Low-Carbon Thermal Energy Technologies for The Textile Industry

apparel impact institute

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Foreword

This report is the first in a series of two reports on low-carbon thermal energy for the textile industry. This first report focuses on assessment of low-carbon thermal energy technologies and sources, while the second report will conduct a quantitative assessment and develop a roadmap for adopting these low-carbon technologies and energy sources in typical wet-processing textile plants in five major textile-producing countries: China, India, Vietnam, Bangladesh, and Indonesia. Taken together, these reports will present detailed information on alternatives to fossil fuels, especially coal, in the global textile industry and lay out specific options and roadmaps for paths to achieve net-zero emissions.

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globalefficiencyintel.com
textilesustainability.com
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Executive Summary

The textile and apparel industry generates approximately 2% of global anthropogenic greenhouse gas (GHG) emissions. The demand for textiles and apparel is expected to grow, highlighting an urgent need for strategies to mitigate the industry's environmental and climate impacts. This report explores the feasibility, challenges, and potential of transitioning to low-carbon thermal energy sources and technologies in the textile industry, focusing on sustainable biomass, solar thermal, electrification technologies, and natural gas (a potential transition fuel). The electrification technologies include electric boilers, industrial heat pumps, and thermal energy storage systems. Overall, six alternative energy sources and technologies are included in this report.

We conducted a readiness assessment for adopting low-carbon energy sources and technologies among the world's leading textile-producing countries in the near term. For each energy source and technology, multiple criteria were assessed, such as the availability of resources domestically, the average carbon intensity of fuel used in the industry, climate policy strength, technology availability in each country, and other considerations. The results divide the countries by readiness to adopt each technology into categories of most ready, moderately ready, and less ready.

We also evaluated each energy source and technology against several indicators: capital and operational expenditures, energy costs, technological maturity, market growth outlook, thermal efficiency, CO_2 emissions, and other environmental risks. The cross-technology comparison highlights the overall maturity and applicability of each energy source and technology for the textile industry. Biomass, despite its potential for carbon neutrality, faces challenges such as deforestation and land use change. Natural gas, while mature, grapples with price volatility and climate and environmental risks, notably methane leakage that can eliminate its climate benefits compared to coal. Solar thermal technologies, although able to provide zero-carbon heat, face challenges for textile applications because of the industry's significant steam and heat requirements above 100°C. They also require significant space and investment and are highly dependent on the location of the plant. Electrification technologies, when tied to renewable electricity, have the best potential to decarbonize the textile industry. However, the scarcity of the required renewable energy at a reasonable price and competition from other industrial sectors for this resource is a challenge in the near term, especially in some low- and middle-income countries.

We then provide a detailed summary of each energy source and technology, including a description of how the technology works, strengths and opportunities as a low-carbon solution for the textile industry, challenges to adoption, supply and infrastructure considerations, and costs. A case study is also provided for each energy source and technology.

Electrification emerges as a highly efficient solution for low-carbon thermal energy, requiring minimal onsite infrastructure adjustments. Widespread adoption is constrained by energy costs, the existing carbon intensity of electricity grids in some countries, and supply of renewable electricity in key textile-producing countries, but in some cases electrification can be economically competitive with conventional technologies in the near- to medium-term (Zuberi et al. 2022). In addition, as in other industrial sectors, renewable electricity can be purchased at textile plants via Power Purchase Agreements (PPA), delivering decarbonization via electrification immediately.

A series of tailored actions and recommendations for apparel companies and textile suppliers emerged from the analysis, aimed at advancing the adoption of low-carbon energy sources and electrification technologies in the textile industry (Table ES1).

TABLE ES1.

Summary of Recommendations for Advancing Low-Carbon Thermal Energy Technologies in the Textile Industry

Energy Source/Technology	Summary of Recommendations
Biomass	Prioritize agricultural residues and waste biomass to avoid land-use change. Develop localized supply chains with robust monitoring, reporting, and verification (MRV) systems to ensure biomass does not contribute to deforestation. Evaluate sustainability at the landscape level to support social and environmental welfare.
Solar Thermal	Due to low efficiency and significant land and irradiation requirements, solar thermal is not prioritized for textile industry decarbonization.
Electrification Technologies (Electric Boilers, Industrial Heat Pumps, and Thermal Energy Storage)	Evaluate local renewable electricity availability and advocate for increased renewable generation. Modernize electric grids to support electrification and sponsor pilot projects to demonstrate feasibility. Disseminate information and invest in workforce training to support the adoption of electrification technologies. Expand financial incentives and develop specific policies for textile industry electrification.
Natural Gas	Establish policies and regulations to minimize methane emissions from natural gas usage. Implement leak detection and repair programs, conduct lifecycle analysis and carbon footprint assessments, and diversify energy sources to reduce reliance on natural gas.

This report serves as a guide for stakeholders in the textile and apparel industry, aiming to navigate the complex terrain of decarbonization. By evaluating and integrating low-carbon energy sources and technologies for process heating, the textile industry can significantly reduce its carbon footprint, contributing to global climate change mitigation efforts.

Table of Contents

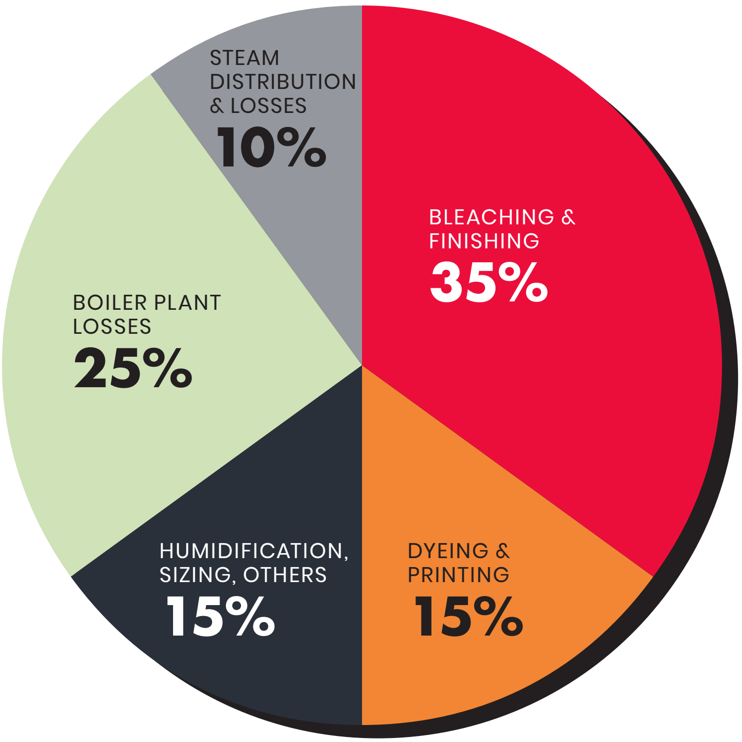
1. Introduction

The textile and apparel industry contributes approximately 2% to global anthropogenic greenhouse gas (GHG) emissions (Sadowski et al. 2021), marking it as a significant player in the dialogue on climate change and environmental sustainability. This industry's growth trajectory, fueled by increasing demand from the growing world population, highlights an urgent need for strategies to mitigate its environmental and climate impacts. As the industry evolves — with production increasingly shifting to low- and middle-income countries to leverage lower labor and resource costs — and as new technologies emerge, the imperative to adopt cleaner and more efficient manufacturing processes becomes even more critical. The textile industry is now more globalized and complex than ever before, making GHG emissions reduction a challenge that spans a wide range of countries and supply chains.

As the effects of climate change worsen and as the world's population continues to grow and consume more textile products, the textile industry must take serious actions to reduce its impact on the climate and environment. A critical aspect in reducing the textile industry's carbon footprint lies in its need for thermal energy for essential processes such as steam generation and hot water use. Heating represents over two-thirds of the total energy demand in the industrial sector globally, including the textile industry. Traditionally powered by fossil fuels, these processes not only contribute significantly to the industry's CO_2 emissions but also suffer from inefficiencies because a considerable portion of energy is lost in steam generation and distribution. Electrification and the use of lower-carbon energy sources present a promising path to decarbonization, offering the potential to replace carbon-intensive fossil fuels with cleaner alternatives. However, there are many challenges to transitioning to these new energy sources, necessitating a clear understanding of the industry's thermal energy consumption profiles, detailed feasibility analyses of the alternatives, and comprehensive action plans.

Figure 1 shows the breakdown of the typical thermal energy use in a composite textile plant with spinning, weaving/knitting, and wet processing. Fabric preparation (de-sizing, bleaching, etc.); dyeing and printing; and finishing together consume the greatest share of thermal energy (50%). A significant amount of thermal energy is lost during steam generation and distribution (35%). Lower carbon energy sources and high-efficiency technologies to electrify heating have a large potential for reducing fossil fuel use and GHG emissions in the textile industry.

FIGURE 1:
BREAKDOWN OF TYPICAL THERMAL ENERGY USED IN A TEXTILE PLANT
Source: Hasanbeigi and Zuberi 2022



Many top textile-producing countries and regions use fossil fuels (coal and petroleum products) to meet heating needs. Coal is a particularly carbon-intensive fuel, driving greenhouse gas emissions from the industry. It is also associated with harmful onsite air pollution and other environmental problems. Notably, coal is very heavily used in the world's top textile-producing countries, including China, India, and Vietnam, which are all within the top five textile producers globally. Other major producers — including Turkey, Taiwan Region, and Indonesia — also use coal extensively.

1.1. Scope of the Study

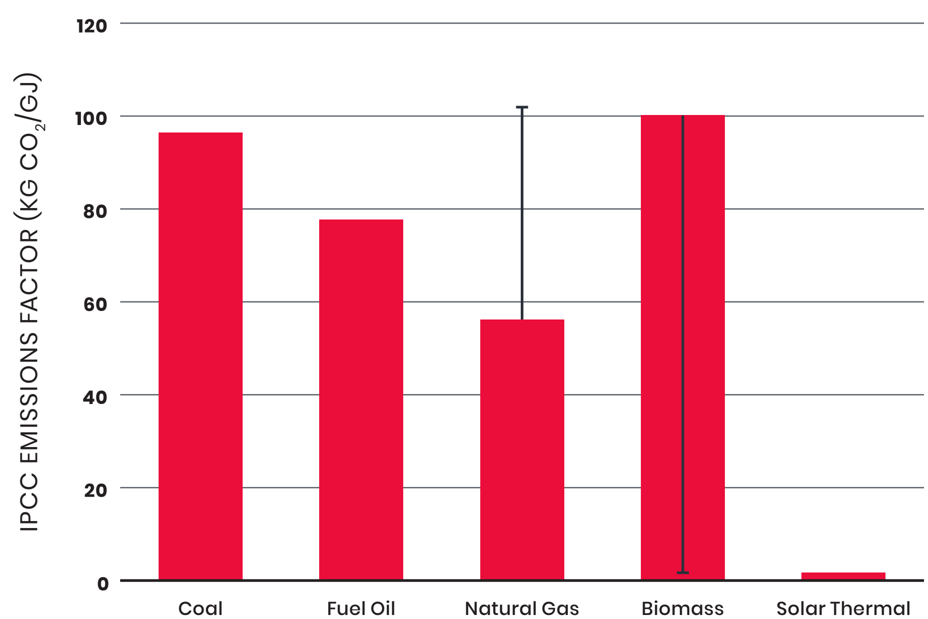
A useful framework for assessing decarbonization technologies is the five pillars of industrial decarbonization (Hasanbeigi et al. 2023) (U.S. Department of Energy 2022). These pillars encompass a broad range of strategies aimed at reducing emissions across various sectors, and help clarify the scope of the report. The five pillars include:

1. **Material Efficiency**, which focuses on reducing material demand through design optimization, reuse, recycling, and the use of low-carbon alternatives;
2. **Energy Efficiency**, which involves enhancing system efficiencies, expanding energy management practices, and recovering energy;
3. **Electrification**, which transitions from fossil fuels for heating to electrified solutions like boilers and heat pumps that can decarbonize when powered by renewable electricity sources;
4. **Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)**, which includes fuel switching or using lower-carbon feedstocks for industrial production;
5. **Carbon Capture, Utilization, and Storage (CCUS)**, a longer-term category of technologies for capturing CO_2 emissions at their source, utilizing them in other processes, or storing them to prevent atmospheric release.

This report focuses on the Electrification and LCFFES pillars for the textile industry, encompassing three electrification technologies and three low-carbon or potentially low-carbon fuel or energy sources.

The three electrification technologies are electric boilers, heat pumps, and thermal energy storage. These technologies can produce hot water and steam at temperatures necessary for textile production. The three lower-carbon energy sources are biomass, solar thermal systems, and natural gas. These technologies and energy sources would replace conventional boilers in the textile industry, which typically burn fossil fuels in industrial steam boilers and thermal oil boilers to provide heating for various stages of textile manufacturing. Figure 2 below compares the emissions factors of the different lower-carbon energy sources analyzed in this report relative to commonly used fossil fuels in industry (coal and fuel oil). Importantly, some estimates of natural gas emissions factors that include methane emissions from upstream sources could make natural gas more emissions-intensive than coal (error bar included to represent variation based on production location). Similarly, the IPCC estimates that the average biomass emissions factor is higher than coal for direct combustion. Taking into account carbon storage during biomass growth, biomass emissions factors could vary significantly and even be carbon neutral (error bar included to show potential range). Chapter 2 further discusses the potential carbon impacts of biomass. Thus, as a minimum requirement, the adoption of natural gas and biomass must use sources that do not increase CO_2 emissions.

FIGURE 2:
COMPARISON OF CO_2 EMISSIONS FACTOR OF BIOMASS & OTHER FUELS
Source: GEI analysis of IPCC 2006 and Clean Air Task Force 2024



Green hydrogen, while promising for broader decarbonization strategies, faces substantial challenges and inefficiencies when considered for heat production in industry. Huge inefficiencies arise from the energy-intensive process required to produce hydrogen via electrolysis and the subsequent energy losses when hydrogen is burned to generate heat. This makes it less efficient compared to its use in other industrial decarbonization applications, such as being directly converted into electricity through fuel cells, using it for direct reduced ironmaking in steel production, or using it as a low/no-carbon feedstock for production of chemicals such as ammonia and methanol. Furthermore, the current cost of green hydrogen production and the infrastructure needed for its deployment are prohibitive, limiting its medium- to long-term viability for the textile industry in most countries, especially textile producing countries in Asia. Green hydrogen is a valuable product and its use in the industry sector should be prioritized only to the applications that make the most climate and economic sense, such as the ones mentioned above. The application of hydrogen for heating, especially low-temperature heating for the textile industry, certainly cannot be a justified use of green hydrogen.

For each low-carbon technology or energy source, we summarize their strengths, opportunities, challenges, supply and infrastructure, and cost. Additionally we provide one or more case studies of application in the textile industry or similar industries.

FIGURE 3: LOW CARBON THERMAL ENERGY SOURCES AND TECHNOLOGIES FOR THE TEXTILE INDUSTRY COVERED

- Biomass
- Solar Thermal
- Electric Boilers
- Industrial Heat Pumps
- Thermal Energy Storage
- Natural Gas

The report assesses technology readiness for each alternative energy source and technology across 20 major textile-producing countries that represent most regions of the world. These 20 major countries are listed in Table 1 below. It is difficult to find comparable production data for all countries, and so we examined both the export value of textiles and the share the textile industry contributed to value added in the manufacturing sector in each country.

In some countries, textiles represent a significant share of the manufacturing sector, namely Cambodia, Bangladesh, Sri Lanka, and Pakistan. In terms of exports, China dominates, followed by Vietnam, Germany, Italy, Bangladesh, and India. Some of these countries may have larger relative production volumes but supply a large amount to the domestic market, such as India. In addition, some countries like Italy specialize in high-value textile and apparel exports but have relatively lower production volumes. We analyze all 20 countries in the readiness assessments in the next chapters, and we also discuss the technology readiness of five top textile-producing countries: China, India, Bangladesh, Vietnam, and Germany.[1] These countries represent a diverse range of textile producers with conditions suitable for different technologies and energy sources. It is important to note that technology readiness can vary widely across facilities within a given country, and facility-level readiness assessment is a critical step in decision-making regarding adoption of low-carbon thermal heating technologies.

Although there are some important differences in challenges across electrification technologies (i.e. electric boilers, industrial heat pumps, and thermal energy storage systems) we grouped them together for this analysis, assessing the countries for their overall readiness for electrification technologies for process heating. These differences are discussed within the electrification section of the report.

Next, each energy source/technology was evaluated on a number of key metrics that would determine facility-level readiness, including capital costs, operational costs, energy costs, CO_2 emissions, other environmental risks, market growth outlook, and technology readiness. These alternatives were evaluated in comparison with coal, the predominant fuel currently used for heating in many textile-producing regions, although natural gas and biomass have already been adopted in many places. It is important to note that actual adoption of these energy sources and technologies at the facility level could be partial, based on process steps that can be readily switched to low-carbon energy.

TABLE 1: 20 MAJOR TEXTILE-PRODUCING COUNTRIES ANALYZED IN THIS REPORT Sources: World Bank World Development Indicators 2024, Atlas of Economic Complexity 2024

Country	Textile Export Value, 2021 (billion USD)	Textile Share of Value Added in Manufacturing
China	478.0	10%
India	48.1	9%
Bangladesh	49.1	57%
Vietnam	83.4	15%
Turkey	41.2	15%
Pakistan	18.2	30%
Cambodia	15.0	87%
Indonesia	24.2	11%
Sri Lanka	6.0	39%
Thailand	9.7	6%
Spain	26.5	3%
Italy	67.4	8%
Germany	68.5	1%
United States	42.1	1%
Taiwan Region	13.2	10%
Japan	10.0	2%
South Korea	14.4	3%
Mexico	19.5	2%
Egypt	4.1	8%
Morocco	5.9	11%

Next, we provide an overview of best practice policies and regulations for the textile industry, focusing on regions that have made major progress in sustainability. Overall, this report aims to illuminate the opportunities and obstacles associated with moving towards a more sustainable and low-carbon production model in the textile industry. By evaluating the potential for integrating electrification and other low-carbon technologies for process heating, this report seeks to provide textile companies with the insights needed to embark on the path to decarbonization.

1 The second report in this series will quantitatively analyze adoption of low-carbon thermal heating solutions in five emerging economies that are major textile producers: China, India, Bangladesh, Vietnam, and Indonesia.

1.2. Barriers to and Drivers for Low-Carbon Thermal Energy in the Textile Industry

1.2.1. Barriers

In the textile industry, transitioning to low-carbon thermal energy faces multiple technical, financial, and regulatory barriers that curtail demand, and these barriers can vary country to country. Knowledge and education gaps, however, pose a major cross-cutting challenge to all the various low-carbon energy sources and technologies in all countries. There is a widespread lack of awareness within textile-producing companies, suppliers, and brands about the range of available options and their applicability to specific industrial processes within textile manufacturing. In particular, the existing workforce often lacks the necessary training to operate and maintain new electrification technologies, for example, which poses a substantial barrier to their effective implementation. In addition, while many textile producers have switched to or are considering switching to natural gas and biomass, the lifecycle carbon footprint of these fuels may be even higher than that of coal (see Section 2 and Section 5 for further discussion of each fuel). To be a viable low-carbon solution, these two alternative fuels must be properly sourced, monitored, and regulated, which is not necessarily achievable at present in many countries.

Transitioning to low-carbon technologies can also be costly, especially in terms of upfront costs. The initial investment required for purchasing new technologies and upgrading systems can be substantial, which may deter companies from making such commitments. In addition, integrating these new technologies into existing processes is not always practical and may need further investments into process redesign. Energy costs are a significant barrier — electricity is typically more expensive than fossil fuels, and some low-carbon fuels may also increase energy costs in some geographies, especially in the near term. For example, biomass is typically more expensive than natural gas in Bangladesh (the main fuel used in steam boilers in the textile industry there), limiting willingness to switch fuels. Similarly, natural gas is more expensive than coal in most countries in Europe and Asia. Fuel costs are also related to the availability of supply for certain fuels that lack infrastructure for transport and distribution in some countries. For example, Sri Lanka, Cambodia, Taiwan Region, and Vietnam have very minimal infrastructure for natural gas distribution.

Financing these transitions presents another significant challenge. Financial institutions are also often unfamiliar with the new low-carbon technologies, increasing the perceived risk as well as the cost of capital. This lack of accessible financing options can further discourage textile companies from pursuing technological upgrades in many circumstances. Moreover, the business models for implementing low-carbon technologies in the textile industry are still developing. Traditional financial models may not fully account for the long-term savings and operational efficiencies these technologies can provide, nor do they always consider the potential revenue streams e.g. carbon credits and other environmental incentives. This can lead to underestimating the economic viability of low-carbon projects, making them less attractive to investors and lenders. Additionally, the payback periods for these technologies can be lengthy, and the return on investment could be perceived as uncertain due to fluctuating energy prices, policy changes, and technological advancements.

Policy and regulatory environments are also insufficiently supportive of the adoption of low-carbon technologies in the textile industry in many countries. Subsidies may encourage the continued use of fossil fuels, while renewable energy may have limited policy support. For example, Indonesia is a top coal exporter. Coal mining companies have significant political power and direct finance towards presidential campaigns, and regional governments receive a share of coal revenues, limiting momentum for transitions away from coal (Jakob et al. 2020). Another issue is the seeming contradictions in national energy policy.

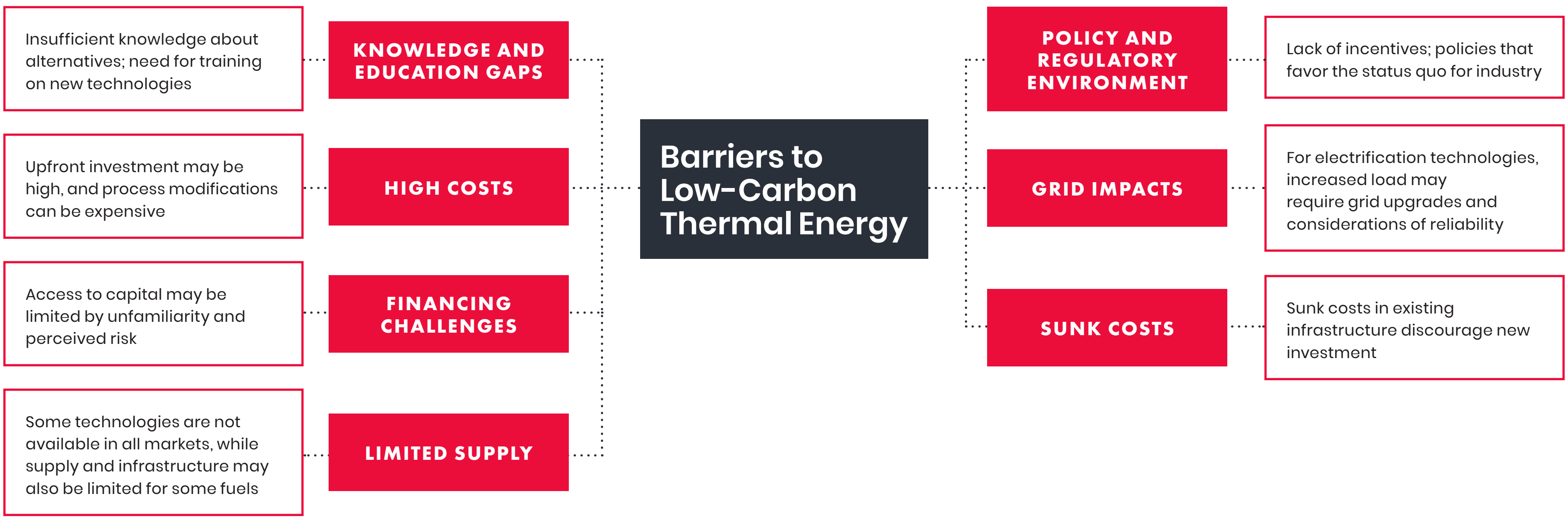
For electrification in particular, the reliance on electric utilities introduces challenges related to infrastructure and reliability. Textile facilities may face increased vulnerability to grid instability as they become more dependent on the electrical grid in countries that still face grid infrastructure reliability issues, such as Pakistan. In addition, if the carbon intensity of the grid is significantly higher than the current fuel mix, electrification may lead to an increase in overall CO_2 emissions, even taking into account the higher efficiency of electrification technologies that reduce overall energy demand. Of the countries we examine in this study, Indonesia and India have the highest grid emissions factors, and near-term electrification would increase CO_2 emissions.

Sourcing renewable electricity from PPAs[2] can circumvent negative impacts of electrification due to high grid emissions factors, but in many countries, such arrangements may not be readily available due to market barriers for independent power producers. Additionally, the complexity of negotiating PPAs in environments with less regulatory certainty can further deter textile manufacturers from securing reliable and cost-effective renewable electricity supply.

In addition, there may also be high competition for limited renewable resources in some low- and middle-income countries. As these countries often prioritize energy access and economic growth, renewable electricity may be directed to critical infrastructure and residential needs. The availability of renewable energy for textile producers can be sporadic and expensive, compounded by the nascent stage of renewable infrastructure in many of these regions.

Lastly, sunk costs are a significant barrier for the shift from established, combustion-based processes to newer technologies. Many companies face sunk costs in their current manufacturing setups, making them understandably hesitant to invest in new equipment of any kind, especially technologies they see as unfamiliar. There may be pressure to stick with conventional processes that are better understood and trusted within the industry. Figure 4 summarizes these barriers for the textile industry, and specific challenges are discussed for each energy source and technology in the following sections.

FIGURE 4: BARRIERS TO LOW-CARBON THERMAL ENERGY IN THE TEXTILE INDUSTRY



2 Power purchase agreements (PPAs) are contracts between electricity producers and electricity buyers, also called offtakers. For a primer on PPAs, see (U.S. Department of Commerce 2016).

