71]. The analysis of high-temperature applications presents similar performance according to the results in Appendix F. For high-temperature applications, a similar scenario is observed, with natural gas being the most advantageous both in terms of CO_2 reduction and its smaller cost increase. When considering grid supply, electrification is not feasible due to the high emission factor associated with the grid, which results in increased emissions compared to diesel. However, when green electricity is used, the cost in USD per ton of CO_2e saved can be significantly reduced. Therefore, electrification may become a viable alternative in the future.

In terms of the energy source scenario in Saudi Arabia, natural gas and diesel come with the lowest cost but highest emissions. Grid electricity does not seem to be attractive in the current scenario, considering its price and the higher emissions associated with it, but once the country progresses towards its renewable electricity targets, this scenario may change in terms of emissions. The use of green electricity appears to be an intermediate source, with zero emissions and a price higher than fossil fuels but lower than grid electricity.

3.1.5. United States (US)

In 2020, industrial activities in the United States contributed approximately 25% of the country's greenhouse gas emissions. This highlights the urgent need for sustainable, zero-emission manufacturing processes to meet the national climate goals of reducing emissions by 50% to 52% by 2030 and achieving net zero emissions by 2050. Projections indicate a substantial rise in industrial electricity demand by 2030 and 2050, with wind and solar energy emerging as cost-effective solutions to meet this demand. The increasing use of renewable energy sources may pose a threat to the economic feasibility of conventional power sources, resulting in the decommissioning of some coal, natural gas, and nuclear plants [72]. For the US, natural gas was used as a baseline to compare against, both for low- or medium- and for high-temperature ranges, cf. Appendix G. An analysis of green electricity was also performed.

Among the various heating technologies evaluated, for low to medium temperature ranges heat pumps stand out as the most cost-effective solution for reducing CO_2 emissions, with a cost reduction of 330.60 USD/ton CO_2 saved. Biomass follows as a viable alternative. Biomethane, however, proves less economical, at 763.40 USD/ton CO_2 saved. The results indicate that all technologies, except electric boilers, achieve significant CO_2 emissions reductions compared to baseline natural gas use. Conversely, electric boilers increase both emissions and costs when grid electricity is considered. However, the scenario changes when green electricity is used, as shown in Appendix G. Electrification, including the use of heat pumps and electric boilers, becomes the most advantageous option, reducing both emissions and costs. The cost of green electricity used in the calculations is based on a mix of wind and solar power for PPAs, priced at 0.0398 USD/kWh according to [67].

In the context of high temperatures, biomass emerges as the most beneficial option, with a cost increase of 12.6 USD/ton CO_2e saved. This is followed by biomethane, which exhibits a significant cost increase of 763.44 USD/ton CO_2e saved. It has been shown that electrification using typical electrical grids is not a favorable approach in terms of CO_2 reduction. However, the use of renewable electricity or grids with a lower carbon footprint can provide a more favorable scenario for electrification and may be a viable solution, as shown in Appendix G. For the use of green electricity, electrification appears to be the most advantageous solution, surpassing the use of biomass.

4. Conclusions

Solutions to decarbonize industrial heat generation vary across different regions. In general, when considering the regions under study, the use of heat pumps emerges as the optimal solution for low temperatures. This system, when connected to clean sources of electricity, still demonstrates enhanced performance compared to other technologies. Furthermore, the utilization of TES facilitates more effective energy management. The use of biomass is the second most prevalent in most of the regions under study, except for Saudi Arabia, where natural gas would be more feasible. However, it should be noted that each region has its own particularities regarding the use of biomass such as price, availability and geographic distribution.

In the case of medium and high temperatures, natural gas represents a viable solution for countries such as Saudi Arabia and China in the short term as it remains reliant on fossil fuels. For the remainder of the countries, the use of biomass and electrification represent the most beneficial solutions. In general, the proportion of electricity in the energy mix is expected to increase. However, to achieve decarbonization targets, it will be necessary to develop cleaner energy mixes or projects for PPAs that have demonstrated competitive prices. It is, however, recommended to conduct a deeper analysis of the conditions and risks associated with such projects.

Brazil is the region with the highest proportion of renewable energy sources and offers the most favorable conditions for using electricity while reducing emissions. Solar thermal energy systems could further support the renewable energy supply and justify further exploration. Furthermore, the electrification of energy sources raises concerns about the installed capacities required to meet demand. Another aspect when changing electrification is the capital expenditure (Capex) associated with it, as the replacement of fossil fuel equipment and potential process adjustments comes with an investment cost. When considering biofuels, this replacement may not be necessary or may require smaller adaptations. It is important to note that this study does not provide a detailed comparison of Capex and maintenance costs, as these can fluctuate depending on technology migration type, operational temperature ranges, and regional factors, such as economic incentives. Therefore, careful consideration of cost implications is essential when making technology choices to select the most suitable solution for each context.

The utilization of biomethane appears to be a promising prospect in the near future, provided that its costs and incentives become more aligned with those of other sources, as is the case in the EU. However, it is notable that some regions are already anticipating a limit on its production. Finally, the use of TES is more efficient when configured with multiple systems, integrating energy management and electrification. Nevertheless, ongoing advancements in these systems may offer even more optimal configurations in the future.

A limitation of these results is that policies and economic incentives can influence decisions about energy sources applied in technologies, and economic incentives can lead to diverse decisions that should be made based on the initial efficiency data. Basically, every region analyzed has its own policy for increasing the share of renewable energy sources in its energy mix. This will probably lead to cleaner electricity that can be used for the industrial heating processes. On the one hand, this fact will result in some decarbonization. On the other hand, choosing the most carbon-efficient technique will also gain decarbonization. It is not the aim of this study to consider possible incentives or state support in the economic calculations. The calculations refer to the current conditions. It should be added that another investigation should be carried out regarding the effects of environmental economic incentives to support the development of renewable energy use and to support those solutions that in their current sate are not so favorable economically, but would be more favorable in terms of emissions reduction.

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Appendix A

A.1. Conversion of Coal Prices from USD/Ton to USD/kWh

1. Assumptions:
   - The heat content of coal is assumed to be 6600 kcal/kg.
   - The conversion factor from kcal to kWh is approximately $\frac{1}{860}$ kWh/kcal, because 1 kWh = 860 kcal.
   - Given coal prices in USD/t:

Table A1. Coal prices used in the calculations.

Country	Price
Brazil	143.34 USD/t
China	108.20 USD/t
European Union	184.19 USD/t
Saudi Arabia	184.19 USD/t
United States	143.34 USD/t

2. Conversion Formula:

The cost of coal was converted from USD per metric ton (USD/mt) to USD per kilowatt-hour (USD/kWh) using the following steps:

- The cost per metric ton was converted to cost per kg by dividing by 1000, given there are 1000 kg in a metric ton.
- The cost per kg was used to find the cost per kcal by dividing it by the heat content per kg.
- The cost per kcal was then converted to cost per kWh using the conversion factor.

$$\text{Cost in USD/kWh} = \frac{\text{CostinUSD/mt}}{1000} \times \frac{1}{6600\ \text{kcal/kg}} \times 860\ \text{kcal/kg}$$

3. Calculations:

After performing the calculations, the converted price could be found:

- Brazil: 0.01868 USD/kWh
- China: 0.01410 USD/kWh
- European Union: 0.01678 USD/kWh
- Saudi Arabia: 0.01678 USD/kWh
- United States: 0.01868 USD/kWh

A.2. Conversion of Biomass Prices from USD/Ton to USD/kWh

1. Assumptions:
   - For conversion from mmBtu to GJ, it was assumed that 1 mmBtu = 1.055 GJ.
   - The conversion factor from GJ to kWh is given as 1 GJ = 277.778 kWh.
2. Calculation:

Given the biomass prices and heat content:
Brazil (Sugarcane Bagasse):

- Price per ton: 55 USD
- Heat content: 8.96 GJ/ton
- USD/GJ: $\frac{55}{8.96}$ = 6.14
- USD/kWh: 6.14 × $\frac{1}{277.77}$ = 0.024

European Union (Woody Biomass):

- Price per ton: 370 USD
- Heat content: 17 mmBtu/ton (converted to GJ)
- USD/GJ: $\frac{370}{17 \times 1.055}$ = 20,63
- USD/kWh: 20.63 × $\frac{1}{277.77}$ = 0.0743

United States (Wood and Wood Residuals):

- Price per ton: 222.46 USD
- Heat content: 17 mmBtu/ton (converted to GJ)
- USD/GJ: $\frac{222.46}{17 \times 1.055}$ = 12.41
- USD/kWh: 12.41 × $\frac{1}{277.77}$ = 0.044

Appendix B

Additional data include green electricity prices for the regions under study, as well as calculations based on equipment efficiency.