1.2.2. Drivers

Despite these barriers, there are also a number of enabling factors that are currently driving adoption of low-carbon thermal energy sources and technologies in the textile industry, including technological, economic, and regulatory factors. One driver is supply – the increasing technological and market readiness of low carbon technologies. Some electrification technologies are commercially available and have large market growth potential, while others are emerging but increasingly commercialized. Ongoing research and demonstration continue to improve efficiency and applicability to a wide range of temperatures, enhancing the feasibility of these technologies for wider adoption. For a list of case studies, see Chapter 4.

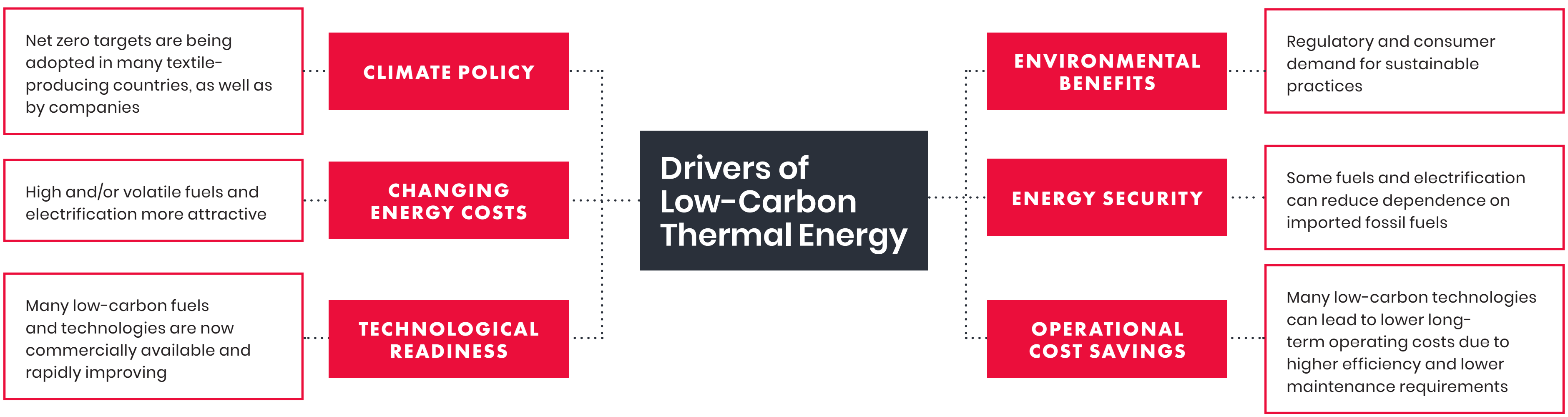
Climate policy is also driving adoption. There are increasing governmental and corporate commitments to net-zero targets and emissions reductions of 45% by 2030, including by many apparel brands and in many textile-manufacturing countries. Governmental policies and market incentives are key for implementing these climate targets. Various support mechanisms such as tax credits, grants, and financial incentives for technology adoption and development play a significant role in making low-carbon technologies more accessible and economically viable for textile manufacturers.

In addition, consumer demand for more sustainable and environmentally responsible manufacturing practices is also having a bottom-up effect. Many consumers are aware of concepts such as carbon footprints and create public pressure on apparel companies to improve their climate performance.

In terms of costs, although upfront costs are a significant barrier for heat pumps and thermal energy storage, the transition to electrification technologies and low carbon energy sources in some cases can reduce operational costs, resulting in longer-term savings. These savings are primarily due to the higher efficiency of electrified systems and potentially lower maintenance needs.

Switching to lower-carbon fuels and technologies can also reduce reliance on volatile fossil fuel markets. In countries reliant on fossil fuel imports, such as Bangladesh,[3] South Korea, Japan, and Italy, renewable electricity and some low-carbon fuels that are domestically available can offer a more secure form of energy. Figure 5 summarizes these drivers for the textile industry, and specific opportunities are discussed for each energy source and technology in the following sections.

FIGURE 5: DRIVERS OF LOW-CARBON THERMAL ENERGY IN THE TEXTILE INDUSTRY



3 It is important to note that electricity prices in Bangladesh have also faced volatility, due to reliance on imported fossil fuels for electricity generation.

2. Biomass as an Alternative Low-Carbon Fuel for the Textile Industry

Biomass is one of the oldest forms of energy, with wood being the primary fuel used before the Industrial Revolution. It currently represents 7.2% of industrial energy consumption globally (IEA 2024) and has increasingly been a fuel source of interest due to its low carbon potential under some circumstances. Biomass has a higher emissions factor than coal when combusted. Sustainable biomass, referring to biomass sources that sequester as much carbon as they release during combustion and do not harm local ecosystems, has the potential to be a carbon-neutral alternative to traditional fossil fuels for process heating, depending on how the biomass is produced, transported, and processed. As this section shows, however, sustainable biomass faces many challenges for adoption in the textile industry.

Biomass boilers have already been adapted in countries throughout Southeast Asia. This is facilitated by the region's abundant biomass resources, such as sugarcane bagasse, wood waste, palm oil mill effluent, rice husks, and biofuel plantations. For instance, Vietnam has already built several biomass boilers in textile plants, and biomass use in the industrial energy fuel mix has increased in recent years. Another example is Cambodia, which has adopted boilers that combust biomass resources in textile plants. These boilers have met the heating needs of these textile plants, but in many cases, biomass has been linked to deforestation offsite and the release of local air pollutants onsite. In addition, sustainable biomass supply is limited, which can lead to competition across industrial sectors and factories, increasing cost and limiting its appeal for low-carbon fuel switching.

2.1 Description of Technology

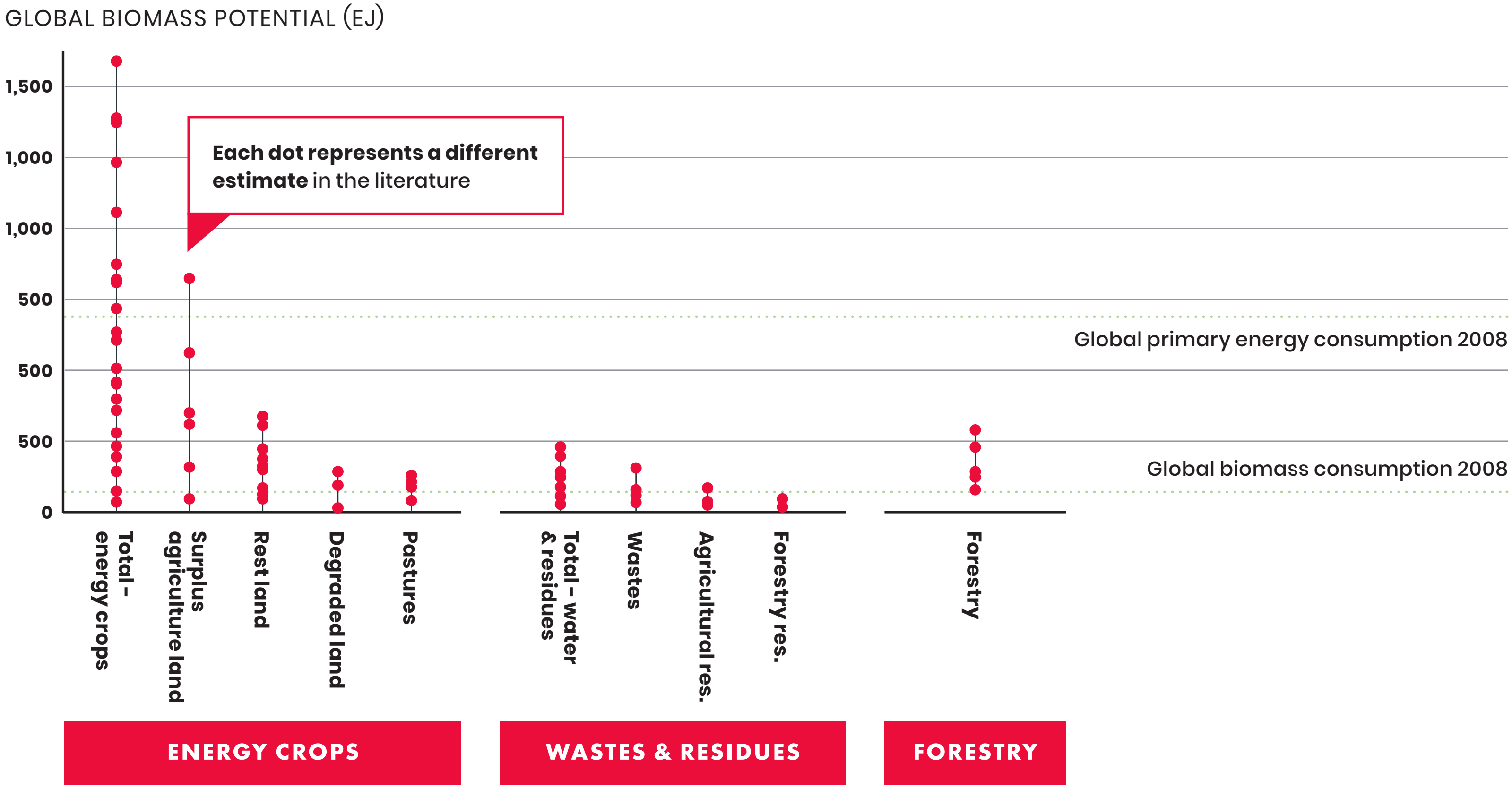
Biomass that can be sourced sustainably from carbon-neutral sources, as defined later in this section, is a potential low-carbon heating solution for the textile industry. Key properties of biomass as a fuel include an ability to produce heat at temperatures up to 1,950°C and a high heat flux, making it an ideal fuel source for heating in industry. Biomass is currently produced from three major feedstock categories. In increasing order of usage, these are:

- **Energy crops** - plants grown specifically for the ability to generate large amounts of biomass. Some examples of energy crops include woody crops such as willow, poplar, and eucalyptus, which are grown for their wood.
- **Waste biomass** - byproducts from other production categories, such as agricultural production and food and wood processing. This can also include solid waste.
- **Forestry products** - harvesting tree forests.

Figure 6 shows a summary of estimates on the potential for biomass supply from each of the three major feedstock categories, showing that estimates vary substantially but energy crops are the potentially largest category. However, as we will discuss in this section, wastes and residues are likely the only category of feedstock that can be sustainably sourced and carbon neutral.

FIGURE 6: ESTIMATES OF BIOMASS POTENTIAL FROM THREE MAJOR FEEDSTOCK SOURCES

Source: Energy Transitions Commission 2021



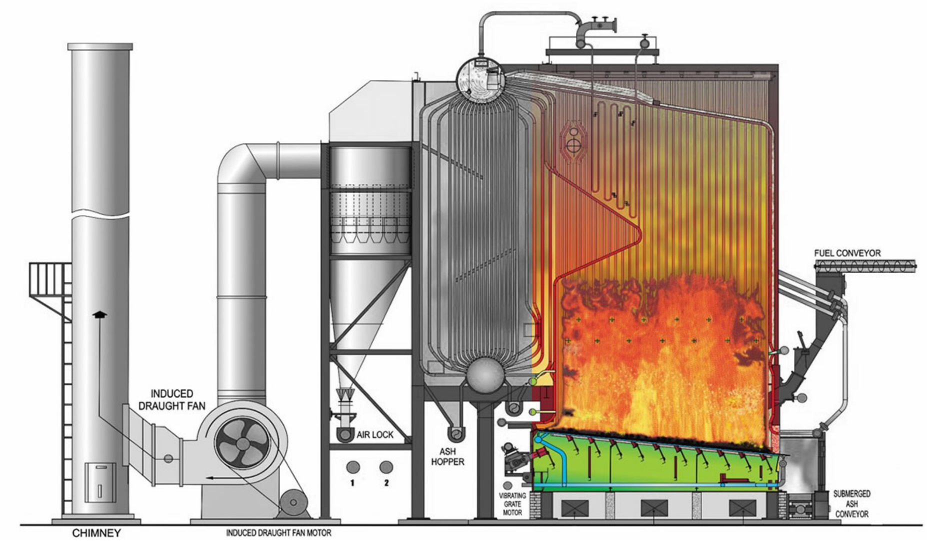
Biofuels refer to liquid fuels derived from biomass, and they are primarily used for the transport sector due to their liquid form. Converting biomass into biofuel uses additional energy, and it has limited to no applications for process heating in the textile industry, as discussed further below.

Biomass use in industry is a mature technology, and it is used widely in many industries for power generation and process heating. It is currently considered the largest source of renewable industrial heating and is heavily used in the food and beverage and pulp and paper industries. In these industries, biomass is used to generate electricity or as fuel for air heaters, boilers, and ovens for a variety of purposes. In the textile industry, biomass use would primarily be for steam boilers and thermal oil boilers.

The primary method of using biomass for industrial heating is through direct combustion in boilers to generate steam. Biomass combustion is currently conducted in two major types of boilers: fluidized bed boilers and fixed bed boilers. Fluidized bed boilers are the most common type of biomass boiler, wherein biomass is burned with a hot bed of sand or other inert particles. An upward flow of combustion air suspends the fuel-particle mix, which exhibits fluid-like properties (Crawford 2012). Fixed bed boilers supply combustion air from below a grate and solid fuels are combusted on the grate with some gasification. Secondary combustion then takes place in a higher chamber (Figure 7).

FIGURE 7: INDUSTRIAL BIOMASS BOILER

Source: Boilermech 2024



As noted above, biomass comes in many forms, with varying energy density, combustion properties, and logistics characteristics, which complicates comparisons with other types of fuels. Given that agricultural residues are likely the most sustainable source of biomass, as discussed below, their residue-to-crop ratio (RCR) is also an important metric for understanding biomass potential. Table 2 from a report by the World Bank draws from a survey study of Vietnam to present the RCR, moisture content, and lower heating value of different agricultural residues, demonstrating their variation even within the same type of residual biomass (World Bank 2018). Some of these residues require further processing to be suitable for use as biomass for energy.

TABLE 2: CHARACTERISTICS OF KEY AGRICULTURAL RESIDUES IN VIETNAM

Source: World Bank 2018

Agricultural Biomass Residue	Residue to Crop Ratio	Moisture Content	Net Calorific Value (MJ/kg residue)
Rice straw	0.33-2.15	12%	12.6
Rice husks	0.15-0.36	10.5%	13
Sugarcane trash	0.05-0.30	25%	12.5
Sugarcane bagasse	0.14-0.40	50%	7.5
Maize waste	1.0-3.8	16%	12.5
Maize cobs	0.2-0.5	17.6%	14.1
Maize husks	0.2-0.4	16%	12.5
Cotton stalks	2.76-4.25	12.5%	15

Sustainable biomass generally refers to biomass that is carbon neutral and does not cause environmental damage when harvested. This is a best-case scenario for biomass, as many if not most sources of this fuel are not in fact carbon neutral. Indeed, wood and wood-derived sources, the dominant biomass fuel in many places, are a less efficient energy carrier than coal, and produce more CO_2 emissions per unit of energy based on IPCC guidelines. Scientific research has shown that in the long term, tree plantations and agroforestry for biomass have less carbon sequestration potential than natural forests that are left undisturbed (Lewis et al. 2019). In addition, tree monocultures for harvesting do not have other ecosystem benefits that natural forests do, such as providing habitat for a wide range of species.

The inclusion of forest biomass in the EU's Renewable Energy Directive has provoked strong opposition to its categorization as a renewable energy source with carbon benefits. Yet most bioenergy used in the EU comes from woody biomass from forests, and over one-third of this is from primary sources rather than waste wood (Robinson 2023).

Another major point of opposition to woody biomass as a renewable energy source is the idea that tree growth compensates for the combustion of the harvested biomass. The re-growth of trees can take between 44 and 104 years to pay back the carbon debt of the initial combustion, calling into question biomass as a near-term or even medium-term mitigation strategy (Sterman et al. 2018). A group of prominent scientists estimated that replacing fossil fuels with wood could lead to 2-3x more emitted carbon per unit of final energy by 2050 (Searchinger et al. 2018). A European Commission study found that of all woody biomass products, only certain types of slash (small branches and twigs) can demonstrate climate benefits within the short term while having a positive or neutral effect on biodiversity and ecosystem condition. All other woody biomass sources pose risks to local ecosystems (such as converting grasslands to plantations), are unlikely to have any carbon benefits (such as removing stumps or converting forests to plantations), or both (Camia et al. 2021).

In addition to definitions by governments and international institutions, there are also many available certifications for sustainable biomass (Table 3). Some are voluntary, while others are mandatory for biomass in their jurisdictions. However, implementation of these certifications has faced challenges, and they should not be considered a panacea for biomass sourcing.

Biofuels are a broad energy category encompassing various liquid fuels derived from biomass. Within this spectrum, some main types of biofuels include biogas/Renewable Natural Gas (RNG), bioethanol, and biodiesel, each serving different applications from heating and power generation to fueling automobiles, with transport being the dominant destination for biofuels. Of these, the only biofuel that might be relevant to the textile industry is biogas/RNG, although it has limited applicability. Biogas/RNG can be produced from several sources including biomass, animal farm waste, food processing by-products, and landfill methane, making its feasibility highly dependent on geographic and local industrial contexts. It requires significant investment and is often utilized on-site by producers like food processing plants due to logistical and economic considerations, limiting its availability for external industries such as the textile industry. Therefore, biogas/RNG has limited potential in contributing to decarbonization of the textile industry.

TABLE 3: KEY VOLUNTARY AND REGULATORY CERTIFICATION SCHEMES THAT CERTIFY BIOMASS Source: Carbon Direct 2023

Title	Voluntary or Regulatory	Status	Date of last update	Geographical scope
Better Biomass	Voluntary	Active	April 12, 2022	Global, based out of Netherlands
Bioenergy Renewable Auction Mechanism (BioRAM)	Regulatory	Active	Sept, 2018	California
Biomass Biofuels voluntary scheme (2BSvs)	Voluntary	Active	June 14, 2022	Global
Green Gold Label (GGL)	Voluntary	Active	May, 2018	Global
International Sustainability and Carbon Certification (ISCC EU)	Voluntary	Active	July, 2023	Global
KZR INig system	Voluntary	Active	Dec 14, 2022	Global, but primarily Poland
Netherlands Programme Sustainable Biomass (NPBS)	Regulatory	Inactive	Last updated in 2013	Netherlands
Responsible Biomass Program	Regulatory	Active	August, 2022	Denmark
Roundtable on Sustainable Biomaterials (RSB)	Voluntary	Active	March 22, 2022	Global
Sustainable Biomass Program (SBP)	Voluntary	Active	June 16, 2023	Global
Sustainable Resources (SURE)	Voluntary	Active	Oct, 2020	Global

2.2 Strengths and Opportunities

Biomass that is sustainably sourced can be considered a carbon-neutral energy source. The carbon-neutral aspect of biomass comes from the growth phase of biomass plants. During the growth phase, plants will naturally sequester CO_2 through photosynthesis, drawing CO_2 from the atmosphere. Carbon neutrality refers to the fact that the burning of biomass, which releases the CO_2 back into the atmosphere, can be balanced by the amount of carbon sequestered by the biomass during its growth phase in a time frame that adheres to climate targets. Sustainable biomass combustion applications can reduce life cycle GHG emissions by up to 90% compared to the fossil fuels alternatives under best case scenarios. Even greater amounts of CO_2 reduction can be achieved with carbon capture and storage (CCS) technologies, referred to as BECCS (bioenergy with carbon capture and storage) or carbon-negative technologies. However, carbon capture and storage technologies are still under development, and face challenges with economic viability and creating infrastructure for CO_2 transport and storage. In the textile industry, it is important to note that the size of waste CO_2 streams of biomass steam boilers is not large enough to make CCS a viable technology.

Another strength of biomass use is the reduction of byproduct waste. When biomass is the byproduct of other industrial processes (e.g. in the food and beverage or pulp and paper industry), it can be a cheap and sustainable fuel source. By using these byproducts for heating purposes, it helps reduce waste materials in the economy. In the textile industry, textile solid wastes consisting of cotton seed and cotton gin trash with high amounts of organic compounds can be converted into bioenergy, potentially contributing to onsite circular economy.

Relative to intermittent wind and solar energy, sustainable biomass is also an attractive clean energy source since it can be supplied continually. Another important factor is that industrial biomass boilers are commercially mature technology that have demonstrated the ability to meet the high temperatures needed for process heating across different industries including the textile industry in various countries.

2.3 Challenges

The main challenge associated with biomass is whether the source of the biomass is sustainable. As discussed previously, claims of carbon neutrality for some sources of biomass are scientifically contested. Plantations for biomass, for instance, has led to massive loss of forest cover and resulting CO_2 emissions. In Southeast Asia, even though byproduct palm kernel husks can be used as a source for biomass fuel, palm oil plantations have historically been one of the largest drivers of deforestation, with massive associated CO_2 emissions due to destruction of tropical rainforest and peatlands. Reduction in forest cover results in a loss of natural CO_2 sequestration, negating any carbon benefits of biomass use. Biomass production is also associated with CO_2 emissions from application of fertilizers, which release large amounts of CO_2 emissions during their production, as well as N_2O, a potent GHG.

There are also concerns that poor land management can lead to trade-offs between agricultural land for food and land for energy crops. That is, if more land is dedicated to growing energy crops there is less land dedicated to food crops, which can lead to food security issues at a local level, particularly in regions with limited resources. Competition with other applications can lead to constrained supply and increased prices, making a switch to biomass less cost-effective for the textile industry.

Unlike natural gas, which can be pumped over long distances through pipelines, biomass has to be collected and transported above ground. The emissions from this transportation lowers the environmental benefits of using biomass. Biomass transportation is usually done through trucks, freight trains, or ships (for international trade), which run on carbon-intensive fossil fuels. The harvesting process of energy crops, often done with large diesel tractors, also generates emissions that are not always considered when calculating CO_2 associated with using biomass. These additional sources of CO_2 emissions along with unsustainable harvesting demonstrate that biomass may not be a true carbon-neutral energy source under ordinary use conditions. It should be noted that according to the Intergovernmental Panel on Climate Change (IPCC), the emissions factor from the combustion of biomass (kg CO_2/GJ) is higher than that of coal.

Aside from CO_2 emissions, biomass combustion also generates other local air pollutants such as volatile organic compounds, NOx, and particulate matter (PM). In addition, the residue ash that is left after burning biomass in industrial boilers and heaters contains multiple toxic elements such as polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and other elements, which raises environmental concerns about ash disposal. This is a major concern especially near populated areas and in countries with weak environmental regulation.

Another issue with biomass heating is the variability of water content in biomass. The higher the moisture content in the biomass, the lower the heating value. Thus, utilizing biomass with high moisture may lead to a lower net-calorific value and lower combustion efficiency.

2.4 Supply and Infrastructure

The biomass supply chain varies depending on the type of feedstock and proximity to the final destination. These processes range from advanced systems to collect and harvest timber and forest residues, to large-scale agricultural harvesting systems, to simple manual firewood collection for traditional usage. However, the timeframe to collect these residues and energy crops is often limited by seasonal weather conditions and can limit the overall amount of biomass generated.

As biomass harvesting often occurs at different locations to the industrial setting, it needs to be transported. A major logistical problem is the fact that base biomass often has a low energy density and irregular shapes, which add complexity and costs to the transportation stage. Biomass generally has a lower energy density compared to fossil fuels, making it more expensive to transport per unit of energy provided. There are many different options for transporting biomass. For short distances (<100km) when flexibility is needed, trucks are ideal for carrying biomass to production sites. For longer overland transport, trains are much more common, and for long distances ships are the cheapest and least energy-consuming transport mode.

The viability of switching from traditional energy sources to biomass in the industrial sector varies significantly depending on the scale of the operation and the industrial density of the region. Smaller-scale operations, such as facilities with small boilers, are better candidates for biomass conversion because they require less biomass fuel and have more manageable storage requirements. These smaller systems can more easily adapt to the logistics and space constraints associated with biomass storage and handling. At larger scales, particularly in densely industrialized areas like industrial parks, the switch to biomass becomes less feasible. Large-scale industrial operations require vast amounts of energy, and thus, a correspondingly large supply of biomass would be needed, which can be logistically challenging and economically unfeasible. Storage requirements for such large quantities of biomass are significant, not only in terms of space but also in maintaining the quality of biomass over time. Moreover, the density of industries in such regions often leads to a competitive demand for limited biomass resources, further complicating the supply chain and escalating costs.

2.5 Cost

The cost of biomass as a fuel can vary widely depending on the type of biomass, supply-demand dynamics within a given market, and proximity to biomass production areas. As such, the cheapest forms of biomass are generally biomass waste by-products used within the same facility or neighboring facilities, as there is no harvesting and collection cost, and minimal transportation is needed.

Biogas is often expensive to produce. For facilities that use their own waste to produce biogas (e.g. food processing facilities), they often utilize the biogas onsite and would be unlikely to supply it others, e.g., a nearby textile plant.