Summary of green electricity costs discussed in Section 2.4.

Table A2. Compilation of green electricity prices for PPAs.

Region/Country	Green Electricity Cost (USD/kWh)
Brazil	0.026
China	0.091
European Union	0.062
Saudi Arabia	0.032
United States	0.040

Table A3. Calculations of emissions and costs fromthe solutions using green electricity and considering the COP.

Technology	COP	$kgCO_2e$ and USD/kWh Energy Output	Region/Country				
			Brazil	China	European Union	Saudi Arabia	United States
Heat pump	3	CO_2e	0.	0	0	0	0
		Energy cost	0.01	0.03	0.02	0.01	0.01
Electric boiler	1	CO_2e	0	0	0	0	0
		Energy cost	0.03	0.09	0.06	0.03	0.04
Thermal energy storage	0.85	CO_2e	0	0	0	0	0
		Energy cost	0.03	0.11	0.07	0.04	0.05
Electric arcfurnace	1	CO_2e	0	0	0	0	0
		Energy cost	0.03	0.09	0.06	0.03	0.04

Appendix C

Table A4. Rankings in Brazil for energy solutions at low and medium temperatures, compared with natural gas usage.

Comparison: Natural Gas	COP: 0.8	CO_2e	$kgCO_2e$/kWh Output	0.233	
		Energy Price	USD/kWh Output	0.053	
Technology	**$kgCO_2e$/kWh Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e$/kWh**	**Increase in Energy cost (USD/kWh)**	**USD/tonCO_2e Saved**
Biomass boiler	0.009	0.04	0.224	−0.10	−447.37
Heat pump	0.014	0.06	0.218	−0.08	−376.24
Electric boiler	0.043	0.17	0.190	0.03	164.91
Biomethane boiler	0	0.31	0.233	0.17	747.31

Table A5. Comparison using green electricity for the low-temperature scenario in Brazil.

Technology	$kgCO_2e$/kWh Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e$/kWh	Increase in Energy Cost (USD/kWh)	USD/tonCO_2e Saved
Heat pump	0	0.009	0.233	−130	−559.50
Electric boiler	0	0.026	0.233	−113	−485.95

Table A6. Rankings in Brazil for energy solutions at high temperatures, compared with natural gas usage.

Comparison—Gas Boiler	COP: 0.8	CO_2e	$kgCO_2e$/kWh Output	0.233	
		Energy Price	USD/kWh Output	0.053	
Technology	**$kgCO_2e$/kWh Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e$/kWh**	**Increase in Energy cost (USD/kWh)**	**USD/TonCO_2e Saved**
Electric arc furnace	0.043	0.17	0.190	0.03	164.90
Thermal energy storage	0.051	0.20	0.182	0.06	336.70
Biomethane furnace	0	0.31	0.233	0.17	747.31

Table A7. Comparison using green electricity for the high-temperature scenario in Brazil.

Technology	$kgCO_2e/kWh$ Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e/kWh$	Increase in Energy cost (USD/kWh)	USD/TonCO_2e Saved
Electric arc furnace	0	0.026	0.233	−0.113	−485.90
Thermal energy storage	0	0.031	0.233	−0.108	−465.20

Appendix D

Table A8. Rankings in China for energy solutions at low temperatures, compared with natural gas usage.

Comparison: Natural Gas	COP: 0.8	CO_2e	$kgCO_2e/kWh$ Output	0.23	
		Energy Price	USD/kWh Output	0.06	
Technology	**$kgCO_2e/kWh$ output**	**Energy price USD/kWh output**	**Reduction in $kgCO_2e/kWh$**	**Increase in energy cost (USD/kWh)**	**USD/tonCO_2e saved**
Heat pump	0.186	0.03	0.047	−0.03	−645.90
Biomass boiler	0.010	0.09	0.223	0.03	122.79
Biomethane boiler	0.000	0.24	0.233	0.18	758.06
Electric boiler	0.557	0.09	−0.325	0.03	97.84

Table A9. Comparison using green electricity for the low-temperature scenario in China.