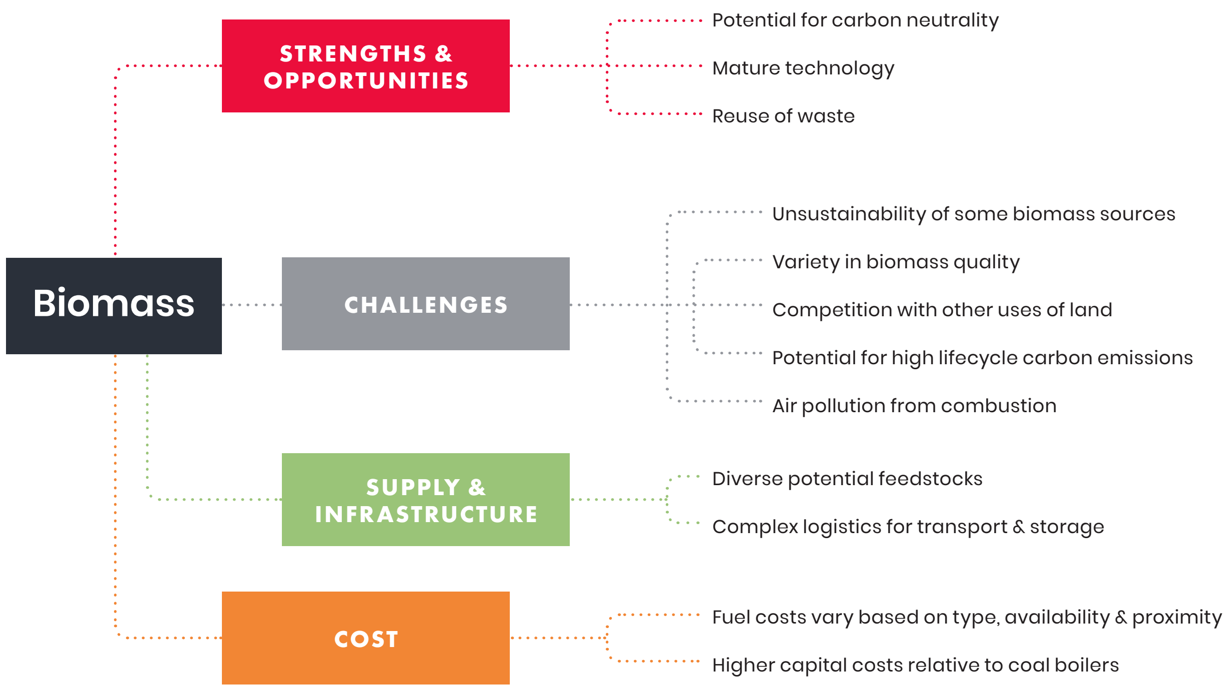
Biomass boilers are expected to be more expensive than new coal-fired boilers in terms of capital costs. Figure 52 in Section 6 shows relative capital costs per unit of capacity for alternative boiler technologies. Biomass boilers are also expected to be more expensive than electric or natural gas boilers.

2.6 Case Study

Many textile facilities in Asia are switching to biomass, including suppliers for H&M, Gap, and Zara. H&M converted a coal-fired boiler to a biomass boiler at a textile facility in Pakistan, sourcing local agricultural residues. Hansae, a supplier for Gap, increased biomass usage at its facilities by 39% in 2020 relative to 2015 as a GHG mitigation strategy, replacing liquid fuel and coal. Hansae uses firewood, sawdust briquettes, wood waste, and rice hulls as biomass sources, describing them as sustainable sources (Hansae 2024). Azgard Nine Ltd, a supplier for Zara (Inditex) based in Pakistan, fully switched to biomass from fossil fuels (Ahmed 2018). Many textile plants in Vietnam, Sri Lanka, Cambodia, and several other Asian textile producing countries are rapidly switching to biomass, which raises serious concern about the sustainability of biomass used given that this recent rapid increase in demand has been driven by international brands' pressure on suppliers to lower their CO_2 emissions in line with brands' climate targets. This is a critical issue that international brands need to address to avoid their climate targets and decarbonization efforts having an opposite effect on climate because of the use of unsustainable biomass by their suppliers in Asia.

Figure 8 summarizes the strengths and opportunities, challenges, supply and infrastructure situation, and cost of biomass boilers for the textile industry.

FIGURE 8: SUMMARY OF BIOMASS BOILER FEATURES FOR THE TEXTILE INDUSTRY



2.7 Biomass Readiness for Major Textile-Producing Countries

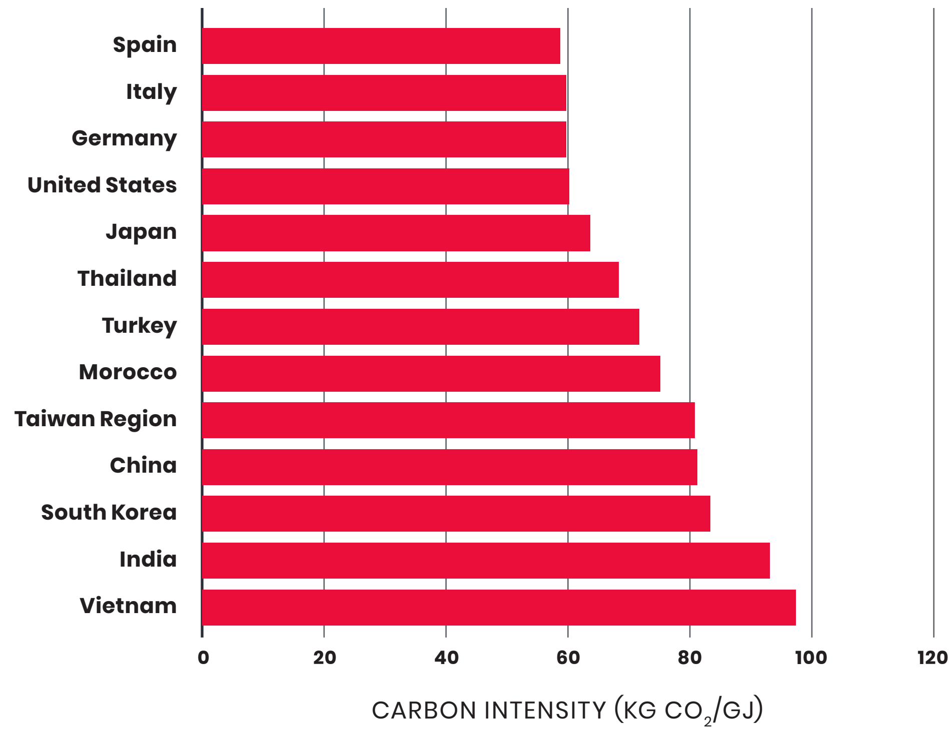
The main concern with biomass for low-carbon thermal energy is whether or not biomass can be sourced from sustainable origins that make it carbon neutral, since its emissions factor from direct combustion is higher than that of coal (Figure 2). A substantial amount of biomass that is currently used is not sustainable and cannot be considered carbon neutral.

Country readiness for switching to biomass-fired boilers in the textile industry in the near term was assessed based on several quantitative metrics: Fuel carbon intensity in the textile industry, availability of agricultural residues, share of biomass in the country's total energy supply, primary forest loss over time, domestic supply chains and infrastructure for biomass, and environmental regulation strength. First, we assessed the fuel carbon intensity of the textile industry in each country (Figure 9). Countries with a higher fuel carbon intensity, such as Vietnam and India, which are also very important global manufacturing centers, could capture greater climate benefits by switching to sustainable biomass. This metric is used across the studied energy sources and technologies. It should be noted that biomass is already used extensively in boilers in the textile industry in some countries, such as Sri Lanka, and this assessment represents the readiness for **additional** adoption of biomass.

The next metric, availability of domestic agricultural residues, is key to sustainable biomass supply. To proxy availability, we assessed the production volume of the top agricultural products whose residues are used for biomass energy – corn, sugar (i.e. bagasse from sugarcane), rice, wheat, palm oil, and cotton – in each of the 20 countries. We then ranked each country for each crop and summed the ranks, creating a final score of agricultural residue availability. India, China, Pakistan, and Turkey were the top four countries in terms of likely availability of agricultural residues. India is a significant producer of all six crops, while China, Turkey, and Pakistan are significant producers of all crops except for palm oil. Indonesia is the top producer of palm oil globally, and ranked fifth for the overall residue availability assessment as it is also a major producer of corn, sugar, and rice.

FIGURE 9: FUEL-WEIGHTED CARBON INTENSITY OF THE TEXTILE INDUSTRY IN TOP TEXTILE-PRODUCING COUNTRIES

Source: GEI analysis of IEA 2022 data



We also assessed the share of biofuels and waste used in a country's total energy supply. This metric is meant to measure existing biomass usage within a given country, indicating that the country might already be fully exploiting available domestic supply. Countries that are already using a substantial amount of biomass are unlikely to be able to sustainably source more biomass supply from agricultural waste, meaning that less supply might be available for the textile industry without requiring additional land-use change or direct use of crops. Data was collected from the International Energy Agency. Countries with the most biomass in their current energy supply include Cambodia, Sri Lanka, and Pakistan

FIGURE 10: SHARE OF BIOMASS AND WASTE IN TOTAL ENERGY SUPPLY OF THE COUNTRY Source: GEI analysis of IEA 2022 data

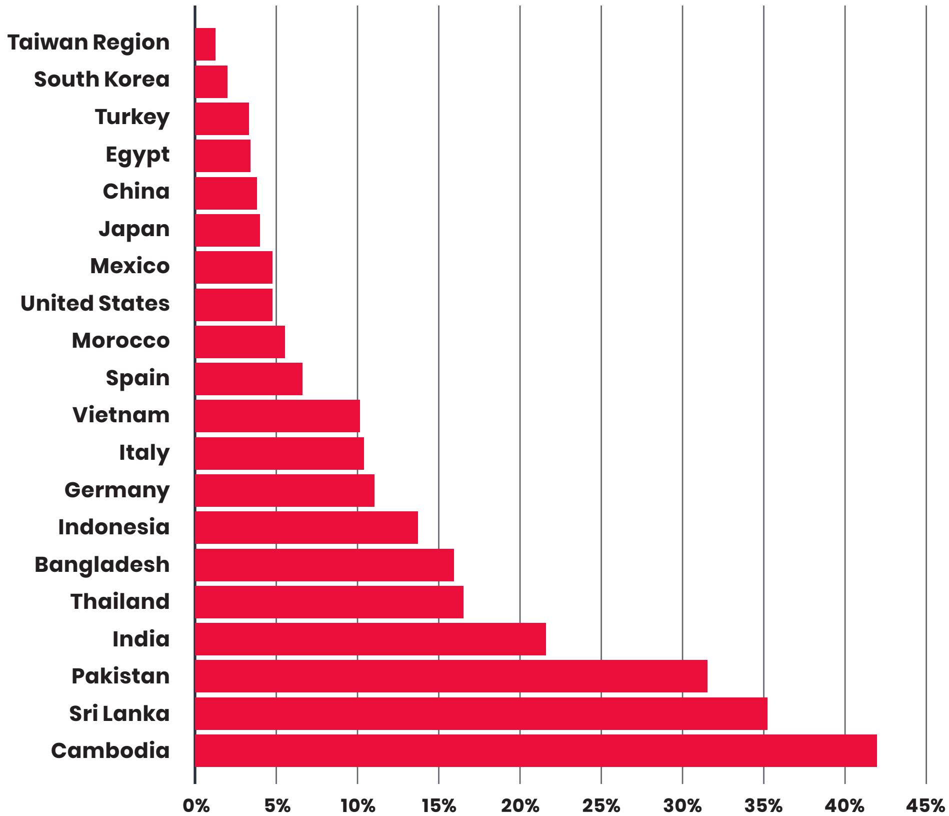
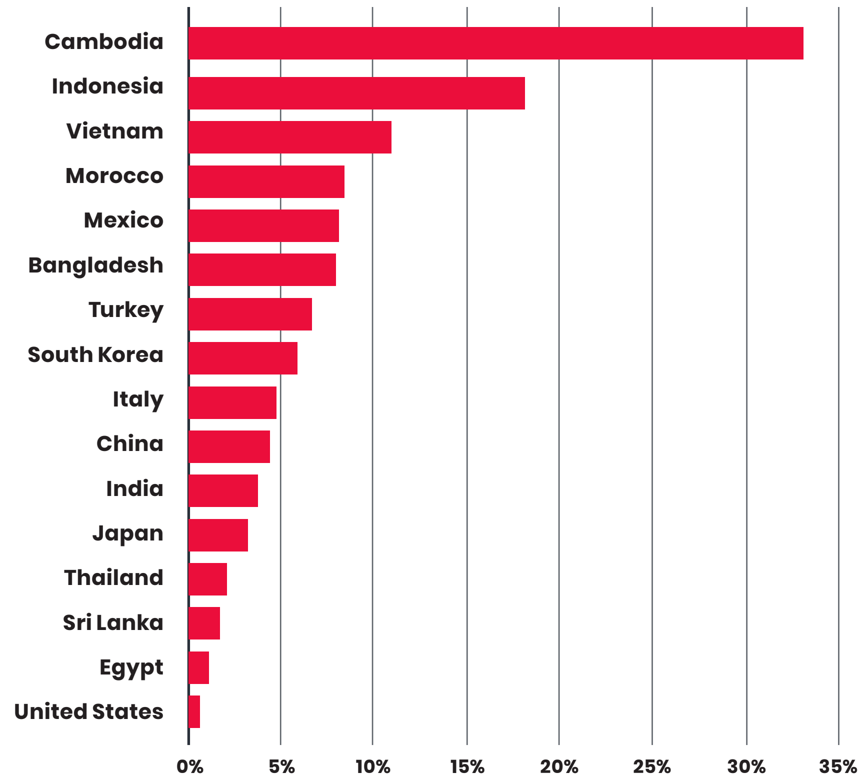


FIGURE 11: PRIMARY FOREST LOSS, 2001-2022 (PERCENT OF PRIMARY FOREST DECREASE) FOR TOP TEXTILE-PRODUCING COUNTRIES WITH AVAILABLE DATA Source: Global Forest Watch 2024



(Figure 10), indicating that meeting demand for biomass in industrial facilities could pose a challenge to sourcing only from waste sources.[4]

In order to understand potential risks of rising biomass demand for the local environment, we also assessed primary forest loss in each country over the past two decades. Primary forest, sometimes called old-growth forest, refers to forests of native species that have not ever been cleared by humans. They are often major biodiversity hotspots and carbon sinks, and harvesting them for direct biomass production or indirectly to expand agricultural land that could be used to meet demand for agricultural residues would significantly decrease any benefits of switching to biomass. The largest driver of tree cover loss is agriculture, including permanent conversion of forests for production of agriculture commodities as well as slash-and-burn practices for more temporary farming (World Resources Institute 2024). The countries with the least primary forest loss are likely able to sustain agriculture and biomass cultivation without harming forests. Among the top five textile producing countries, Vietnam had the highest rate of primary forest loss, followed by Bangladesh (Figure 11).

The last metrics we evaluated were qualitative indicators. The first qualitative indicator is the general, country-level availability of domestic supply chains and infrastructure for delivering biomass. We evaluated the existence and efficiency of supply chains for collecting, processing, and transporting biomass in each country. This included the availability

4 It is important to note that a portion of biomass use in low- and middle-income countries is traditional biomass use, such as collecting wood for cookstoves, rather than industrial-scale use.

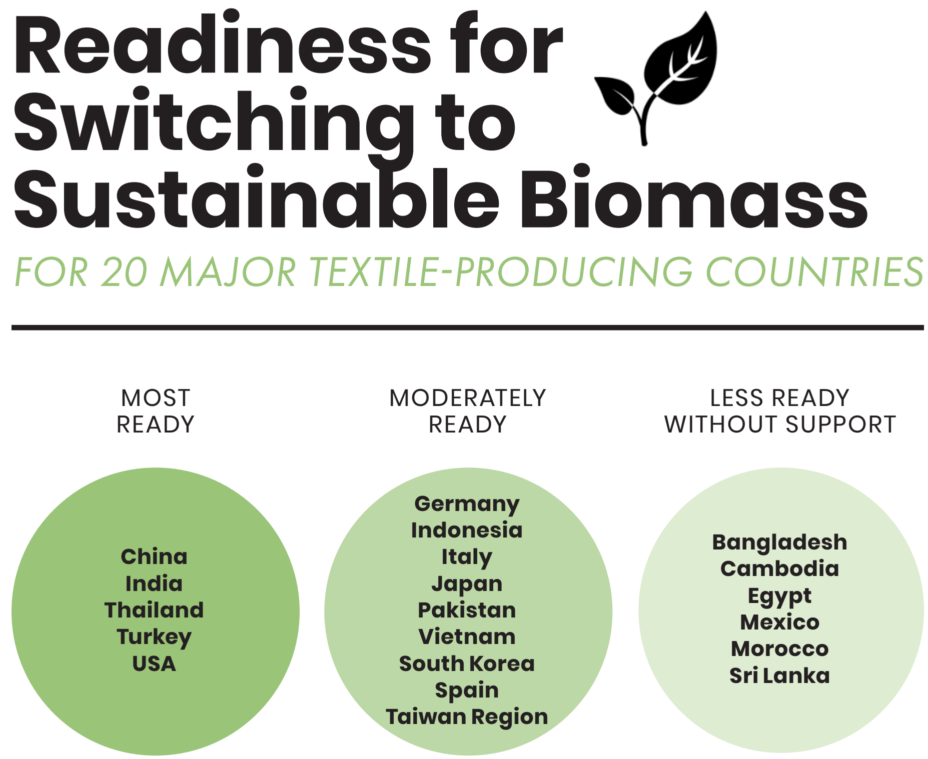
of logistics infrastructure like roads, ports, and storage facilities, which are necessary to deliver a constant biomass supply. Next, we evaluated the strength of environmental regulations in each country. Countries without adequate protections for forests and other areas where biomass might be sourced are at risk for producing biomass unsustainably if demand increases. On the other hand, in countries with stronger laws, sustainable biomass can be an important low-carbon fuel source. It is important to note that these are country-level generalizations and facility-level supply and availability can vary greatly within a single country.

We combined the aforementioned metrics by ranking each country and creating an overall composite readiness score, where a higher score indicates more readiness for switching to biomass in the textile industry in the near term as an alternative to currently used fossil fuels. Figure 12 below categorizes countries based on their readiness for switching to sustainable biomass based on percentiles for their readiness scores. China and India stand out as the most important "most ready" countries, given their status as the top two global textile manufacturers. Thailand, Turkey, and the US also might be most ready to potentially supply sustainable and carbon-neutral biomass to the textile industry in the near term, while the countries listed as "Less Ready Without Support" would require additional financial and regulatory support to adopt sustainable biomass. This readiness evaluation is focused just on biomass readiness and does not look at whether biomass is the best alternative for any of the "most ready" countries compared to the other alternatives described in this report.

The top five textile-producing countries (China, India, Vietnam, Bangladesh, and Germany) vary in their potential readiness for sustainable biomass adoption in the textile industry. China, as the world's largest agricultural producer, also generates a significant amount of agricultural residues. Wood waste (such as furniture and pallet waste) is the dominant source of biomass fuel for the textile industry in China (BEIPA 2024). China has increasingly strong environmental regulations; however, enforcement at the local level tends to pose challenges.

India is also one of the world's top agricultural producers, and a major producer of all crops that are major biomass sources, as discussed above. India already has a fairly high share of biomass and waste used in its total energy supply, indicating that expanding biomass supply from waste sources for the textile industry may be competing with existing demand.

FIGURE 12: READINESS FOR SWITCHING TO SUSTAINABLE BIOMASS FOR 20 MAJOR TEXTILE-PRODUCING COUNTRIES



China, India, and Vietnam all likely have significant agricultural residue sources for biomass, and they have high fuel carbon intensity for the fuel used in their textile industry, indicating that switching to low-carbon biomass could yield large GHG emissions reductions. However, environmental regulations are not always strong, indicating a risk of sourcing from unsustainable sources if demand for biomass were to increase. In addition, Vietnam has experienced significant primary forest loss over the last two decades, creating concerns about the association of biomass sources with deforestation.

The other two of the top five textile producers, Bangladesh and Germany, have less carbon-intensive fuel mixes in their textile sectors, relying in large part on natural gas. Therefore, fuel switching to biomass could significantly increase emissions from heating in the textile industry if the biomass is not carbon neutral. In addition, both countries face constraints in the supply of sustainable biomass sources. Germany is not a major agricultural producer.

In Bangladesh, there is not a formal system for industrial facilities to source biomass, leading to sustainability risks. There is a ban on extracting forest products from government forests in Bangladesh, but not village-level forests. Farmers are likely to use agricultural residues for higher-value purposes, such as livestock feed or bedding, or building materials, limiting the total amount of residues available. In addition, the vast majority of biomass in Bangladesh is used for traditional cooking, and the diversion of this biomass to other sources would require a simultaneous transition to clean cookstoves. Rice husks in Bangladesh fluctuate seasonally in their availability, leading to higher costs for industrial facilities relative to natural gas (Butt 2022).

3. Solar Thermal as an Alternative Low-Carbon Energy Source for the Textile Industry

Solar energy is clean, abundant, and increasingly cost-effective. Two main technologies to harvest solar energy are solar photovoltaics (PV) to generate electricity and solar thermal technology to generate heat. The focus of this section is solar thermal technology and its application for industrial heating (as opposed to solar PV for direct electricity provision).

Currently, solar thermal technologies account for less than 1% of global heat demand (IEA 2022). Solar thermal heating can contribute to decarbonizing thermal heat generation. However, solar thermal faces fundamental issues with suitability for steam production, limited geographical suitability, and relatively large infrastructure needs.

3.1 Description of Technology

There are two major categories of solar thermal technologies: non-concentrating (flat plate, evacuated tube, integral collector storage, thermosiphon collector) and concentrating (parabolic trough, parabolic dish, power tower, linear Fresnel). The primary technological difference between the two categories is the temperatures they can achieve. Non-concentrating solar thermal can provide heat up to 100°C while concentrating solar thermal can deliver up to 1,200°C.

Non-concentrating solar thermal collectors, specifically flat-plate collectors (FPC) and evacuated tube collectors (ETC), are mature technologies used in harnessing solar energy for heating purposes. In FPCs, sunlight is absorbed by a dark surface and heat is transferred to tubes that circulate a heat transfer fluid within an insulated enclosure to minimize heat loss (Rissman 2024). These collectors are efficient at temperatures of up to 100°C. ETCs consist of rows of glass tubes, each enclosing a heat pipe collector with a heat transfer fluid in a vacuum, significantly reducing heat losses. ETCs are capable of reaching temperatures up to 120°C.

FPC and ETC technologies are well-established and have two main applications that could work in the textile industry. First, they can be used

FIGURE 13: SOLAR THERMAL DIRECTLY HEATING THE WATER USED IN THE INDUSTRIAL PROCESS IRENA 2023

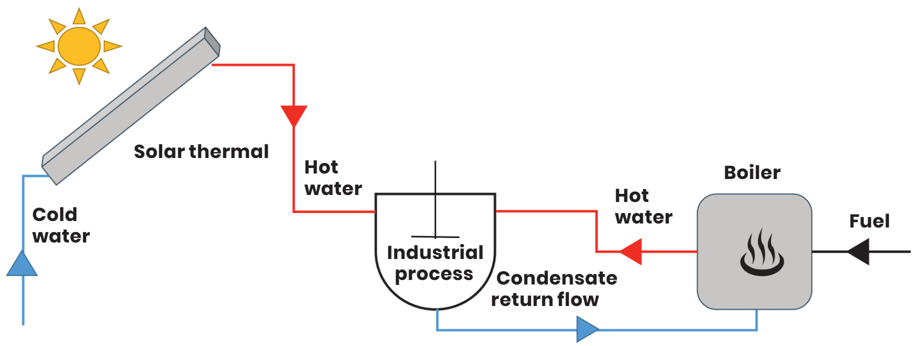
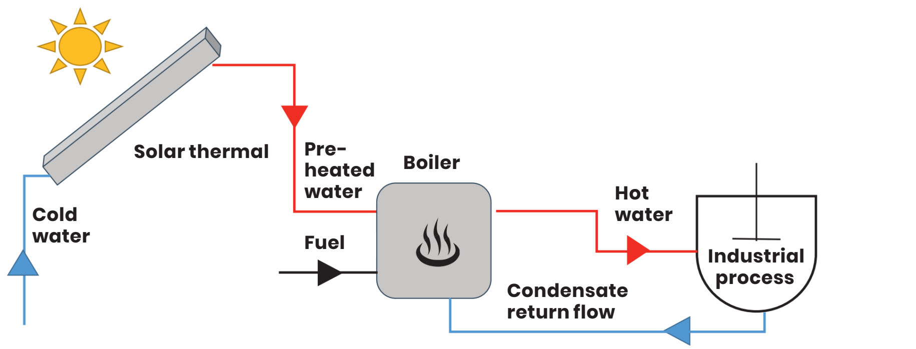


FIGURE 14: SOLAR THERMAL ENERGY USED TO PRE-HEAT BOILER'S FEED WATER IRENA 2023



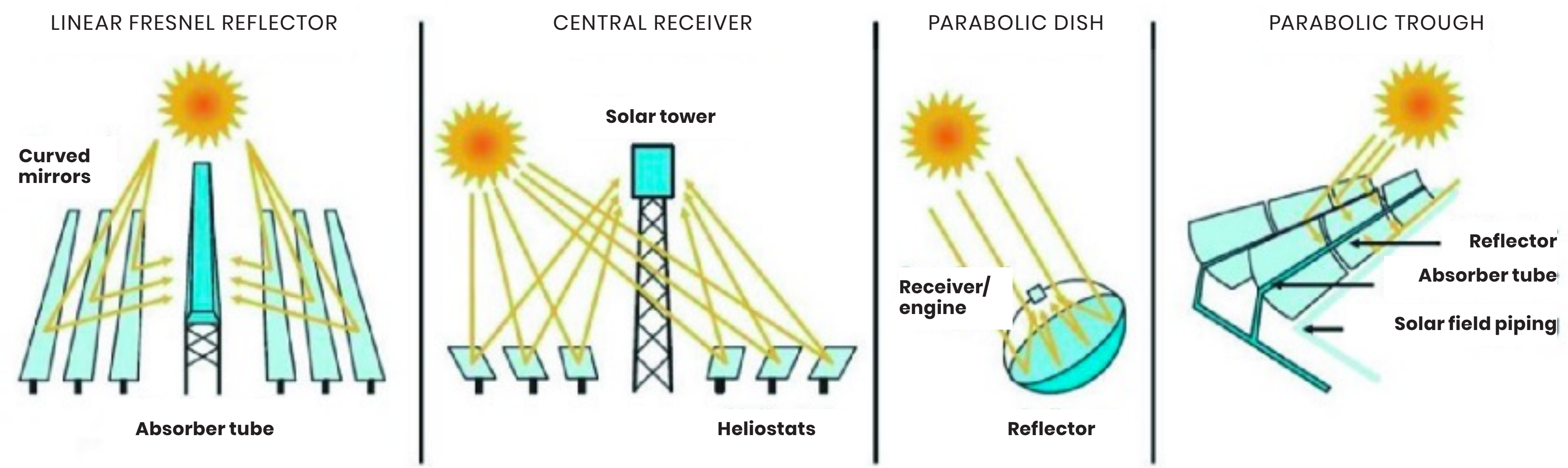
to directly heat circulating fluids such as water (Figure 13). In this case, it is essential to pair solar thermal heating with storage systems to ensure heating during non-production times. Second, solar thermal technologies can help pre-heat water to be used in steam boilers (Figure 14). However, neither of these applications is suitable for steam production, which is crucial for textile manufacturing.

Concentrated solar technology (CST) is a technology that involves mirrors and lenses to focus solar radiation on one area, usually a tube filled with some form of fluid such as oil, molten salt, or any other heat-retaining fluid, which then heats water in a heat exchanger. The heated water can reach practical temperatures of 400°C, with a theoretical limit of 1200°C. There are multiple configurations of CST that can provide varying outputs of thermal energy (Figure 15).

Other CST technologies, including linear Fresnel reflectors, parabolic dishes, and parabolic troughs, vary in whether the mirrors or reflectors can track along single or multiple axes, and if the mirrors are curved (Rissman 2024).

FIGURE 15: DEMONSTRATION OF VARIOUS CONFIGURATIONS OF CONCENTRATED SOLAR TECHNOLOGY

HVAC-Eng 2023



3.2 Strength and Opportunities

The adaptability of solar thermal systems, including both non-concentrating and concentrating technologies, can allow for unique configurations that could align with some thermal demands of the textile industry. The largest potential advantage of solar thermal technology is its ability to provide zero-emissions heating. The transition towards solar thermal heating can also facilitate compliance with increasingly stringent environmental regulations. In addition, there are no fuel costs associated with solar energy. With strengthening climate policy and available financial incentives, the economic viability of solar thermal systems is increasing.

Solar thermal energy can also address energy security concerns for a specific country and/or site by diversifying energy sources and reducing reliance on imported fossil fuels. It offers a renewable heat source, mitigating the risks associated with fuel price volatility and supply disruptions.

Another significant advantage of solar thermal technology is its maturity, ensuring a zero-carbon heat source that can integrate with existing manufacturing operations. Solar thermal storage technologies for industrial heat are also emerging and offer the potential to store excess solar heat, which can then be used to support heating required for various textile processes outside of sunlight hours. Current research and development efforts aim to lower costs and increase the durability of storage materials, making solar thermal energy a more viable option for a wide range of applications.

3.3 Challenges

While solar thermal technology presents a potential zero-carbon alternative for the textile industry, several challenges and barriers hinder its widespread adoption. The key challenge for solar thermal technology is that it is less suitable for producing steam for industrial applications and it commonly only produces hot water for industries. However, textile processes often use steam to deliver heat and maintain temperatures at a certain level. To produce steam in the temperature range needed for the textile industry, only 10% of energy use is to bring the water up to 100°C, while the remaining 90% is used to turn water into steam (vaporization). Therefore, if using solar thermal to pre-heat water that is then used in conventional boilers to produce steam, only up to 10% of total fuel use can be saved. Thus, relative to other technologies, solar thermal on its own is not an effective way to reduce energy use and emissions in the textile industry. There may be some cases in which hot water for washing could be readily provided by solar thermal technology, but overall this is not a significant route for fuel savings.

Initial capital investment and the cost of technology integration remain significant obstacles, as the upfront expenses for solar thermal systems and necessary infrastructural modifications can be substantial. The textile industry would need relatively large solar thermal systems co-located with the production facility, posing issues for space and infrastructure modification.

Resource limitations, particularly in regions with variable solar irradiation across seasons and years, can affect the consistency of heat supply, necessitating robust storage solutions or hybrid systems to ensure uninterrupted process heat. Solar thermal systems can be paired with energy storage systems to reduce the variability and ensure energy flow throughout the day, however, doing so further increases costs and infrastructure requirements. In addition, the manufacturing schedule of plants using solar thermal heating must also be aligned with local resource availability and timing throughout the year, with more resources available during sunny summer months, and less in winter months, for example. Overall, solar thermal systems perform best in areas with strong sunlight of a long duration, limiting its geographical availability.

The lack of awareness and technical expertise among stakeholders in the textile industry further slows the adoption rate, as does the competition from established, conventional energy sources that currently benefit from more developed supply chains and infrastructure. Many facilities are unfamiliar with how to operate, maintain, and repair solar thermal systems.

Moreover, solar thermal has to compete with photovoltaic systems, which are far more cost-effective and are increasingly being installed around the world for electricity generation. While solar thermal systems are efficient for direct heat generation, their installation and maintenance costs can be higher compared to PV systems. Additionally, PV systems often require less space per unit of energy generated. Solar thermal installations, on the other hand, may need more extensive and sometimes more complex setups, particularly when targeting higher temperatures, which can limit their applicability in space-constrained areas. This juxtaposition of cost, space requirements, and the versatility of electricity use make PV systems a more favorable choice for industrial facilities in many scenarios. Onsite generation of renewable electricity could then be used to power electrified technologies (see Chapter 4).

3.4 Supply and Infrastructure

The supply chain for solar thermal technology is characterized by a variety of components, including solar reflectors and receivers, storage systems, heat transfer fluids, and control systems. The global market for these components is growing, supported by manufacturers in Europe, North America, and a few Asian manufacturing countries (e.g. China and India). However, the concentration of expertise and manufacturing capabilities in certain regions can influence the availability and cost of solar thermal technology for countries around the world. The specialized nature of some solar thermal technologies means that accessing the most advanced systems might require engaging with a limited number of suppliers, potentially affecting project lead times and costs.

Implementing solar thermal technology in industrial settings, such as textile manufacturing plants, involves several infrastructure considerations. First, adequate space is essential for the installation of solar collectors. Facilities must evaluate their available roof, ground, or adjacent land space to accommodate these systems. It may be difficult for facilities in urban areas or next to developed land to acquire the space necessary for solar thermal installations, especially in countries already facing competing uses for land.

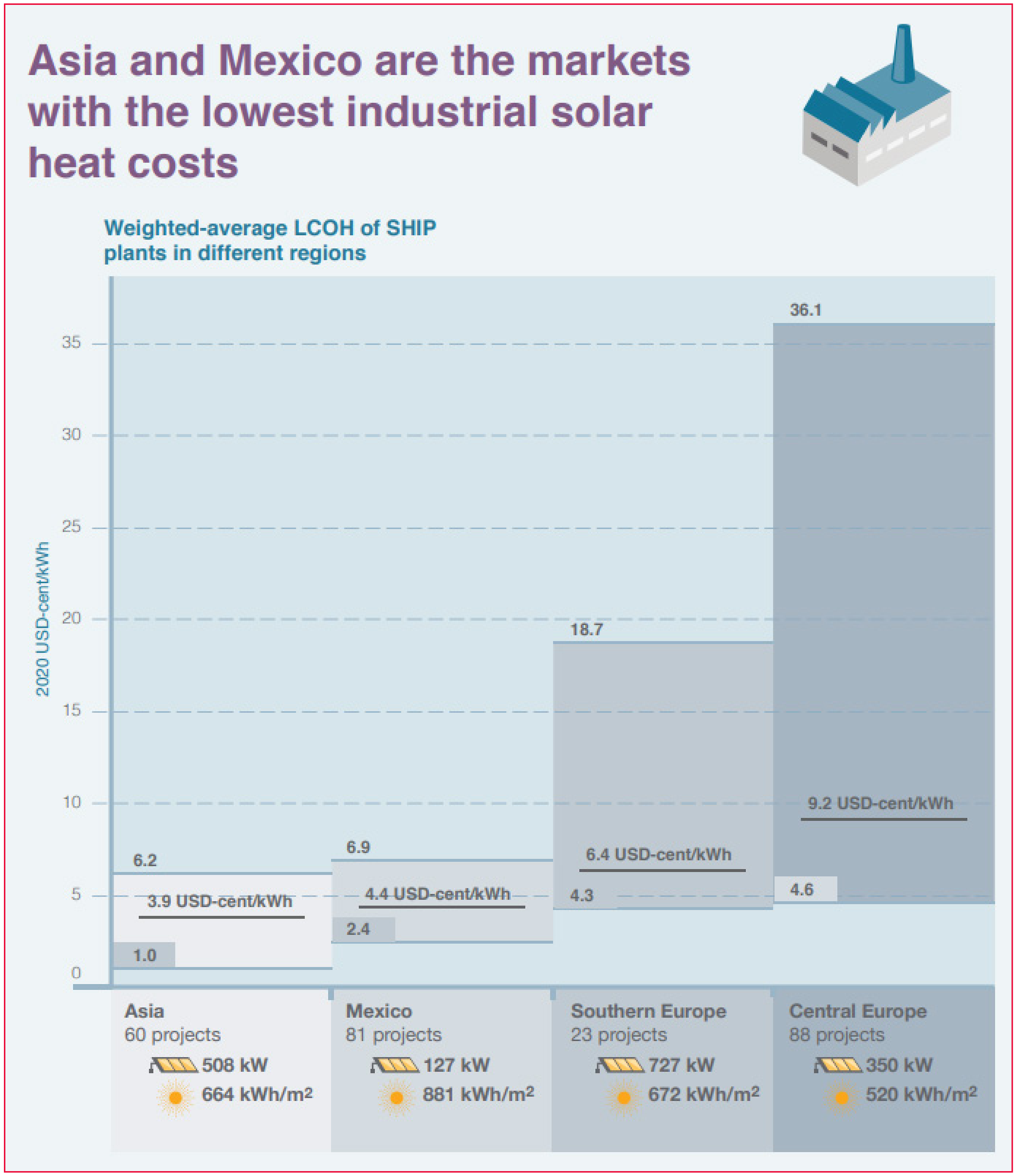
Next, the solar thermal technology must also be integrated with existing heating systems. For facilities not directly adjacent to the solar thermal installation, transmission infrastructure to transport the heat will be needed. This can include insulated piping for hot fluids, which must be designed to minimize heat losses. For manufacturers with thin margins and tight production schedules, the downtime required to install a solar thermal system may be a significant barrier to adoption (McMillan et al. 2021).

To address the intermittent nature of solar energy, incorporating thermal storage systems is often necessary. This ensures a consistent supply of process heat, even during non-sunny periods. The infrastructure for such storage solutions must be planned and built, taking into account the space available and the thermal demand patterns of the facility.

3.5 Costs

FIGURE 16: AVERAGE COST OF SOLAR THERMAL PROJECTS FROM AROUND THE WORLD
Source: Solrico/IRENA, 2022

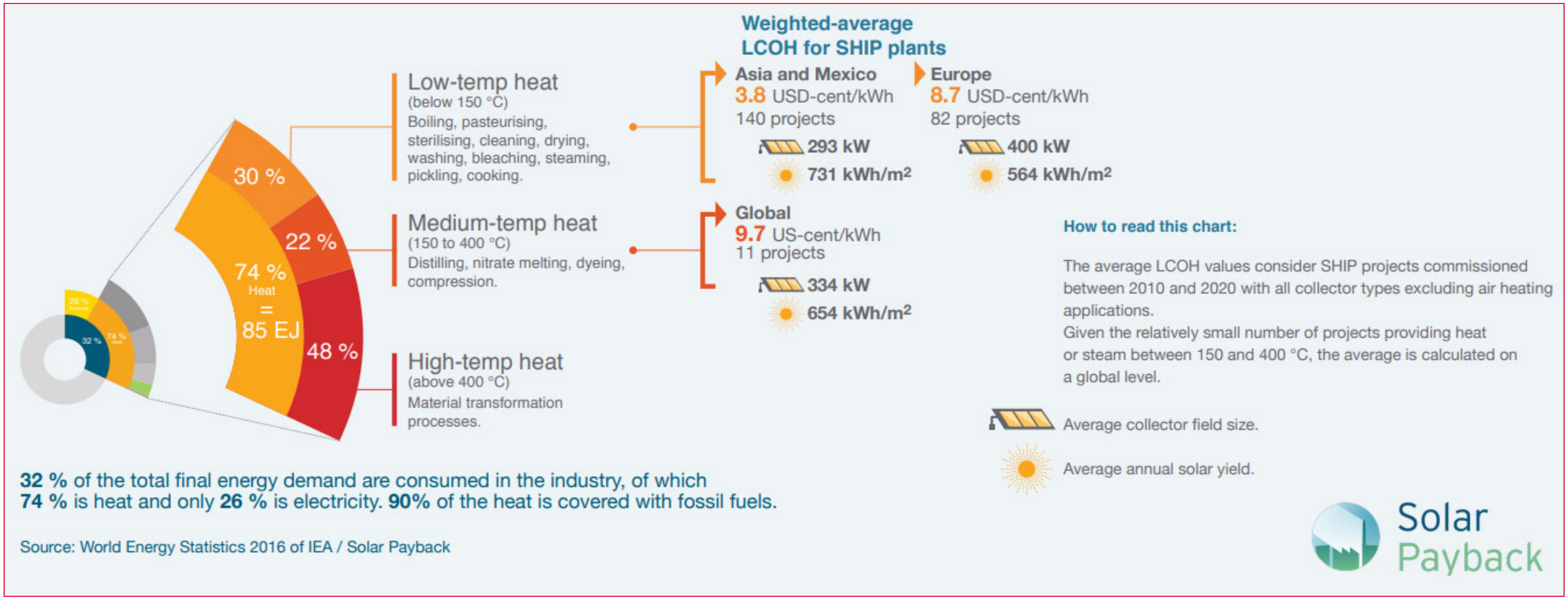
Note: SHIP = solar heat for industrial processes



Solar thermal has seen a decline in costs facilitated by advancements in the competitive supply chain, enhanced developer experience, and the realization of economies of scale. Furthermore, the integration of storage solutions into solar thermal systems has become increasingly common, aiming to match heat supply with demand across varying periods. These developments have collectively contributed to improving the economic feasibility and operational efficiency of solar thermal technology. Figures 16 and 17 show the regions with the lowest industrial solar heat costs.

FIGURE 17: COST OF LOW-MEDIUM TEMPERATURE SOLAR HEAT FOR SELECT COUNTRIES Solrico/IRENA, 2022

Note: SHIP = solar heat for industrial processes



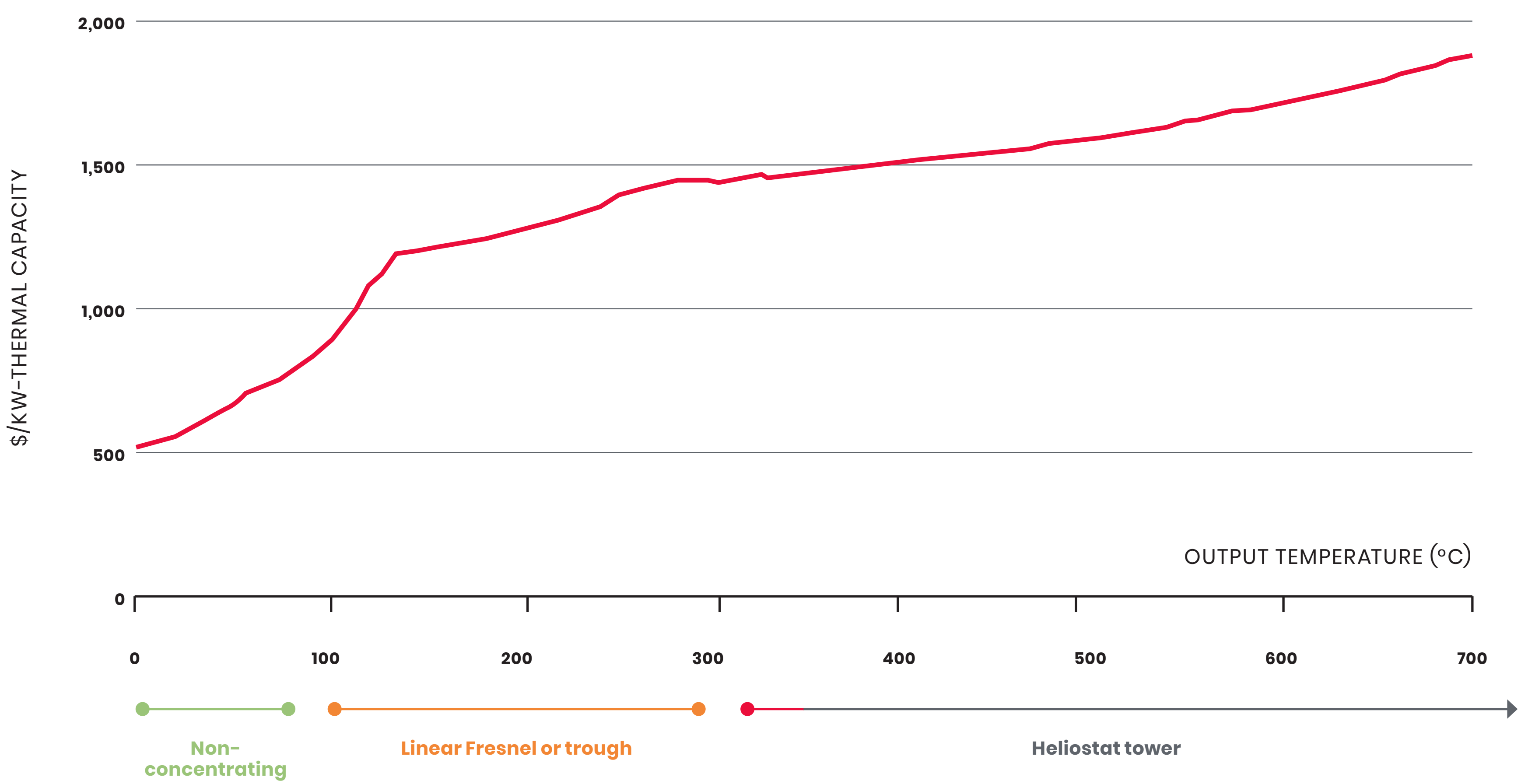
Two key determinants of solar thermal capital costs are the technology type and the output temperature. Higher temperature output necessitates more advanced technologies and thus more expensive materials and system components. Figure 18 shows capital costs per unit of thermal capacity, showing how capital costs increase for technologies that can provide higher output temperature.

Most of the total costs of solar thermal technology are attributed to capital expenses, with the remainder allocated to installation and integration efforts. Most of the upfront capital cost is tied to the price of the collector, which can account for up to 75% of the total installed cost.

Overall economic viability of solar thermal technologies also depends on local solar resources, land availability, proximity to the heat end-user, and the ambient temperature of the location. The viability of solar thermal for textile production is thus highly site-specific.

FIGURE 18: CAPITAL COSTS PER UNIT OF THERMAL CAPACITY FOR VARIOUS SOLAR THERMAL TECHNOLOGIES

Source: IRENA 2023



3.6 Case Study

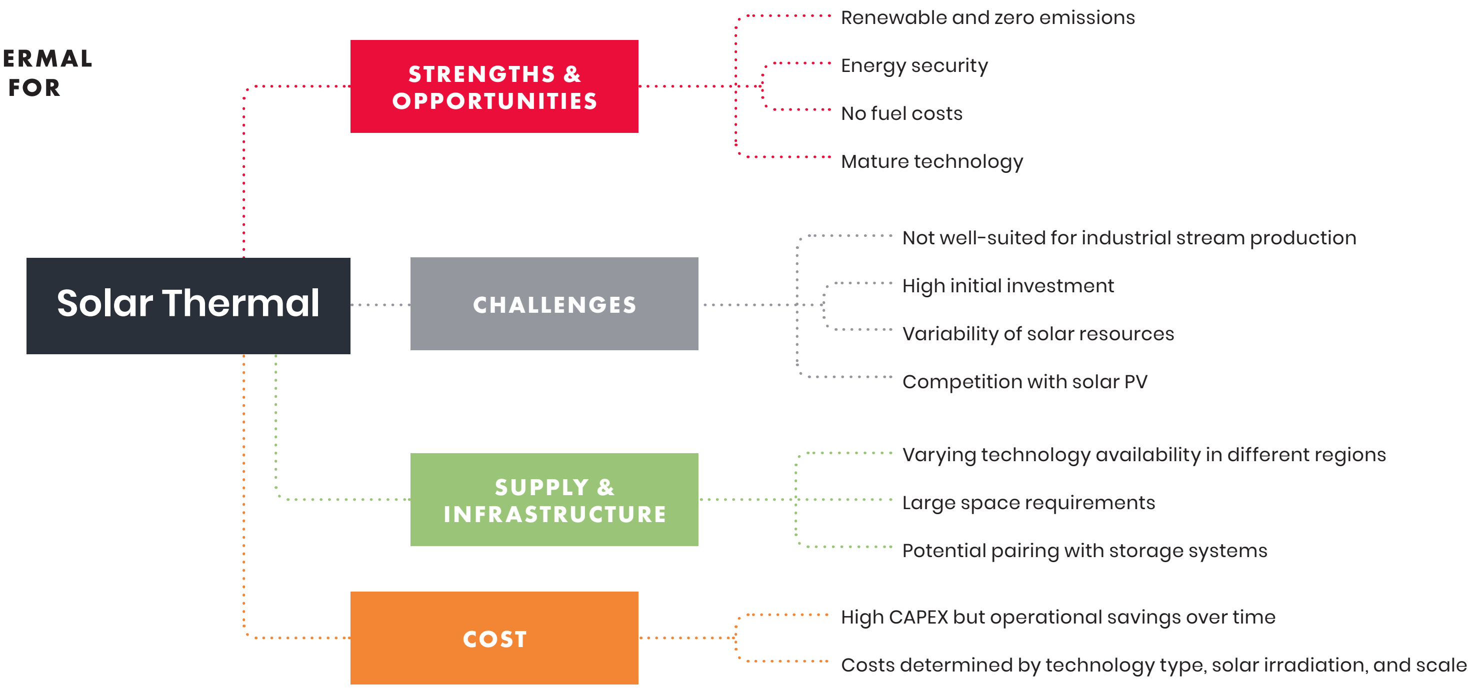
We could not find a commercial application of solar thermal technology in a textile facility. However, there are various applications in other industries such as the food and beverage industry. Like the textile industry, the food and beverage industry also requires relatively low-temperature process heat.

A flat plate collector solar thermal system was installed at the Barrington Brewery & Restaurant in Massachusetts. The brewery was the first establishment of its kind on the U.S. East Coast to use solar thermal for hot water supply, both for brewing and restaurant operations. Initially outfitted with 15 collectors, the system's success led to an expansion to 30 collectors. A 1,500-gallon tank stores the solar energy, ensuring a consistent supply of hot water by preheating incoming cold water. The project reported yearly savings on energy costs and a reduction in CO_2 emissions by substituting conventional fuels with solar thermal energy (Stiebel Eltron 2023).

The multinational brewer Carlsberg partnered with manufacturer Absolicon to pilot solar thermal technology at their Olympic Brewery site in Salonika, Greece. The parabolic trough solar collectors can meet up to 70% of the energy required for can pasteurization during peak sunny months. The installation is expected to help Carlsberg reduce 70 tonnes of CO_2 per year (Absolicon 2024). However, manufacturers working in one industry may be reluctant to develop applications in other industries, such as the textile industry.

Figure 19 summarizes the strengths and opportunities, challenges, supply and infrastructure situation, and cost of solar thermal technology for the textile industry.

FIGURE 19:
SUMMARY OF SOLAR THERMAL TECHNOLOGY FEATURES FOR THE TEXTILE INDUSTRY



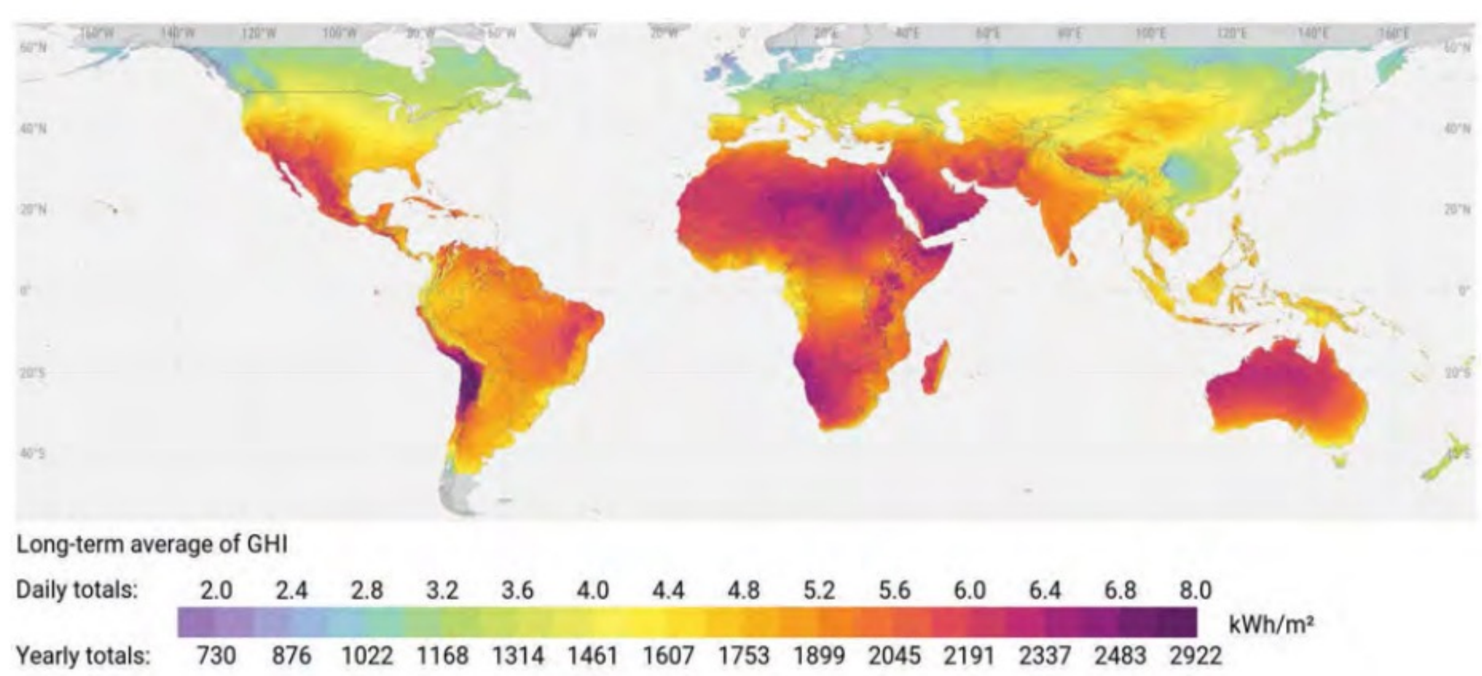
3.7 Solar Thermal Readiness for Major Textile-Producing Countries

To assess readiness to adopt solar thermal technologies for process heating in the textile industry, we examined the following metrics for each country: availability of solar resources, the average carbon intensity of fuel used in the textile industry, climate ambition in the country, and solar thermal technology availability. Solar resources were assessed based on global horizontal irradiation, which is the sum of direct and diffuse irradiation components received by a horizontal surface, measured in kWh/m2 (World Bank Energy Sector Management Assistance Program 2020). Figure 20 displays global horizontal irradiation by country. Among the top textile-producing countries, Egypt, Mexico, Morocco, and Pakistan have the greatest solar resources. There are some countries in which solar thermal would likely not be viable, namely Germany, Japan, and South Korea. Other countries with large land areas, like China, might only have viable levels of solar irradiation in certain regions, which might not be aligned with where textile production is located.