Technology	$kgCO_2e/kWh$ Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e/kWh$	Increase in Energy Cost (USD/kWh)	USD/tonCO_2e Saved
Heat pump	0.00	0.03	0.233	−0.03	−133.10
Electric boiler	0.00	0.09	0.233	0.03	128.10

Table A10. Rankings in China for energy solutions at medium and high temperatures, compared with coal usage.

Comparison: Coal	COP: 0.6	CO_2e	kgCO2e/kWh Output	0.595	
		Energy Price	USD/kWh Output	0.02	
Technology	**$kgCO_2e/kWh$ Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e/kWh$**	**Increase in Energy cost (USD/kWh)**	**USD/tonCO_2e Saved**
Gas boiler/furnace	0.233	0.06	0.363	0.04	104.60
Biomass boiler/furnace	0.010	0.09	0.585	0.07	111.52
Biomethane boiler/furnace	0.000	0.24	0.595	0.21	359.94
Electric boiler	0.557	0.09	0.038	0.07	1833.33
Electric arc furnace	0.557	0.09	0.038	0.07	1833.33
Thermal energy storage	0.655	0.11	−0.060	0.09	1427.64

Table A11. Comparison using green electricity for the medium- and high-temperature scenarios in China.

Technology	$kgCO_2e$/kWh Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e$/kWh	Increase in Energy Cost (USD/kWh)	USD/tonCO_2e Saved
Electric boiler	0.00	0.09	0.595	0.07	113.78
Electric arc furnace	0.00	0.09	0.595	0.07	113.78
Thermal energy storage	0.00	0.11	0.595	0.08	140.77

Appendix E

Table A12. Ranking of EU energy solutions at low and medium temperatures, compared with natural gas usage.

Comparison: Natural Gas	COP: 0.8	CO_2e	$kgCO_2e$/kWh Output	0.23	
		Energy Price	USD/kWh Output	0.06	
Technology	**$kgCO_2e$ per kWh Output**	**Energy Price USD per kWh Output**	**Reduction in $kgCO_2e$/kWh**	**Increase in Energy Cost (USD/kWh)**	**USD/tonCO_2e Saved**
Heat pump	0.120	0.07	0.113	−0.03	−285.18
Biomass boiler	0.039	0.10	0.194	0.00	3.83
Biomethane boiler	0.00	0.24	0.233	0.14	596.77
Electric boiler	0.360	0.20	−0.128	0.10	794.12

Table A13. Comparison using green electricity for the low- and-medium temperature scenarios in the EU.

Technology	$kgCO_2e$/kWh Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e$/kWh	Increase in Energy Cost (USD/kWh)	USD/tonCO_2e Saved
Heat pump	0.00	0.02	0.233	−0.08	−335.65
Electric boiler	0.00	0.06	0.233	−0.04	−157.50

Table A14. Ranking of EU energy solutions for high temperatures, compared with coal usage.

Comparison: Coal	COP: 0.6	CO_2e	$kgCO_2e$/kWh Output	0.60	
		Energy Price	USD/kWh Output	0.04	
Technology	**$kgCO_2e$/kWh Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e$/kWh**	**Increase in Energy Cost (USD/kWh)**	**USD/tonCO_2e Saved**
Biomass boiler/furnace	0.04	0.10	0.56	0.06	106.92
Gas boiler/furnace	0.23	0.10	0.36	0.06	162.07
Biomethane boiler/furnace	0.00	0.24	0.60	0.20	331.93
Electric arc furnace	0.36	0.20	0.24	0.16	680.85
Thermal energy storage	0.42	0.24	0.17	0.20	1138.94

Table A15. Comparison using green electricity for the high-temperature scenario in the EU.

Technology	$kgCO_2e$/kWh Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e$/kWh	Increase in Energy Cost (USD/kWh)	USD/tonCO_2e Saved
Electric air calciner	0.00	0.06	0.60	0.02	37.19
Thermal energy storage	0.00	0.07	0.60	0.03	55.62

Appendix F

Table A16. Ranking of Saudi Arabia's energy solutions for low temperatures, compared with diesel usage.

Comparison: Diesel	COP: 0.7	CO_2e	$kgCO_2e$/kWh Output	0.38	
		Energy Price	USD/kWh Output	0.01	
Technology	**$kgCO_2e$/kWh Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e$/kWh**	**Increase in Energy Cost (USD/kWh)**	**USD/tonCO_2e Saved**
Gas boiler	0.23	0.01	0.15	0.002	11.864
Heat pump	0.20	0.02	0.18	0.01	66.540
Electric boiler	0.61	0.06	−0.23	0.05	217.949

Table A17. Comparison using green electricity for the low-temperature scenario in Saudi Arabia.