In addition, we also characterized the strength of climate policy within each country by using the Climate Action Tracker's assessment of each country's Nationally Determined Contribution under the Paris Agreement on Climate Change. The Climate Action Tracker assigns a rating such as "highly insufficient," referring to how close a country's policies would bring emissions in line with Paris Agreement targets. We changed these ratings to a quantitative Likert Scale-type score. The countries with higher scores we deemed more likely to have supporting policies and incentives for a wide range of renewable energy development, including technologies like solar thermal. Morocco had the most sufficient score from the Climate Action Tracker, while several countries ranked next best: Japan, the US, Spain, Italy, and Germany (Figure 21). It is important to note that the most ambitious countries in terms of climate policy also have less textile production relative to other countries analyzed.

FIGURE 20: GLOBAL HORIZONTAL IRRADIATION LONG-TERM YEARLY AVERAGE

Source: World Bank ESMAP 2020



Finally, we qualitatively estimated technology supply chain availability in each country. Solar thermal technology supply chains might be less mature in some textile-producing countries on our list. We combined the aforementioned metrics by ranking each country and creating an overall composite readiness score, where a higher score indicates more readiness for adopting solar thermal heating in the textile industry. Figure 22 below categorizes countries based on their readiness for switching to solar thermal technologies based on percentiles for their readiness scores. China, India, Italy, Morocco, South Korea, Spain, and the US might be most ready to potentially adopt solar thermal technologies in the textile industry in the near term, while the countries listed as "Less Ready Without Support" would require additional financial and regulatory support to adopt solar thermal.

For the top textile-producing countries, solar thermal readiness varies significantly. China has some regions with high solar irradiation, but there is also significant competition with solar PV as China is the world's leading manufacturer and installer of solar PV energy. India has significant solar irradiation that could generally support solar thermal systems, however, solar thermal technology for industrial heating may not be readily available in India, and facilities face significant land constraints.

While Germany has strong climate policy and mature technology supply chains, solar resources are the lowest of the 20 countries studied, making it unlikely that Germany could sustain large-scale adoption of solar thermal for heating in the textile industry.

Finally, Bangladesh and Vietnam both have moderate solar resources, but technology availability and onsite space constraints are significant challenges. Therefore, of these top 5 textile producing countries, China could be the most ready to adopt solar thermal technologies for heating the textile industry. However, as explained above, solar thermal faces fundamental challenges as an energy source for high-temperature heat and steam generation for the textile industry, and should only be considered in highly specific cases.

FIGURE 21: CATEGORIZATION OF CLIMATE POLICY IN 20 MAJOR TEXTILE-PRODUCING COUNTRIES Source: Climate Action Tracker 2024

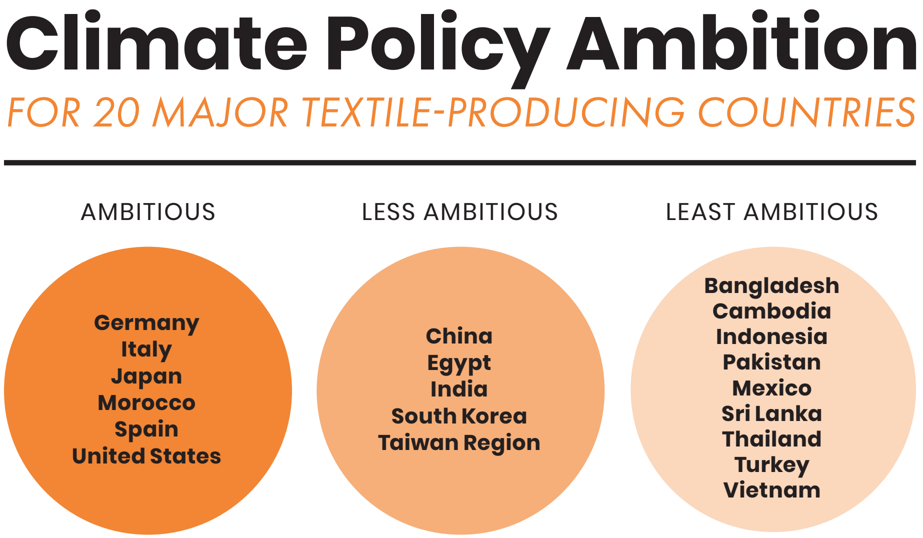
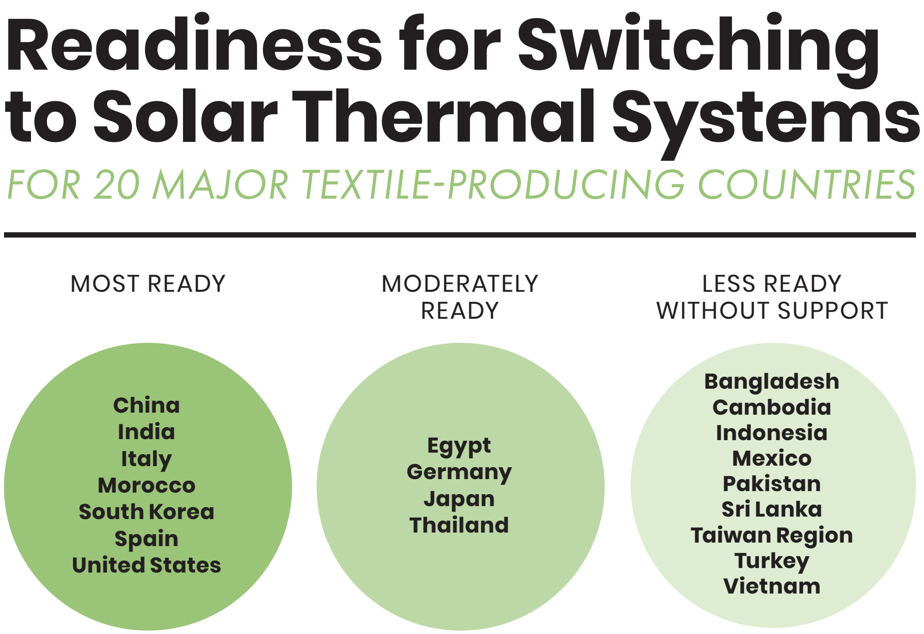


FIGURE 22: READINESS FOR SWITCHING TO SOLAR THERMAL SYSTEMS FOR 20 MAJOR TEXTILE-PRODUCING COUNTRIES



4. Electrification Technologies as an Alternative Technology for the Textile Industry

This section analyzes three key electrification technologies that can provide heating for the textile industry: electric boilers, industrial heat pumps, and thermal energy storage. These technologies can produce hot water and steam at temperatures necessary for textile production. There are additional direct electrification technologies for specific end-use processes in industry; however, they are not considered in this analysis.

4.1 Electric Boilers

Regardless of the energy source they use, industrial boilers heat water or convert water into steam to deliver energy for processes such as regulating temperatures and pressures, drying, separation, and more. Boilers can consume a significant amount of energy in the manufacturing industry, with a typical share of around 50% in most countries outside of the U.S. In many textile-producing countries in Asia, coal is burned to power boilers due to resource availability. Some industries, including the textile industry and others that require relatively low-temperature process heating, have a high share of combustion boiler energy demand in total fuel demand.

The heat from electric boilers can be used for steam generation and hot water production for industrial processes. Transitioning to electric boilers can significantly reduce CO_2 emissions, especially when the electricity is sourced from renewables. Electric boilers also offer advantages like reduced air pollution, quicker ramp-up times, and overall efficiency gains (up to 99% efficiency). Electric boilers still occupy only a small market share, mainly due to economic barriers and the higher cost of electricity compared to conventional fuels, regardless of whether the electricity comes from renewable sources or not.

4.1.1 Description of Technology

Electric boilers function either as electric resistance boilers, where an electrically heated element transfers heat to water, or as electrode boilers, where an electric current directly heats the water to produce steam. Electric resistance boilers are made up of an electric-powered resistive element that transfers heat to water, raising its temperature to the desired level. The flow of electric current and the in-turn heating is controlled through a thermostat. Electric resistance boilers typically possess lower thermal capacities (i.e. up to 5 MWe). Electrode boilers are utilized for certain specialized applications that require quick recovery and high thermal outputs. In an electrode boiler, heat is directly generated by the flow of alternating current across three or more electrodes. Electrode boilers have capacities generally ranging between 3 MWe and 70 MWe.

In addition to steam boilers, thermal oil boilers (or thermal fluid heaters or hot oil boilers) can also be electrified. Thermal oil boilers are used for processes where a medium to high-temperature range is required (up to 400°C), avoiding the high pressures that the use of steam would require. In the textile industry, thermal oil boilers are used to provide heat for fabric heat-setting machines (stenters) that require heat above 200°C. Thermal oil boilers have an exchange body through which the thermal fluid circulates, which receives the energy in the form of heat. This heat is usually provided by the combustion of different fuels, however, electric thermal oil boilers are commercially available.

4.1.2 Strengths and Opportunities

Fossil fuel combustion boilers typically have efficiencies ranging from 70-80%, while electric boilers can achieve 99% efficiency with only minimal radiation losses from the exposed boiler surfaces. The higher efficiency of electric boilers can lead to significant energy savings when they replace conventional boilers and compensate, to some extent, for the higher price of electricity compared to fossil fuels. Due to the higher efficiency of electric boilers, even if the carbon intensity of the electricity used is similar to that of the fuel mix being replaced, it can still lead to CO_2 emissions reductions. In countries with carbon-intensive grids, boiler electrification can lead to immediate emissions reductions when paired with renewable electricity PPAs.

In addition, electric boilers possess many non-energy benefits such as lower criteria air pollution (again depending on the electricity grid fuel mix), lower permitting hurdles, quieter operation, and faster ramp-up times compared to combustion boilers.

Like other electrification technologies, by reducing dependence on fossil fuels, electric boilers can contribute to energy security, reducing risk from volatility of fuel prices and supply disruptions. Finally, it is important to note that compared to some other electrification technologies, replacing combustion boilers with electric boilers is a relatively simple switch regarding processes and equipment.

4.1.3 Challenges

The electrification of steam boilers could lead to an increase in CO_2 in those countries with carbon-intensive grids that produce significantly more emissions per unit of energy than the current fuel mix used in conventional steam boilers. For this reason, boiler electrification has to be carefully evaluated based on the relative carbon intensity of electricity vs. fuels, and may not be suitable in the near-term unless paired with renewable electricity.

The major barrier to the adoption of electric boilers is energy costs. Currently, electricity is more expensive than conventional fuels in most industries and geographies, making electrification unfavorable from the perspective of operational expenditures, even despite the increased energy efficiency of electric boilers relative to conventional fossil fuel boilers. Costs are discussed further in Section 4.1.5. A lack of supportive policies and incentives for industrial electrification also hampers the pace of transition in many geographies. Market structures that do not adequately value the reduction in CO_2 emissions and other environmental benefits associated with electrification further compound the challenge.

4.1.4 Supply and Infrastructure

Electric boilers are a mature technology and are readily available from multiple suppliers. Electric boilers are generally more simple and inexpensive to install and maintain than conventional boilers. Electrification of boilers generally does not require significant changes to existing processes and equipment. Typically, electrification of industrial boilers only requires changes in the boiler room, i.e. replacing the existing combustion boilers with electrified boilers, and the electric boilers take up less space and do not need exhaust systems.

However, since the boilers can require a considerable amount of power, converting existing combustion boilers to electric (especially large-capacity boilers) may require an upgrade to the electricity service feed for industries. This may entail upgrading transformers, enhancing distribution capabilities, and ensuring consistent and reliable power delivery (such as through storage). These upgrades add more cost to the project.

In addition, large-scale electrification will require consideration of the impact on electricity supply, especially in countries where the electric grid may not be fully equipped to handle the increased load from industrial electrification. Although electrification would decrease net final energy demand due to the higher efficiency of electrified technologies, the demand for electricity naturally increases. Managing the additional electric load can be challenging for electric utilities.

4.1.5 Cost

The investment costs of an electric boiler are approximately 40% less on average than that of an equivalent combustion boiler fired with coal. As with any boiler, the investment costs of electric boilers are related to the capacity of the boiler, with larger boilers having a lower investment cost per unit of capacity (Figure 23). A similar curve can be observed for a boiler's annual operation and maintenance costs, which are a small fraction of the capital costs (Figure 24). Boilers in the textile industry tend to be relatively small, with about 50% of boilers in the range of 3-15MW in the U.S. (Zuberi et al. 2021).

Boiler electrification can significant raise energy costs per unit of production in the near term because electricity is typically much more expensive than fuel in most major textile-producing countries. This cost differential is greater than the savings from electrification with more efficient electric boilers. For example, in the U.S. steam boiler industry, the energy cost per tonne of steam production for the electrified process is more than three times that of the conventional process. Using lower-cost electricity, such as from PPAs, can reduce the energy cost of the electrified industrial steam boilers. Additionally, in geographies that put a price on carbon, such as China, fossil fuels will be more expensive relative to electricity as the grid decarbonizes over time.

The energy costs account for around 95% of boiler lifetime costs. However, considering the small share of production costs in final pricing for textile and apparel products, it is important to note that even a significant energy cost increase for electric boilers in 2030 may not significantly increase final product prices.

FIGURE 23: INVESTMENT COSTS OF AN ELECTRIC BOILER AS A FUNCTION OF ITS CAPACITY Source: Zuberi et al. 2021

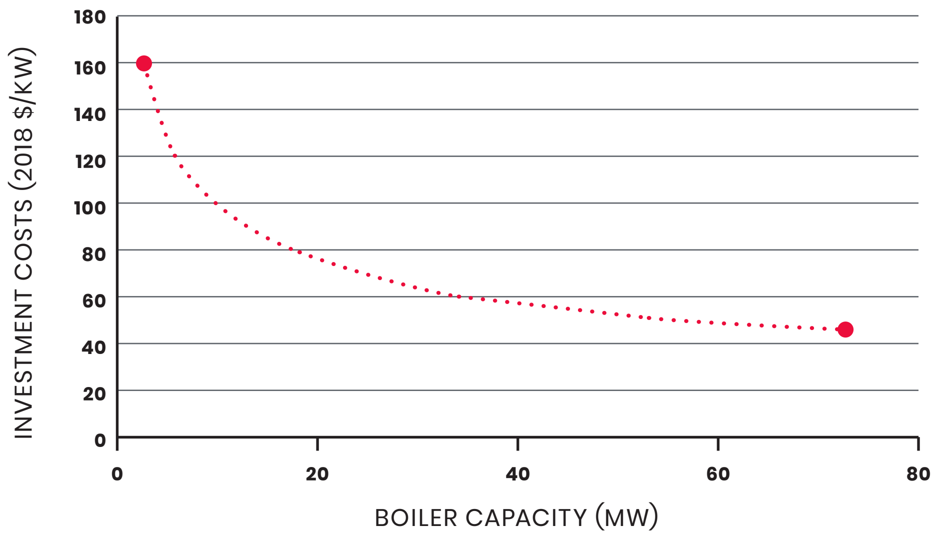
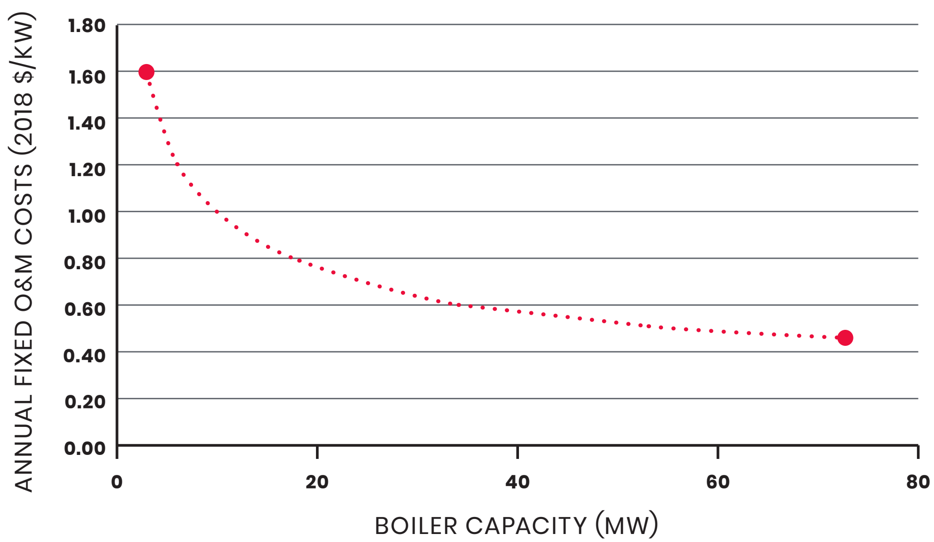


FIGURE 24: ANNUAL OPERATIONS AND MAINTENANCE COSTS OF AN ELECTRIC BOILER AS A FUNCTION OF BOILER CAPACITY
Source: Zuberi et al. 2021



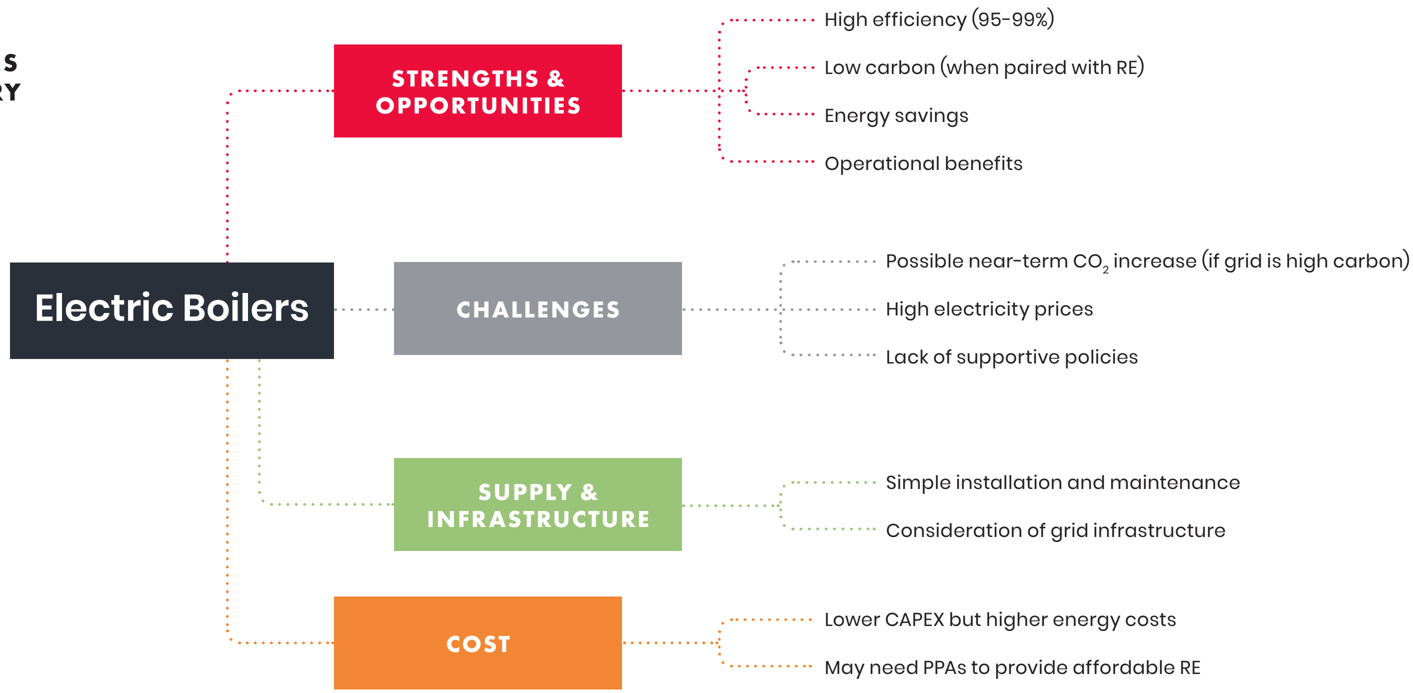
4.1.6 Case Study

The Timaru wool scouring facility in New Zealand recently transitioned from a coal-fired to an electric boiler with a significant reduction in CO_2 emissions by 11,000 tonnes annually. The transition entailed a $9.5 million investment partially funded by Woolworks, New Zealand's largest wool scouring company, with the remainder supported by the New Zealand Energy Efficiency and Conservation Authority (EECA) through the Government Investment in Decarbonizing Industry Fund. The demonstration of emissions reductions is an important marker of how electrification with a low-carbon grid (New Zealand mainly uses hydropower, geothermal, and wind to generate electricity) can be an important decarbonization technology.

In Ethiopia, a newly started textile factory installed a 2.5-ton steam-per-hour electric boiler from Sitong Boiler. The use of electric boilers is favored in Ethiopia due to the lower cost of electricity compared to other fuels like oil, gas, coal, and biomass. The boiler installed produces steam at a temperature of 170°C and has a thermal efficiency of 99% (Sitong Boiler, 2024). This case exemplifies the growing adoption of electric boilers in Ethiopia across various sectors due to their environmental and economic benefits.

Figure 25 summarizes the strengths and opportunities, challenges, supply and infrastructure situation, and cost of electric boilers for the textile industry.

FIGURE 25: SUMMARY OF ELECTRIC BOILER FEATURES FOR THE TEXTILE INDUSTRY



4.2 Industrial Heat Pumps

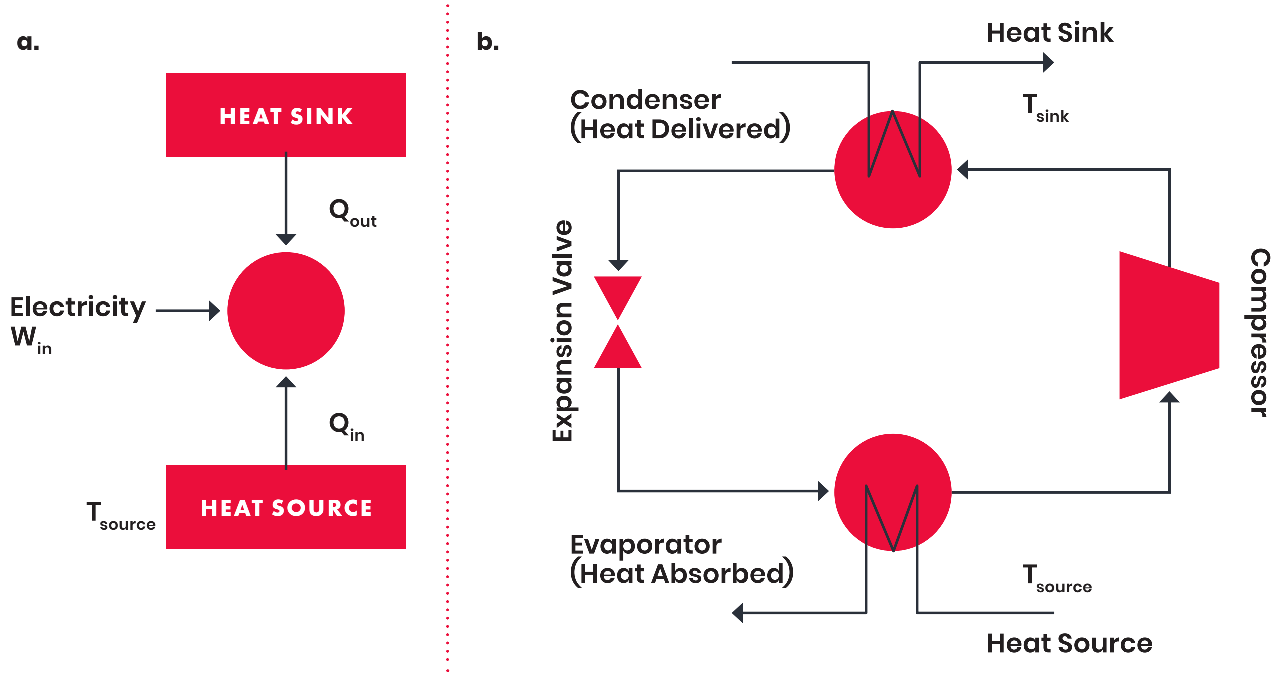
Industrial heat pumps powered by clean electricity can provide low-carbon process heat to various industrial applications. With their ability to transfer rather than generate heat, heat pumps offer significant improvements in energy efficiency and potential emissions reductions over many other process heating technologies. Commercial industrial heat pumps can deliver heat up to 170°C at capacities greater than 10MW, producing both steam and hot water — well within the range for most heating needs in the textile industry. However, their deployment is still limited in industry (McKinsey and Company 2024). This section analyzes steam-generating heat pumps for industrial applications.

4.2.1 Description of Technology

Industrial heat pumps use electricity to transfer heat from heat sources at lower temperatures to heat sinks at higher temperatures. The amount of external energy required to drive a heat pump depends on how much the temperature needs to be raised. Heat pumps use refrigerants as transitional fluids to absorb heat and then vaporize in an evaporator. A compressor is used to further raise the temperature and pressure of the refrigerant and force the high-temperature, high-pressure gas to a condenser. The absorbed heat is released where the refrigerant condenses in a condenser. Finally, the temperature and pressure of the refrigerant are further reduced after passing through an expansion valve (Figure 26).

Heat pumps are very efficient because they only transfer and concentrate heat instead of combusting fuels to create it. The performance of a heat pump is measured by the coefficient of performance (COP), or the ratio of heat output to energy input. The ranges of industrial heat pump capacities and sink temperatures have steadily grown over the years.

FIGURE 26:
THERMODYNAMIC REPRESENTATION OF A HEAT PUMP
Source: Zuberi et al. 2022



Based on data from 40 different textile mills in China, Japan, and Taiwan Region, Table 4 below shows the process temperatures for textile wet processes. Many textile manufacturers, suppliers, and brands are unaware that these temperatures are largely achievable by commercially available industrial heat pumps, and a single heat pump system can provide hot water and steam at multiple temperatures.

TABLE 4: TYPICAL PROCESS TEMPERATURES SUITABLE FOR TEXTILE PROCESSES Source: Hasanbeigi and Zuberi 2022

Unit Operations	Temperature (°C)
Sizing	95
Drying	130
Desizing	90
Scouring / Concise	90
Mercerizing & washing	90
Bleaching & washing	90
Drying	135
Dyeing	135
Printing	130
Heat setting	190-210
Washing	90
Drying	130

4.2.2 Strengths and Opportunities

Heat pumps can capture process heat that would otherwise be lost, helping to reduce the demand for burning any sort of fuel in the industrial boiler. Powered by electricity, they transfer more energy as heat than the electrical energy they consume, delivering two to five units of heat for each unit of electricity needed to run them (i.e. a COP of 2 to 5). The larger the temperature gap between the heat source and the heat sink, the lower the heat pump efficiency and its COP. Higher efficiency can lead to substantial energy savings for textile manufacturers. When powered with low-carbon electricity, heat pumps can significantly reduce CO_2 emissions compared to traditional fossil fuel-based heating systems. A study of China's textile wet-processing industry found that electrification with industrial heat pumps could lead to near term CO_2 emissions reductions even with China's carbon intensive grid in 2030. In addition to these CO_2 emissions benefits, heat pumps do not produce on-site air pollution emissions.

Heat pumps are versatile and can provide both heating and cooling. They can adjust output temperature and capacity rapidly in order to respond to process requirements and seasonal variations.

Ongoing advancements in heat pump technology continue to expand their applicability and efficiency, allowing them to provide steam for even higher temperature processes. Like other electrification technologies, by reducing dependence on fossil fuels, heat pumps contribute to energy security, reducing risk from volatility of fuel prices and supply disruptions.

4.2.3 Challenges

One of the primary barriers to more widespread adoption of industrial heat pumps is the economic feasibility of integrating heat pumps into existing facilities. Tailor-made designs often result in long payback periods, making investments less attractive. As with other electrification technologies, the low fuel-to-electricity price ratio in many countries decreases the attractiveness of electrifying with heat pumps, even though they offer greater efficiency gains than electric boilers and can even provide near-term cost benefits (see Section 4.5).

Another barrier is optimizing the refrigerants used in industrial heat pumps. In the past, hydrofluorocarbons (HFCs) and hydrochlorofluorocarbons (HCFCs) have been the predominantly used refrigerants, but natural refrigerants are increasingly used. There are growing environmental regulations on fluorinated gases like HFCs and HCFCs due to their high global warming potential.

As with other electrification technologies, another major potential challenge is the reliability of electricity supply if electrification takes place on a large scale, especially in countries where the electric grid may not be fully equipped to handle the increased load from industrial electrification.

Barriers to the adoption of heat pumps in industrial applications has led to a lack of product development for higher temperature industrial heat pumps. However, the market for high temperature industrial heat pumps is substantial (Marina et al. 2021). Moreover, a widespread lack of awareness and understanding of industrial heat pump technology among textile companies and investors, coupled with insufficient knowledge on integrating heat pumps into manufacturing processes, hampers its adoption. Finally, the entire value chain, including planners, manufacturers, and installers, faces a lack of training, further slowing the technology's deployment and acceptance in the industry sector.

4.2.4 Supply and Infrastructure

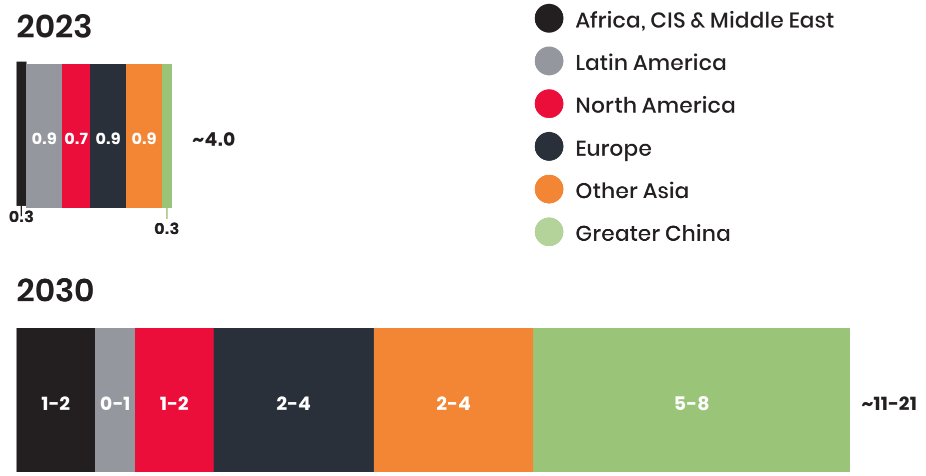
Industrial heat pumps are commercially available in the market. There are various manufacturers of industrial heat pumps that can provide heat of up to 90°C. There are fewer manufacturers that can provide commercial high temperature and steam-generating heat pumps with temperatures over 120°C, but these include major companies like Kobelco (Japan), Mitsubishi (Germany), Siemens (Germany), MAN Energy (Switzerland), Heaten (Norway), Ochsner (Austria), Mayekawa (Japan), Combitherm (Germany), and others.

Industrial heat pump markets are most developed in Europe and Japan due to strong economic and policy incentives. The global market for industrial heat pumps is expected to grow more than 15% per year until 2030, with the largest amount of growth coming from China (Figure 27).

Like electric boilers, the successful integration of industrial heat pumps into textile manufacturing facilities could necessitate upgrades and expansions of the existing electrical infrastructure. Given the substantial increase in electrical demand that accompanies the switch to heat pumps, facilities must consider a broad spectrum of infrastructural needs ranging from on-site upgrades to broader grid enhancements. These enhancements span from upgrading the internal wiring and substations within the facilities to potentially augmenting nearby transmission infrastructure to accommodate the increased load. The complexity of these upgrades often involves coordination with distribution network operators and utility companies early in the project planning phase to ensure the requisite electrical load capacity can be supported (Yuan and Riley 2023). In some places, the process of reinforcing transmission and distribution infrastructure can be subject to lengthy permitting processes and substantial financial investments.

FIGURE 27: PROJECTIONS OF HEAT PUMP MARKET GROWTH BY REGION Source: McKinsey and Company 2024

GLOBAL INDUSTRIAL HEAT PUMPS MARKET (HARDWARE), $ BILLION



4.2.5 Cost

Switching from combustion boilers to industrial heat pumps can result in lower energy costs for the textile plants and simple payback periods that could be acceptable to the companies. Even though electricity prices are generally higher than fuel prices in textile-producing countries, the high efficiency of heat pumps can lead to a lower energy cost per unit of production because of the substantial overall energy savings. In addition, these cost savings can be realized in the near term depending on the electricity-to-fuel price ratio at a given facility, especially if lower cost renewable energy for the electrified heat pump is directly procured. Over the medium- to long- term, as fuel prices and carbon prices rise, heat pumps can be significantly more competitive in terms of energy costs, relative to conventional steam boilers.

Figure 28 below shows the capital costs of various industrial heat pump technologies per unit of capacity. Heat pumps with larger capacity are more economical per unit of heating capacity.

FIGURE 28: CAPITAL COSTS OF INDUSTRIAL HEAT PUMPS AS A FUNCTION OF THEIR HEATING CAPACITY Source: Zuberi et al. 2022

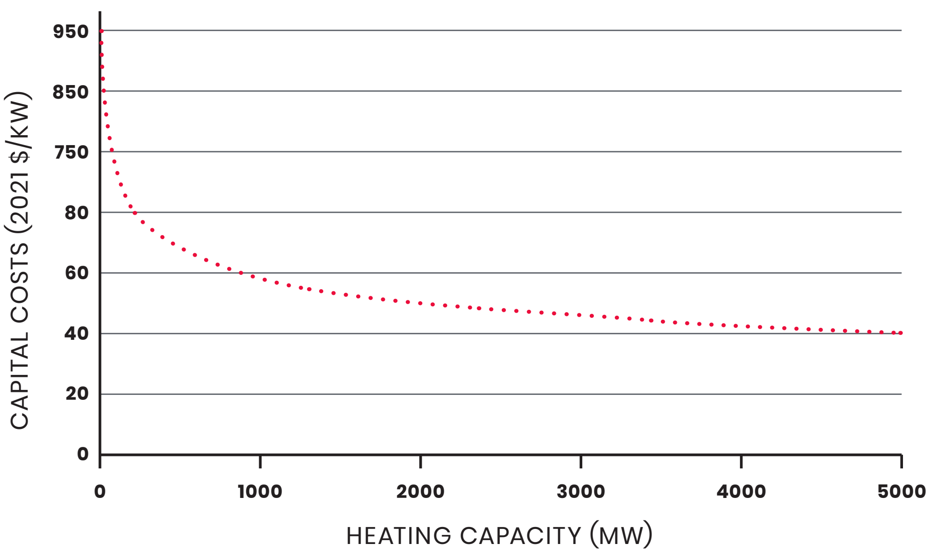


TABLE 5: CASE STUDIES OF HEAT PUMP APPLICATIONS IN THE TEXTILE INDUSTRY

Project Name	Technology	Location
SPINNOVA Textile Plant	Heat Pump	Finland
PONGS Seidenweberei GmbH Heat Recovery	Heat Pump	Germany
HM Facility	Heat Pump	China
Nike Facility	Heat Pump	Vietnam
Muhltroff printing and dyeing facility	Heat Pump	Germany
Apeldoorn washing plant	Heat Pump	Netherlands

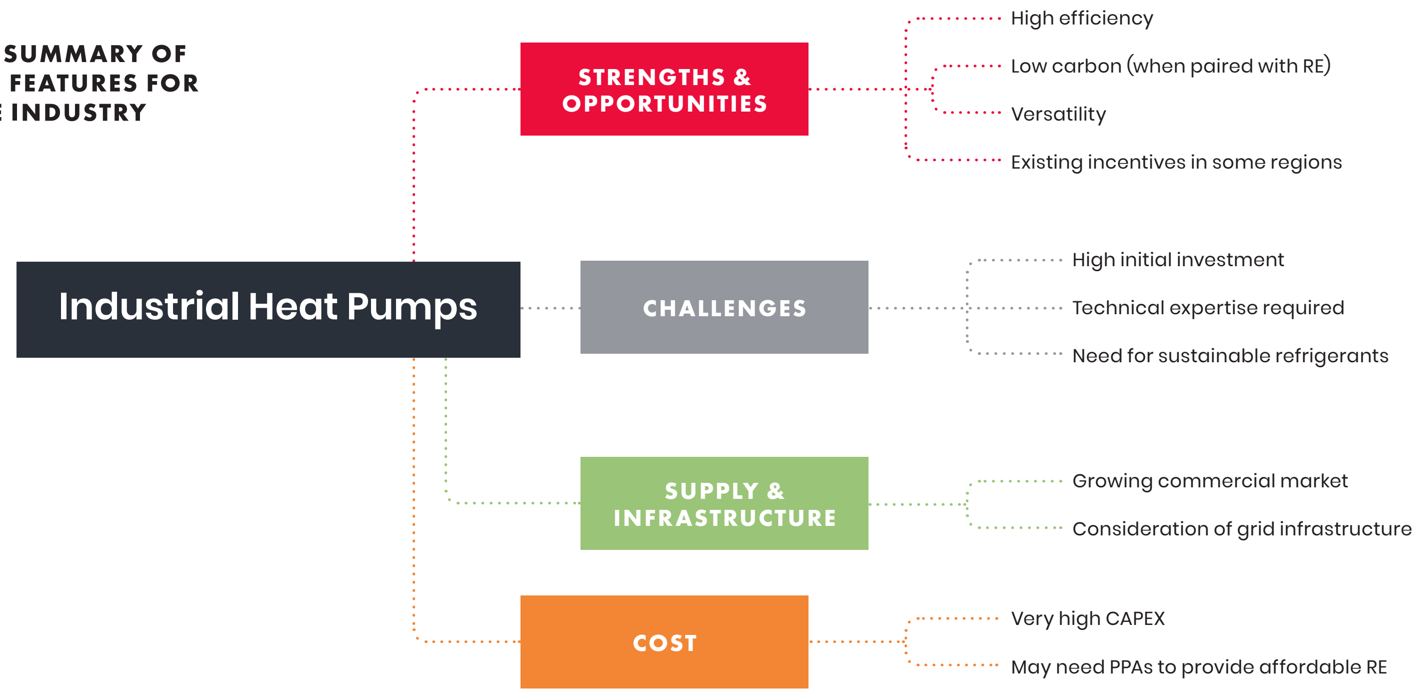
4.2.6 Case Study

The heat pump company Calefa installed a 5 MW heat pump at the SPINNOVA textile plant in Jyväskylä, Finland. The installation is expected to lower CO_2 emissions while providing process heat, cooling, and facility heating for the factory (MaintWorld 2022). Excess heat is recycled back into the local district heating network, thereby enhancing the overall energy efficiency of the community. The facility uses wind power, delivering clean electricity to the heat pumps, ensuring that the scheme delivers decarbonization benefits.

At Pongs GmbH in Germany, a textile facility that produces technical and decorative fabrics, a heat pump was installed for heat recovery from dyeing. The facility's dyeing process releases warm exhaust air, and the installed system recovers heat for a heat pump to deliver hot water for space heating. The system has a reported COP of 5.1, which indicates the system can deliver 5.1 units of heat for every unit of electricity consumed. Pongs has subsequently installed a second heat pump system to further enhance their energy savings and operational efficiency. Table 5 above lists these and several other case studies we have identified of heat pump applications at various textile facilities.

Figure 29 summarizes the strengths and opportunities, challenges, supply and infrastructure situation, and cost of heat pumps for the textile industry.

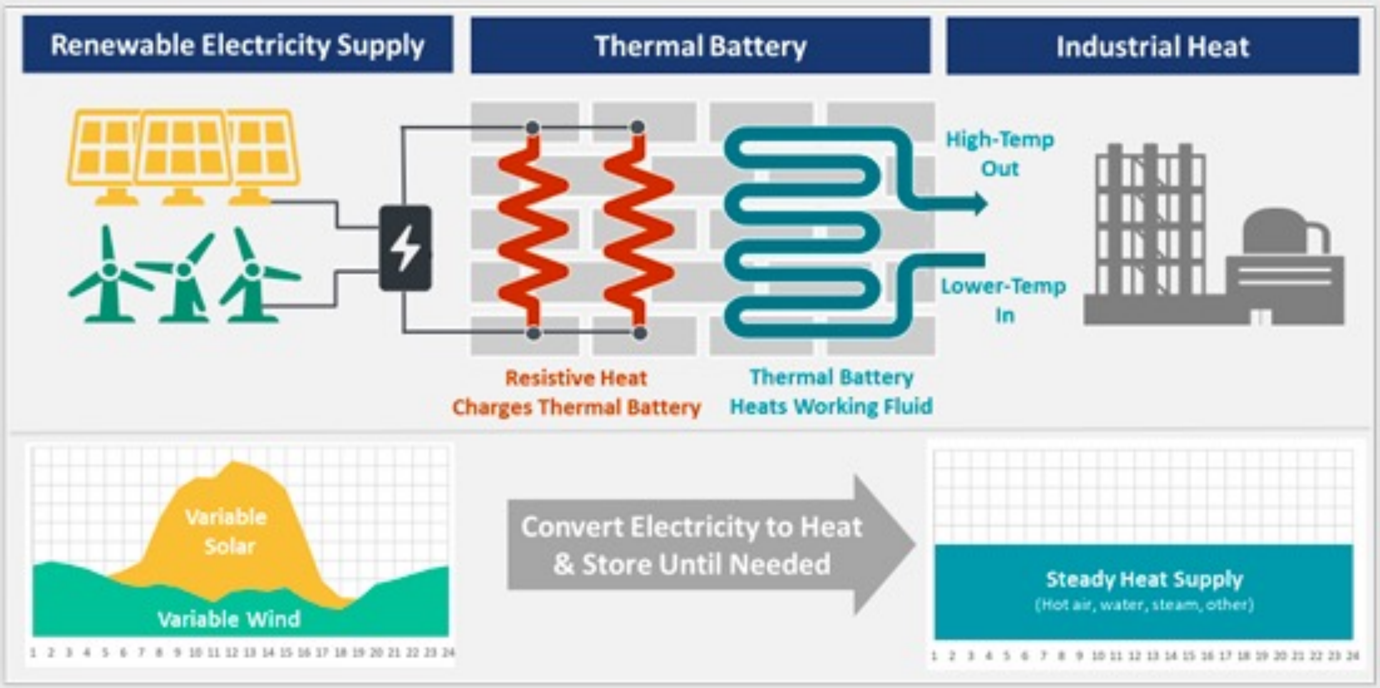
FIGURE 29: SUMMARY OF HEAT PUMP FEATURES FOR THE TEXTILE INDUSTRY



4.3 Thermal Energy Storage

Thermal Energy Storage (TES) technologies represent a new approach to managing and utilizing energy in industrial processes, including those within the textile industry. At its core, TES allows for the storage of heat energy that can be derived from renewable sources or off-peak electrical energy to be used when needed for heating purposes in industrial settings. This allows industries to overcome the mismatch in supply and demand due to the intermittent nature of renewable energy. For further information on TES and other energy storage technologies, see the Carbon Trust report, "Potential for On-Site Energy Storage to Drive On-Site Renewables in the Textile and Apparel Sector."

FIGURE 30:
DIAGRAM DEMONSTRATING THERMAL ENERGY STORAGE TECHNOLOGY
Source: RTC 2023



4.3.1 Description of Technology

Figure 30 demonstrates how renewable electricity, e.g. generated intermittently from solar or wind resources, can be utilized to power resistive heaters during periods of (excess) production. Resistive heaters can heat a storage medium such as electric coils, bricks, molten salts, or other materials to efficiently store heat within the thermal battery. A working fluid, such as steam, air, or water, circulates through the storage medium, absorbing heat and reaching the necessary temperatures for various industrial operations.

The heat can be stored for durations ranging from 1 to 2 days, or even longer for specific applications, with minimal loss. This enables the conversion of fluctuating renewable electricity sources into a consistent and stable supply of high temperature heat, effectively replacing/supplementing traditional fossil fuel boilers, kilns, dryers, or other heat-generating processes.

Thermal energy storage technologies encompass three main types: sensible heat storage, latent heat storage, and thermochemical storage. Each of these storage types utilizes different methods to store and release thermal energy, catering to various applications and efficiency requirements. Sensible heat storage, the simplest and most cost-effective, utilizes materials like water, sand, and molten salts to store energy through temperature changes, though its capacity is limited by the material's specific heat and achievable temperature range. Latent heat storage, more space-efficient, uses phase change materials that absorb and release energy at constant temperatures, ideal for thermal regulation; however, it faces challenges in material compatibility and heat transfer management. Thermochemical storage, the most complex and efficient type, involves chemical reactions to store and release heat, offering high energy density and long-term storage capabilities, but it requires intricate system design and precise reaction control, resulting in higher initial costs.

4.3.2 Strengths and Opportunities

In addition to being a zero-carbon source of process heating if paired with renewable electricity, the most compelling advantage of TES lies in its ability to store excess energy and provide it on demand. This advantage dramatically minimizes the primary weakness of renewable energy sources such as solar and wind, by being able to store energy to be discharged during periods where renewables might not be able to produce energy. TES systems ensure a stable energy supply, protecting the textile industry from the intermittency of renewables, which is critical for maintaining continuous production processes and high product quality standards. This characteristic allows TES to take advantage of the benefits of renewable energy such as significantly reducing the environmental impact associated with energy production and consumption. By storing excess energy generated during peak production times, TES can supply the textile industry with a constant and reliable energy source without the detrimental emissions associated with fossil fuel combustion. In order to maximize TES advantages, the technology needs to be paired with electricity generated via clean renewable energy sources.

Thermal Energy Storage also offers flexibility and scalability, allowing textile industries to adjust their energy usage based on production needs and availability of renewable energy sources. TES systems can be designed to cater to specific energy demands of a facility, making it easier to scale up or down based on the growth of the production or changes in energy consumption patterns.

TABLE 6: COMPARISON OF THREE THERMAL ENERGY STORAGE TECHNOLOGIES Source: IRENA 2023

Storage Type	Efficiency	Temperature Range	Storage Period	Readiness
Sensible	50%-90%	150°C-1000°C	Hours - Months	Medium-High
Latent	75%-90%	50°C-850°C	Hours - Days	Medium
Thermochemical	75%-100%	500°C-900°C	Hours - Months	Low-Medium

4.3.3 Challenges

Adapting thermal energy storage so that renewable sources can serve as a viable alternative to fossil fuel in the textile industry presents several challenges. Firstly, the upfront investment for TES systems can be substantial, requiring significant capital for installation and integration into existing processes. Technical expertise is required not just for installation but for ongoing operation and maintenance of TES systems, posing a barrier in regions where such expertise is scarce. There is an additional challenge in that TES technologies are not as well-known as other clean energy technologies, both to industrial customers and policy makers. This awareness gap can lead to a lack of supportive policies and considerations in climate planning, hindering the adaptation of TES into industrial settings.

There are also remaining technical challenges to TES systems. Sensible heat storage system are hindered by their low energy density and a tendency for the output temperature to decline over time during discharge. Furthermore, the storage materials may deteriorate over time, diminishing their capacity for thermal storage or making them inoperable. Certain latent heat storage substances, like molten salt, may present safety hazards due to their corrosive or toxic nature. Moreover, latent heat storage systems can incur thermal losses through conduction, convection, and radiation, decreasing the system's overall efficiency. Identifying materials that can endure high temperatures, pressures, and thermal cycling remains a significant challenge for thermochemical TES systems. Factors such as reaction heat, reaction kinetics, and the rate of heat transfer between the storage substance and the heat exchanger can influence the efficiency of the system (Saha and Rupam 2023).

4.3.4 Supply and Infrastructure

There are a number of existing companies providing TES technologies (Table 7). As these and other TES companies continue to scale and increase production, the manufacturing costs are expected to decrease over time.

The integration of TES systems with existing thermal and electrical infrastructure in textile factories could be a complex issue. Many facilities rely on legacy heating systems that may not be readily compatible with modern TES solutions. Upgrading these systems to interface effectively with TES technology may require modifications, including the installation of new heat exchangers, pumps, and control systems. Ensuring seamless operation between traditional and TES-based heating requires careful planning and substantial investment.

TABLE 7: TECHNICAL CHARACTERISTICS OF SOME COMMERCIALLY AVAILABLE TES TECHNOLOGIES AND THEIR RESPECTIVE MANUFACTURERS

Source: RTC 2023

Company	Thermal Battery Model (if relevant)	Temperature Range	Storage Medium	Commercialization Status	Source
Antora Energy	-	Up to 1,500°C (2,730°F)	Carbon Blocks	Early Commercialization	[1]
Caldera	Storage Boiler	Primarily 90°C-300°C (194°F-572°F)	Recycled Aluminum and Crushed Rock	Pilot	[2]
Brenmiller Energy	bGen ZERO	130°C-750°C (270°F-1,380°F)	Crushed Rocks	Early Commercialization	[3]
Electric Thermal Solutions	Joule Hive Thermal Battery	Up to 1,800°C (3,300°F)	Firebrick	Pilot	[4]
Rondo Energy	RHB300	80°C-1,500°C (180°F-2,730°F)	Brick	Early Commercialization	[5]

Sources & Notes: [1] Canary Media, This startup's energy storage tech is 'essentially a giant toaster,' April 2022. [2] Caldera, personal Communication, September 13, 2023. [3] Brenmiller Energy, Brenmiller - thermal energy storage (bren-energy.com). [4] Electrified Thermal Solutions, Electrified Thermal Solutions - Electrifying industrial heat. [5] Rondo Energy, Products - Rondo Energy.