Technology	$kgCO_2e$/kWh Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e$/kWh	Increase in ENERGY cost (USD/kWh)	USD/tonCO_2e Saved
Heat pump	0.00	0.01	0.38	0.003	7.018
Electric boiler	0.00	0.03	0.38	0.024	63.158

Table A18. Ranking of Saudi Arabia's energy solutions for medium and high temperatures, compared with diesel usage.

Comparison: Diesel	COP: 0.7	CO_2e	$kgCO_2e$/kWh Output	0.380	
		Energy Price	USD/kWh Output	0.01	
Technology	**$kgCO_2e$/kWh Output**	**Energy price USD/kWh OUTPUT**	**Reduction in $kgCO_2e$/kWh**	**Increase in Energy cost (USD/kWh)**	**USD/tonCO_2e Saved**
Gas boiler/furnace	0.233	0.01	0.148	0.002	11.86
Electric boiler	0.614	0.06	−0.234	0.050	217.95
Electric arc furnace	0.614	0.06	−0.234	0.051	217.95
Thermal energy storage	0.723	0.07	−0.342	0.061	179.38

Table A19. Comparison using green electricity for the medium- and high-temperature scenarios in Saudi Arabia.

Technology	$kgCO_2e$/kWh Output	Energy Price USD/kWh Output	Reduction in $kgCO_2e$/kWh	Increase in Energy Cost (USD/kWh)	USD/tonCO_2e Saved
Electric boiler	0	0.032	0.380	0.02	63.158
Electric Arc Furnace	0	0.032	0.380	0.02	63.158
Thermal energy storage	0	0.038	0.380	0.03	78.019

Appendix G

Table A20. Ranking of US energy solutions for low and medium temperatures, compared with natural gas.

Comparison: Natural Gas	**COP: 0.8**	**CO_2e**	**$kgCO_2e/kWh$ Output**	**0.23**	
		Energy Price	**USD/kWh Output**	**0.06**	
Technology	**$kgCO_2e/kWh$ Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e/kWh$**	**Increase in Energy Cost (USD/kWh)**	**$USD/tonCO_2e$ Saved**
Heat pump	0.13	0.03	0.10	-0.03	−330.60
Biomass boiler	0.01	0.06	0.23	0.003	12.60
Biomethane boiler	0.00	0.24	0.23	0.18	763.40
Electric boiler	0.39	0.08	−0.16	0.02	115.01

Table A21. Comparison using green electricity for the low- and medium-temperature scenarios in the US.

Technology	**$kgCO_2e/kWh$ Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e/kWh$**	**Increase in Energy Cost (USD/kWh)**	**$USD/tonCO_2e$ Saved**
Heat pump	0	0.01	0.23	−0.05	−201.004
Electric boiler	0	0.04	0.23	−0.02	−86.882

Table A22. Ranking of US energy solutions for high temperatures, compared with natural gas.

Comparison: Natural Gas	**COP: 0.8**	**CO_2e**	**$kgCO_2e/kWh$ Output**	**0.23**	
		Energy Price	**USD/kWh Output**	**0.06**	
Technology	**$kgCO_2e/kWh$ Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e/kWh$**	**Increase in Energy Cost (USD/kWh)**	**$USD/tonCO_2e$ Saved**
Biomass boiler/furnace	0.01	0.06	0.23	0.003	12.60
Biomethane boiler/furnace	0.00	0.24	0.23	0.18	763.44
Electric arc furnace	0.39	0.09	−0.16	0.03	202.97
Thermal energy storage	0.46	0.09	−0.23	0.03	141.08

Table A23. Comparison using green electricity for the high-temperature scenario in the US.

Technology	**$kgCO_2e/kWh$ Output**	**Energy Price USD/kWh Output**	**Reduction in $kgCO_2e/kWh$**	**Increase in Energy Cost (USD/kWh)**	**$USD/tonCO_2e$ Saved**
Electric arc furnace	0.00	0.04	0.23	−0.020	−86.88
Thermal energy storage	0.00	0.05	0.23	−0.013	−56.67

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