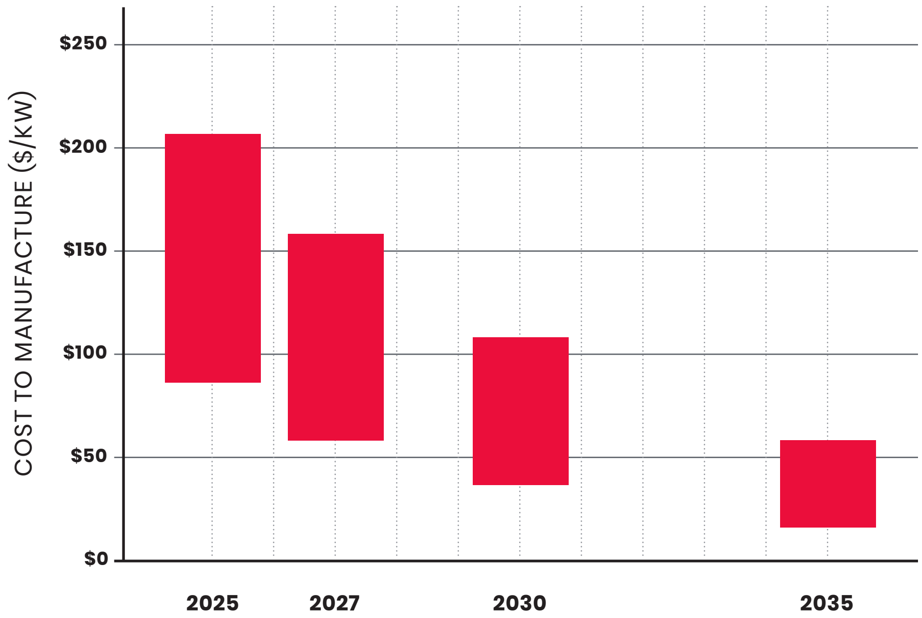
4.3.5 Cost

Capital costs for TES systems are significant, encompassing the purchase of the TES system itself, along with any necessary modifications to existing heating systems to ensure compatibility. This can include the integration of advanced heat exchangers, upgrading insulation, and implementing control systems to manage the storage and release of thermal energy effectively.

Like other electrification technologies, the fuel-to-electricity price ratio can substantially affect the cost-effectiveness of the TES systems. These systems are most economical when they can take advantage of very low or even negative prices of renewable electricity when they are being curtailed. However, this type of renewable pricing option is not available in all geographies.

From the market perspective, the share of TES is expected to be dominated by Sensible Heat Storage systems in the industry sector. Sensible Heat Storage systems are typically more affordable than Latent Heat or Thermochemical systems because they consist of a simple tank containing the storage medium and the charging/discharging equipment (Pompei et al. 2023). Manufacturing costs for TES systems are expected to decrease over time, from around $200 per kWh to less than $50 per kWh by 2035 (Figure 31).

FIGURE 31: EXPECTED FUTURE MANUFACTURING COSTS OF THERMAL ENERGY STORAGE Source: RTC 2023)



4.3.6 Case Study

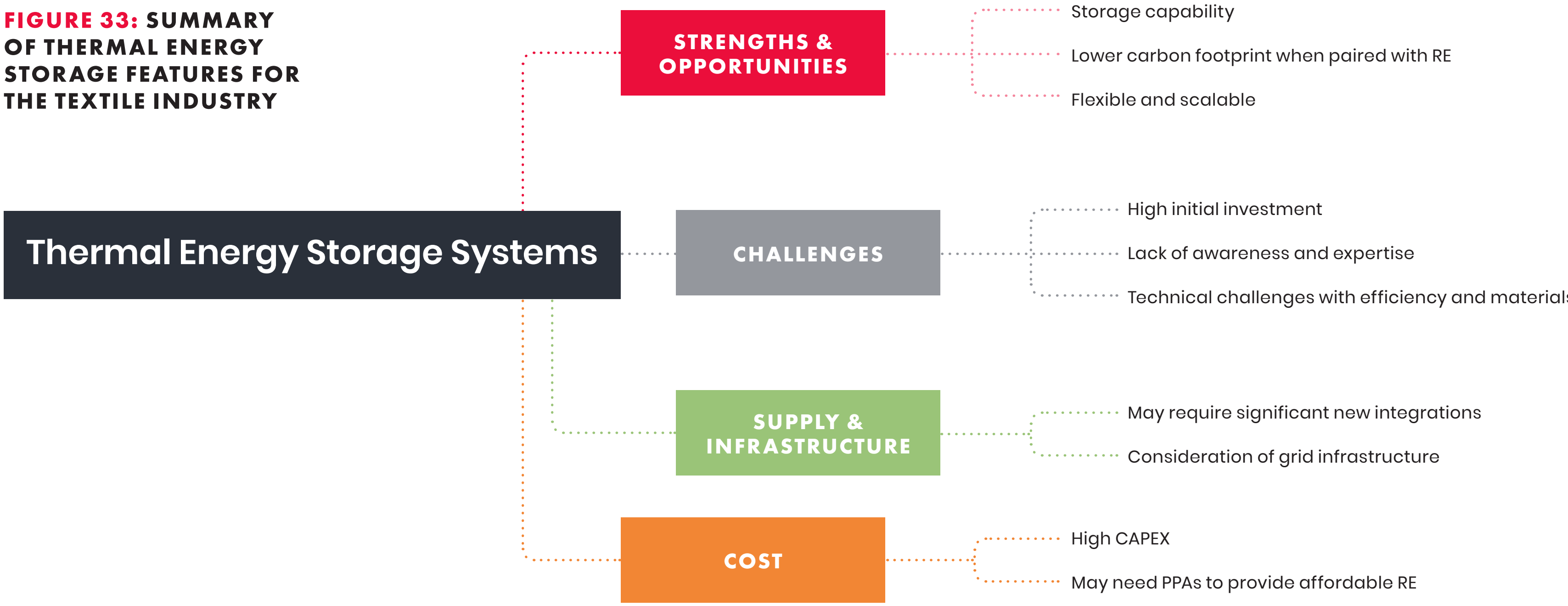
A major textile supplier in China is installing a TES system in collaboration with the local utility, which offers TES systems at an industrial scale. This system utilizes a molten salt storage heat exchange integrated steam boiler. By leveraging molten salt as a storage medium, the system capitalizes on off-peak, low-tariff electricity available during nighttime to heat the salt. The stored energy is then used to generate steam on demand, capable of producing both saturated steam below 200°C and superheated steam up to 350°C, with steam flows ranging from 0.05 to 0.5 tonnes per hour.

FIGURE 32: THE RONDO HEAT BATTERY AT THE CALGREN FACILITY
Source: Rondo 2023

There is little information about other applications of TES in the textile industry. Instead, we feature an example from a biofuel production facility. Rondo, a U.S.-based manufacturer of thermal energy storage systems, installed a 2MWh heat battery at the Calgren Renewable Fuels facility in Pixley, California (Figure 32). This thermal energy storage system can store heat at temperatures exceeding 1,000°C in brick materials, and provides continuous industrial heat on demand. The installation represents the first electric thermal energy storage system in commercial operation in the U.S. The battery is expected to double CO_2 savings per gallon of biofuel produced without necessitating downtime or changes to the production process or feedstock by replacing the fossil fuels previously used for process heating. The heat battery has efficiencies of over 90% (Rondo 2023). The facility uses renewable electricity, guaranteeing emissions reductions relative to conventional fuel. It should be noted that the temperature of heat/steam needed in the textile industry is much lower (below 200°C) than what is used in the aforementioned facility.

Figure 33 summarizes the strengths and opportunities, challenges, supply and infrastructure situation, and cost of thermal energy storage for the textile industry.

FIGURE 33: SUMMARY OF THERMAL ENERGY STORAGE FEATURES FOR THE TEXTILE INDUSTRY



4.4 Electrification Readiness for Major Textile-Producing Countries

We assessed country readiness for the adoption of three electrification technologies for process heating: electric boilers, heat pumps, and thermal energy storage. To assess readiness for electrification as a low-carbon heat source, we examined six metrics: the electricity grid emissions factor in each country, the fuel carbon intensity in the textile industry, the level of energy security in each country, readiness for Power Purchase Agreements, the share of zero-carbon energy in total electricity generation, and electrification technology availability in each country. The electricity grid emissions factor determines whether or not electrification leads to lower CO_2 emissions. In countries that burn large amounts of fossil fuels for electricity, a high grid emissions factor will not lead to lower emissions upon electrification and may even lead to higher emissions. We used IEA data on country grid emissions factors, finding that Spain, Italy, Germany, and the United States had the cleanest electricity grids and could benefit most from electrification (Figure 34). As countries decarbonize their electricity grids, they will be able to realize more emissions reductions from electrification.

Next, we developed a metric to assess energy security in the studied countries. Electrification can be a strategy to enhance energy security because electrification allows industries to diversify their energy sources beyond traditional fossil fuels, thereby reducing dependence on a single energy supply chain that can be susceptible to geopolitical tensions, price volatility, and supply disruptions. Electricity can be generated from a variety of sources including renewable energy like wind and solar, which are by their nature local resources. We calculated the share of net energy imports in total energy supply using IEA data (Figure 35). The countries with the highest share of energy imports are the least energy secure and could benefit the most from electrification as an energy security strategy. These countries areTaiwan Region, Morocco, and Japan.

FIGURE 34: ELECTRICITY GRID EMISSIONS FACTOR IN 20 MAJOR TEXTILE-PRODUCING COUNTRIES

Source: IEA data for 2019, based on its most recent 2024 update

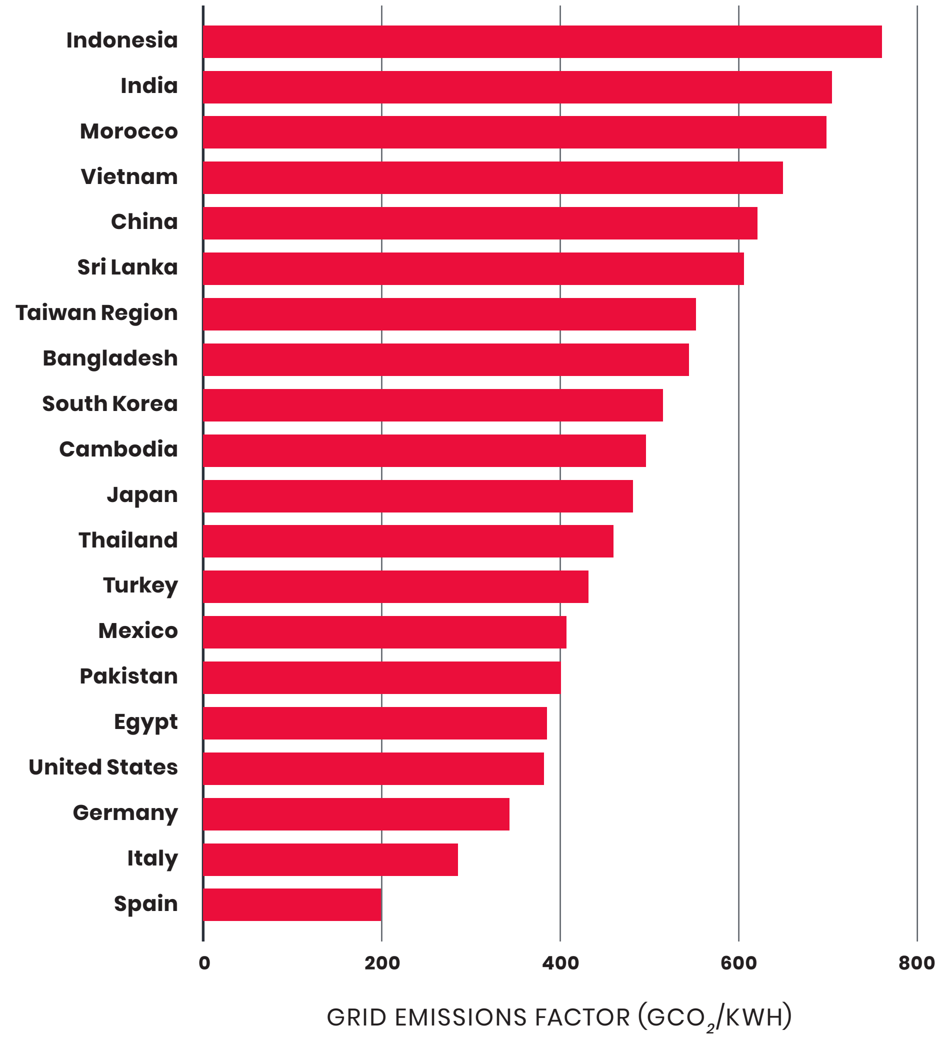
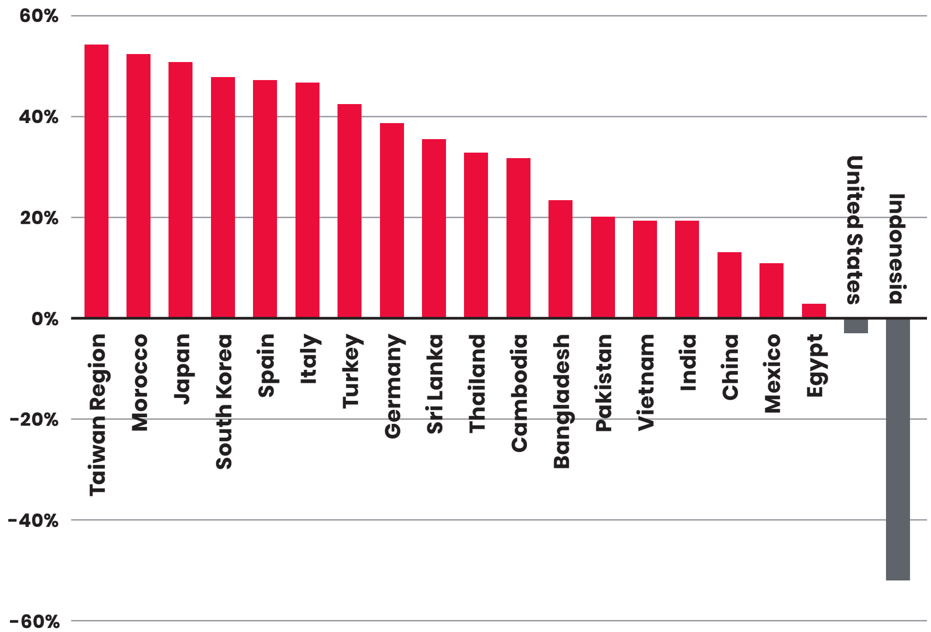


FIGURE 35: SHARE OF ENERGY IMPORTS IN TOTAL ENERGY SUPPLY
Source: GEI analysis of IEA 2022 data

Note: negative values indicate energy exports exceed the total energy supply in the country.



Another crucial factor for electrification readiness is the availability of renewable energy power purchase agreements (PPAs). These agreements enable companies to easily acquire additional renewable electricity for their facilities as electrification raises onsite demand, rather than relying solely on the grid. EY publishes an index based on analysis of 100 markets to identify the top 30 countries for corporate PPA development and integration. We used the EY rank to identify the top PPA markets, and proxied other countries in our dataset to the most similar country. Figure 36 sorts countries into the categories of most ready, moderately ready, and least ready regarding availability of corporate PPAs. The most ready countries, in order of their EY PPA rank, are Spain, Germany, and the US.

We also examined the metric of the current share of zero-carbon energy (including nuclear power and hydropower as well as renewables – wind, solar, geothermal, and biomass) in total electricity generation (Figure 37). This share represents the available proportion of zero-carbon energy sources within a country and the effectiveness of electrification as a near-term decarbonization solution. While some of these countries have very low amounts of renewable capacity, such as Sri Lanka and Cambodia, they have high amounts of hydropower for clean energy generation.

We also qualitatively estimated electrification technology supply chain availability in each country. While electric boilers are prevalent and available worldwide, industrial heat pump markets are more developed in Europe and Japan. Thermal energy storage technologies are emerging and their availability and supply chain are limited, particularly in some low- and middle-income regions.

FIGURE 36: PPA READINESS FOR THE 20 MAJOR TEXTILE-PRODUCING COUNTRIES Data source: EY 2022

*In 2024, Vietnam introduced policies to encourage the domestic PPA market, discussed further below.

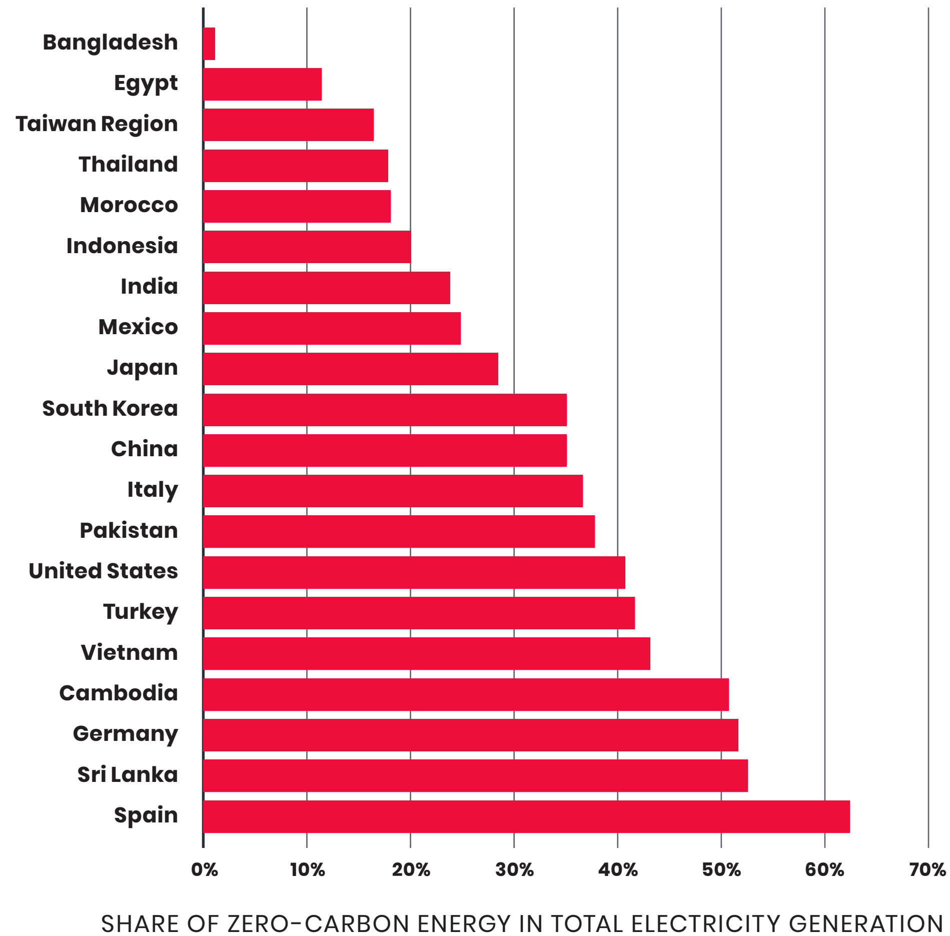
Finally, we estimated the electricity-to-fuel price ratio in each country, comparing industrial electricity prices with the weighted average fuel price for energy used in industry, or for the dominant fuel use in industry overall or the textile industry, depending on available data. The lower the electricity-to-fuel price ratio, the more likely that electrification of heating is economically viable. A ratio of less than one would mean that electricity is currently cheaper than fuel. This is the most important metric for the near-term economic viability of electrification.

However, It should be noted that the electricity-to-fuel price ratio does not need to be less than one for the electrification project to be economically viable. Because of the increased efficiency of electrified heating compared to fuel-based combustion heating, the electricity-to-fuel price ratio could be higher than one and the electrification technology still be cost-competitive with conventional systems. The breakeven point will depend on the electricity-to-fuel ratio as well as the efficiency gain achieved with electric technologies. Countries with very cheap domestic fuel, such as Pakistan, Indonesia, and Morocco, have high ratios (Figure 38).

We combined the aforementioned metrics by ranking each country and creating an overall composite readiness score, where a higher score indicates more readiness for adopting electrification technologies for process heating in the textile industry. Figure 39 categorizes countries based on their readiness for adopting electrification technologies based on percentiles for their readiness scores. Germany, Italy, Japan, South Korea, Spain, Turkey, and the US are most ready to adopt electrification technologies for decarbonization in the textile industry in the near term based on this overall score, while the countries listed as “Less Ready Without Support” would require additional financial and regulatory support to adopt electrification technologies and drive decarbonization. Of these, Turkey is of significant interest, given its ranking as a major textile-producing country and its reliance on coal for about one-third of its fuel use in the sector. Turkey’s grid emission factor, though far from low, ranks in the low-middle range of the 20 countries evaluated in this report (Figure 37).

FIGURE 37: SHARE OF ZERO-CARBON ENERGY IN TOTAL ELECTRICITY GENERATION FOR THE 20 MAJOR TEXTILE-PRODUCING COUNTRIES

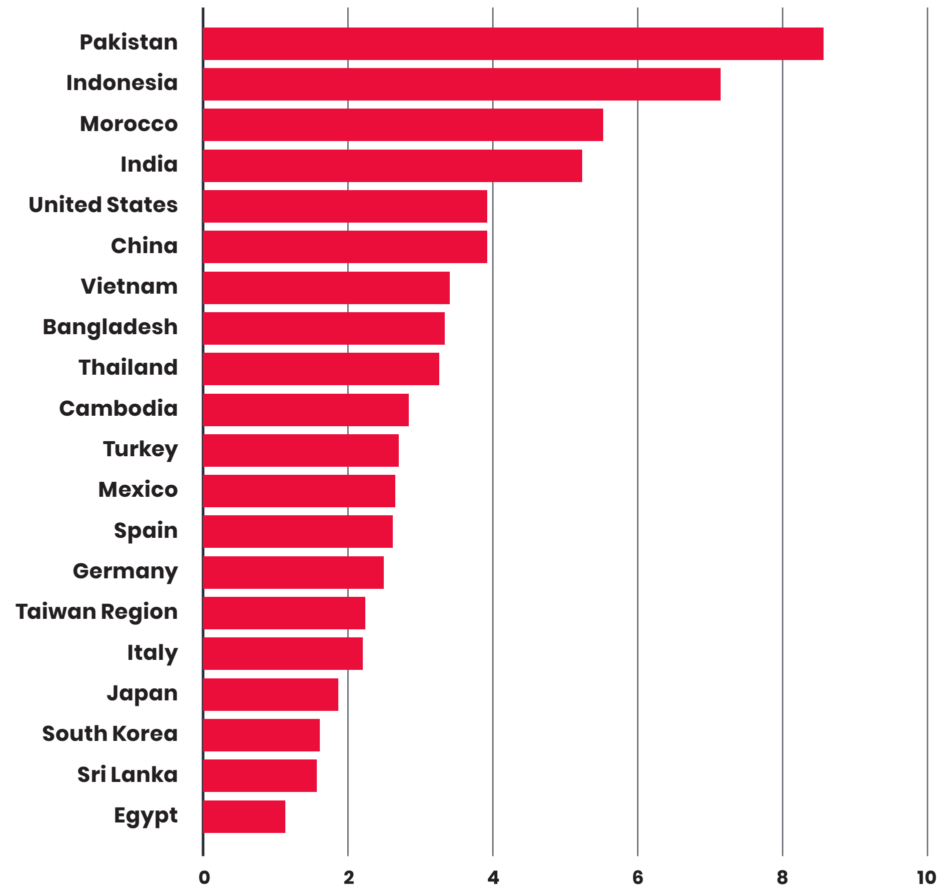
Source: Energy Information Administration 2024



For the top five textile-producing countries, readiness for electrification varies significantly. China and India have relatively high grid emissions factors, although there is also significant availability of renewable electricity through PPAs. However, China and India's electricity-to-fuel price ratio is currently relatively high, which would make electrification technologies more costly in terms of energy costs in the near term. For China, heat pumps could be a viable electrification technology because their increased efficiency reduces energy costs per unit of production, and China also has a growing market for heat pump technologies. The thermal energy storage technologies could benefit from the regulatory environment in China, which includes incentives for storage providers such as system-wide time-of-use (ToU) tariffs.[5] India's ToU tariff system is less established than China's, although the country has ambitious targets for renewable energy deployment (500 GW of new renewable energy capacity by 2030).

For Bangladesh, electrification may be challenging without near-term support. Large renewable energy PPA markets are nascent, limiting supply for textile manufacturers seeking to electrify. In addition, as a nation with fewer economic resources, Bangladesh could face high costs in acquiring emerging electrification technologies and sustaining its supply chains. The Carbon Trust notes that in Bangladesh, there are no ToU tariffs and the policy environment for renewables and storage is generally poor.

FIGURE 38: ESTIMATED ELECTRICITY-TO-FUEL PRICE RATIO IN 20 MAJOR TEXTILE-PRODUCING COUNTRIES



5 The Carbon Trust report "Potential for On-Site Energy Storage to Drive On-Site Renewables in the Textile and Apparel Sector" ranks top textile-producing countries on their suitable for various energy storage technologies, including TES. China is ranked as highly suitable, India as moderately suitable, and Bangladesh and Vietnam as low suitability.

FIGURE 39: READINESS FOR ADOPTING ELECTRIFICATION TECHNOLOGIES IN THE 20 MAJOR TEXTILE PRODUCING COUNTRIES IN THE NEAR TERM

Readiness for Electrification

FOR 20 MAJOR TEXTILE-PRODUCING COUNTRIES

MOST READY	MODERATELY READY	LESS READY WITHOUT SUPPORT
Germany	**China**	**Bangladesh**
Italy	**Egypt**	**Cambodia**
Japan	**India**	**Egypt**
South Korea	**Sri Lanka**	**Indonesia**
Spain	**Taiwan Region**	**Mexico**
Turkey	**Thailand**	**Morocco**
United States	**Vietnam**	**Pakistan**

Vietnam has a high grid emissions factor, and electrification with grid electricity could potentially increase emissions in the near term. However, Vietnam recently implemented new regulations that enable direct PPAs between Independent Power Producers (IPPs) and energy consumers, increasing the accessibility of renewable energy sources for manufacturers.

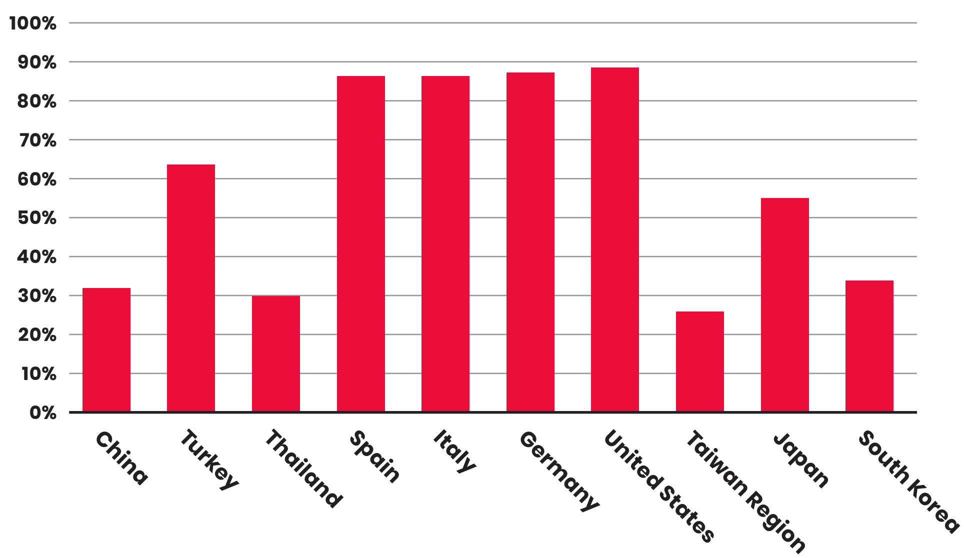
For Germany, the country's grid emissions factor is relatively low due to high generation from wind and solar resources in recent years, plus some baseload hydropower and nuclear power. Germany imports a significant share of its fuel, indicating that there would be energy security benefits from electrifying with renewable energy. Most importantly, fuel prices are high in Germany, and the electricity-to-fuel price ratio is less steep, indicating that electrification could be cost-competitive in terms of energy costs in the near- to medium-term.

Thus, for electrification technologies, Germany is the top textile producer with the most promise for near-term electrification, especially for heat pumps and TES, emerging technologies with primarly Western manufacturers. Electrification with heat pumps and TES could be viable in China as well, although China faces a high electricity-to-fuel price ratio. Electric boilers are commercially available, have low capital costs, and could be deployed in any of the top-producing countries with support for the procurement of low-cost renewable electricity.

5. Natural Gas as an Alternative Fuel for the Textile Industry

Natural gas, which is comprised nearly completely of methane, is recognized for its cleaner combustion compared to coal and has become an increasingly preferred energy source in various industries. This transition is driven by the need for low-carbon and cost-effective energy solutions, where natural gas stands out over coal under best-case circumstances. In some top textile-producing countries like Turkey, natural gas already makes up the largest share of fuel use for the textile industry (Figure 40). However, natural gas is still a fossil fuel that produces GHG emissions from production, transport, and end-use. Importantly, methane leaks from natural gas drilling, transport, and processing can be extensive — in fact, so large that the total emissions from using this fuel can be higher than coal. In addition, natural gas supply is a challenge for many countries that rely on imports.

FIGURE 40: SHARE OF NATURAL GAS IN FUEL USE FOR THE TEXTILE INDUSTRY IN TOP TEXTILE-PRODUCING COUNTRIES WITH AVAILABLE DATA Source: GEI analysis based on IEA 2022 data.



5.1 Description of Technology

Industrial natural gas boilers are used in many industries due to their high efficiency and lower CO_2 emissions compared to coal or oil boilers, where natural gas is available. They are specifically designed to meet the robust demands of industrial operations, with capacities that can handle large-scale energy requirements. Natural gas boilers are utilized across a wide range of industries, including the textile industry, offering precise temperature control, operational flexibility, and lower environmental impact than coal.

In the textile industry, natural gas is mainly used in industrial steam boilers and hot oil boilers, which are essential for various stages of textile manufacturing. These boilers offer consistent and reliable heat, ensuring that textiles are processed under optimal conditions to achieve the desired quality. Some processes such as dyers and heat-setting machines may also have direct natural gas-fired systems to provide heat to the process. However, the availability of natural gas is a major constraint in most textile and apparel-producing countries.

5.2 Strengths and Opportunities

Natural gas releases less CO_2 upon combustion than coal does, with the CO_2 emissions factor of natural gas being less than half that of coal, not counting upstream methane emissions (Figure 2). Burning natural gas also has air pollution benefits, resulting in less than a third of nitrogen oxides and a mere fraction of sulfur oxides compared to coal combustion (Table 8).

Natural gas also provides significant safety benefits over coal, reducing risks associated with coal mining and storage, such as health hazards from dust. The infrastructure for onsite natural gas storage and delivery is also less space-intensive than coal facilities, allowing for more efficient use of manufacturing spaces.

TABLE 8: LOAD-WEIGHTED AVERAGE EMISSION RATES FOR US COAL PLANTS VS REPLACEMENT WITH NATURAL GAS PLANTS

Source: Lueken et al. 2016

Plant type	Combustion Emission rates (kg/MWh)					
	CO_2	NO_2	SO_2	CH_4	$PM_{2,5}$	PM_{10}
Coal	910	0.69	0.72	0.01	0.14	0.14
Scenario a): High-efficiency gas	300	0.09	0.02	0.008	0.06	0.07
Scenario b): Average gas	450	0.17	0.02	0.009	0.06	0.07

5.3 Challenges

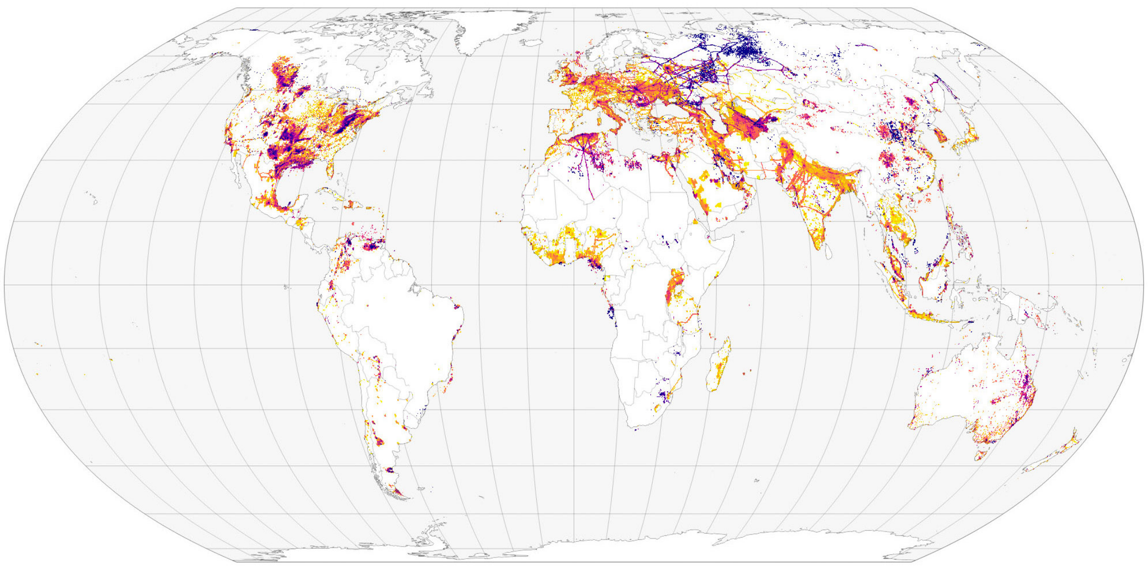
The availability of natural gas infrastructure, such as pipelines, is not uniform globally or even within a given country, posing a significant, and potentially insurmountable, barrier in regions where this infrastructure is underdeveloped or absent. This issue is especially present in countries without domestic natural gas sources.

Transitioning to natural gas necessitates initial investments. Textile manufacturers must retrofit or entirely replace existing coal-based systems with those designed for natural gas, involving upfront capital expenditure. The need for new combustion equipment, modifications to existing facilities, and the establishment of a reliable connection to natural gas supply lines can be a challenge to some companies, especially small- and medium-sized enterprises, due to the upfront costs.

The higher cost of natural gas compared to coal in most countries and the volatility of natural gas prices is also a barrier to adoption. Unlike coal, which can be stored for long periods, natural gas requires a continuous supply chain, making it susceptible to price fluctuations. Dependence on natural gas introduces vulnerability to supply disruptions caused by geopolitical issues, natural disasters, or infrastructure failures. For textile manufacturers operating in regions dependent on natural gas imports, this risk is amplified by potential geopolitical tensions or trade disputes that can restrict access to natural gas, thereby impacting production schedules and operational efficiency.

Although natural gas is considered cleaner than coal, it is not without environmental impacts. It is a much more potent greenhouse gas than CO_2, and it is often unintentionally released during the production and transportation process (the gas is referred to as methane when it leaks but as natural gas when it is discussed as a fuel.) Methane leaks can occur in all parts of natural gas production and transportation, from connections between pipes and vessels, to valves and equipment. The International Energy Agency estimates that the production and use of natural gas resulted in 29 million tonnes of methane emissions in 2023 (Figure 41). Of the top textile-producing countries, the US and China were also top methane emitters. Addressing these methane emissions is crucial for the climate advantages of natural gas to be realized.

FIGURE 41: MAP OF METHANE EMISSIONS FROM FOSSIL FUEL EXTRACTION, 2016 Source: Cassidy 2022



5.4 Supply and Infrastructure

Natural gas is generally transferred through pipelines, but it can also be chilled and turned into a liquid form called liquid natural gas (LNG). LNG takes up approximately 1/600th the volume of gaseous natural gas, allowing it to be efficiently transferred. LNG is the primary way to export natural gas via large tankers around the world to areas that lack natural gas.

For many top textile-producing countries, natural gas largely comes from imports as opposed to domestic production. For example, Turkey and Germany are fully reliant on imported natural gas.

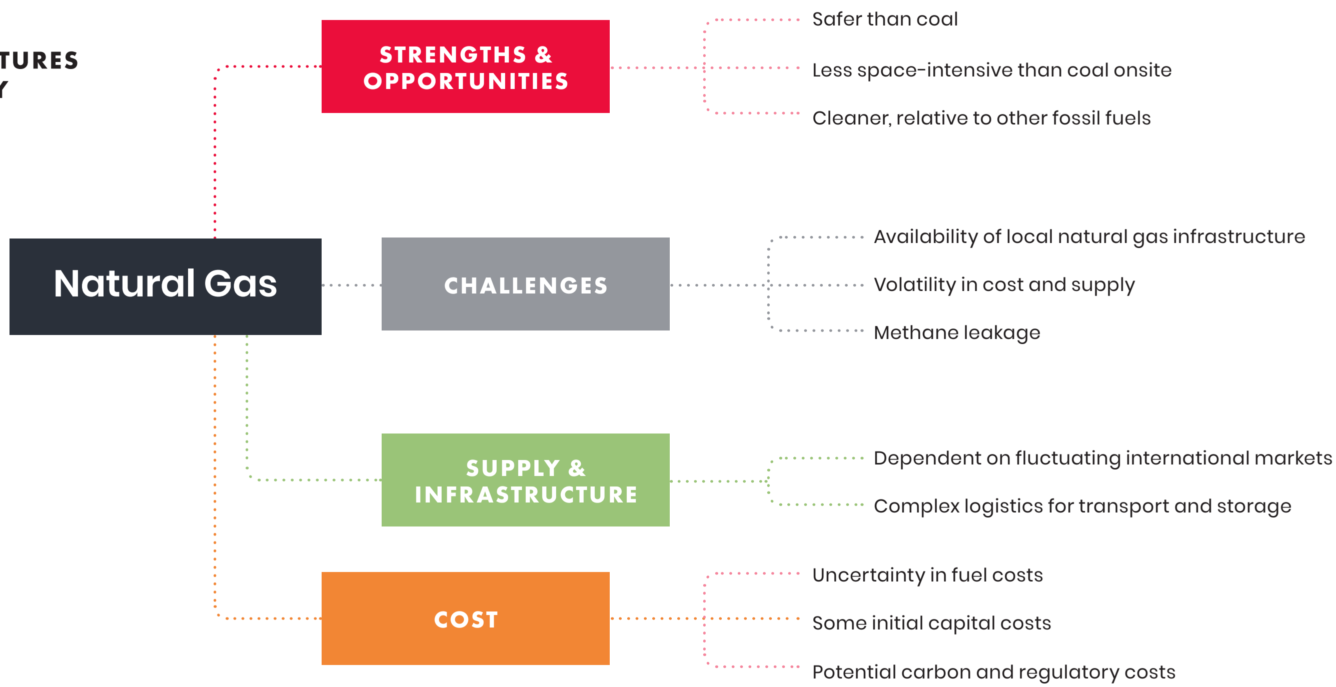
5.5 Cost

Switching to natural gas requires an initial capital investment to retrofit or replace existing coal-fired boilers and heating systems with natural gas-powered alternatives. This transition not only involves potentially purchasing new combustion equipment but also encompasses expenses related to modifying existing infrastructure to accommodate natural gas use, such as installing gas pipelines. Figure 49 shows that the capital cost of natural gas boilers is lower than for new coal boilers. While replacing coal with natural gas boilers may have initial CAPEX costs, they generally offer lower operational and maintenance expenses over their lifecycle compared to coal-fired boilers.

The availability and cost of natural gas are also influenced by regional infrastructure and supply dynamics. In regions without well-developed natural gas pipelines and supply networks, the costs and logistical challenges of establishing a reliable natural gas supply may be prohibitive. For facilities in remote areas or countries heavily reliant on imported natural gas, considerations around LNG imports—including the need for regasification infrastructure—can further add costs.

Figure 42 summarizes the strengths and opportunities, challenges, supply and infrastructure situation, and cost of natural gas boilers for the textile industry.

FIGURE 42: SUMMARY OF NATURAL GAS BOILER FEATURES FOR THE TEXTILE INDUSTRY



5.6 Natural Gas Readiness for Major Textile-Producing Countries

To assess readiness to switch to natural gas in the textile industry, we examined the following metrics for each country: fuel carbon intensity of the textile industry, the share of gas in the total energy supply, reliance on imported natural gas, and the total length of gas pipelines in each country. The fuel carbon intensity methodology has been discussed above in Section 2.2. For the share of gas in the total energy supply, we analyzed data from the IEA. Countries that have more gas in their total energy

FIGURE 43: SHARE OF NATURAL GAS IN TOTAL ENERGY SUPPLY
Source: IEA 2022

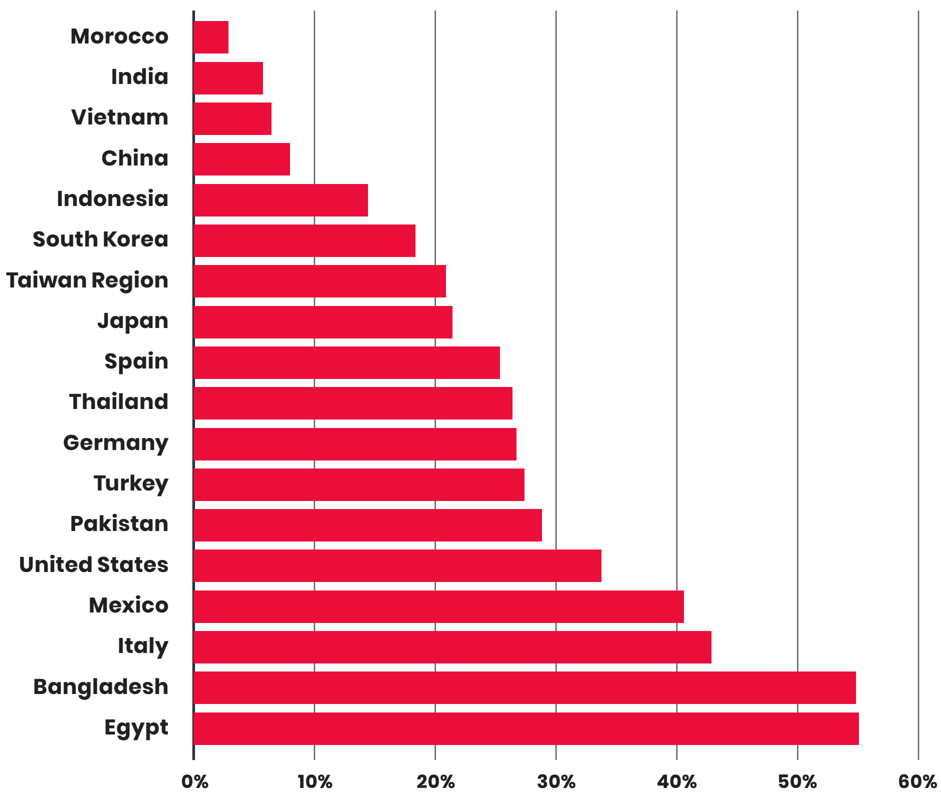
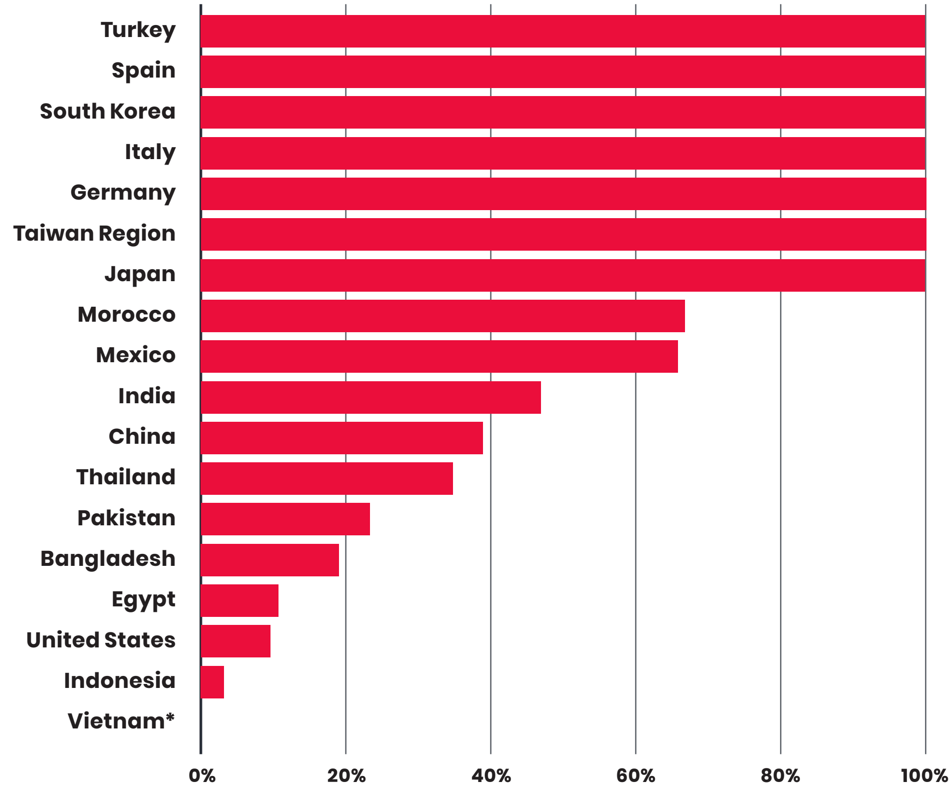


FIGURE 44: SHARE OF IMPORTED NATURAL GAS IN TOTAL GAS CONSUMPTION FOR THE 20 MAJOR TEXTILE-PRODUCING COUNTRIES
Source: IEA 2022

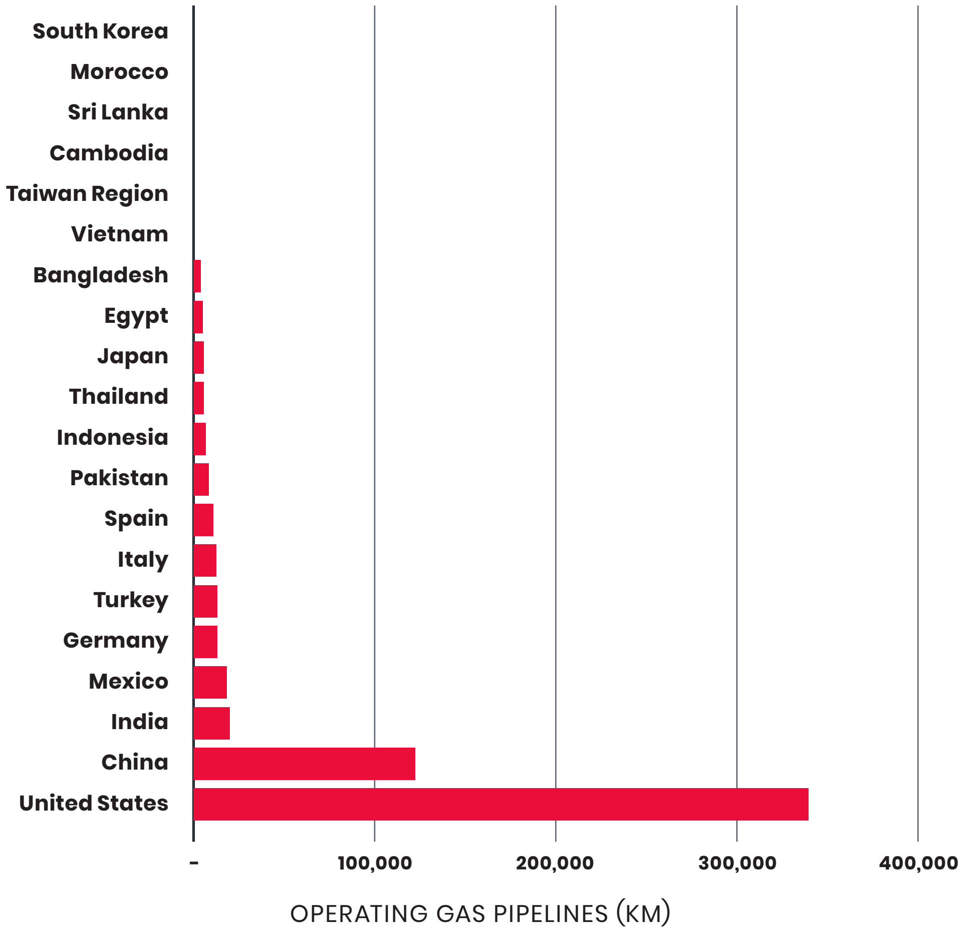
Note: Vietnam imports no natural gas, but it also uses very little natural gas.



supply have more infrastructure for transporting and distributing natural gas and likely have a more readily available supply for facilities interested in switching fuels. These countries are Egypt, Bangladesh, Italy, and Mexico (Figure 43).

Another important metric for natural gas supply is the share of natural gas imports in total natural gas consumption. This shows how reliant a country is on external sources of natural gas, which can be subject to price and supply volatility that could hamper switching to natural gas in the textile industry. Seven of our 20 countries studied imported 100% of their natural gas: Turkey, Spain, South Korea, Italy, Germany, Taiwan Region, and Japan (Figure 44).

FIGURE 45: OPERATING NATURAL GAS PIPELINES IN MAJOR TEXTILE-PRODUCING COUNTRIES Source: Global Energy Monitor 2024



In addition, we collected data on the total length of currently operating natural gas pipelines in each country based on the Global Energy Monitor Global Gas Infrastructure Tracker (Global Energy Monitor 2024). While pipeline length is generally correlated with the land area of the country, it is also an important metric for how much natural gas infrastructure is available to potentially deliver it to industrial facilities. By far, the US has the longest pipeline lengths as it is a major natural gas producer, user, and exporter. South Korea and Morocco had no natural gas pipelines, while Sri Lanka, Cambodia, Taiwan Region, and Vietnam had less than 1000 km of pipelines.

We combined the aforementioned metrics by ranking each country and creating an overall composite readiness score, where a higher score indicates more readiness for adopting natural gas to decarbonize heating in the textile industry. Figure 46 below categorizes countries based on their readiness for switching to natural gas based on percentiles for their readiness scores. We excluded Bangladesh and Egypt because they already use a significant amount of natural gas in their industrial sectors. China, Pakistan, Thailand, and the US are most likely to have available natural gas and infrastructure for potential supply to the textile industry in the near term, while the countries listed as “Less Ready” are not producers of natural gas, rely on imports, and have more attractive decarbonization options.

FIGURE 46: READINESS FOR SWITCHING TO NATURAL GAS IN MAJOR TEXTILE-PRODUCING COUNTRIES IN THE NEAR TERM

Note: Bangladesh and Egypt are excluded since they already have significant natural gas use in the textile industry.

Readiness for Switching to Natural Gas

FOR MAJOR TEXTILE-PRODUCING COUNTRIES

MOST READY	MODERATELY READY	LESS READY WITHOUT SUPPORT
China	**Germany**	**Cambodia**
India	**Indonesia**	**Morocco**
Mexico	**Italy**	**Spain**
Pakistan	**Japan**	**South Korea**
Thailand	**Taiwan Region**	**Sri Lanka**
United States	**Turkey**	**Vietnam**

China and India had favorable scores for switching to natural gas relative to other countries evaluated, of which only the U.S. is a major natural gas producer. While both China and India do have some natural gas transmission and distribution infrastructure, it is unlikely that the textile industry would be a priority for directing limited supply, as both countries are also reliant on a large share of imported natural gas. In addition, China has relatively limited infrastructure for detecting methane leaks from fossil fuel-related activities (Yang et al. 2022), creating risks for natural gas as a lower carbon solution for industrial heating. Thus, the ranking of "most ready" should only be considered in relative terms, as even these countries still face major challenges in adopting natural gas as an alternative fuel for the textile industry.

Vietnam ranked as least ready, with Vietnam using a negligible amount of natural gas. Germany ranked moderately well, with a large share of natural gas already in Germany's total energy supply and associated infrastructure. However, given the ongoing war in Ukraine and conflict with Russia that will affect fuel supply and prices, natural gas switching is a poor strategy for Germany in the near- to medium-term, and electrification is much more attractive for the country. Overall, while our assessment shows relative readiness for natural gas adoption across countries, natural gas is less favorable as a low-carbon thermal heating solution for the textile industry relative to other technologies and energy sources.

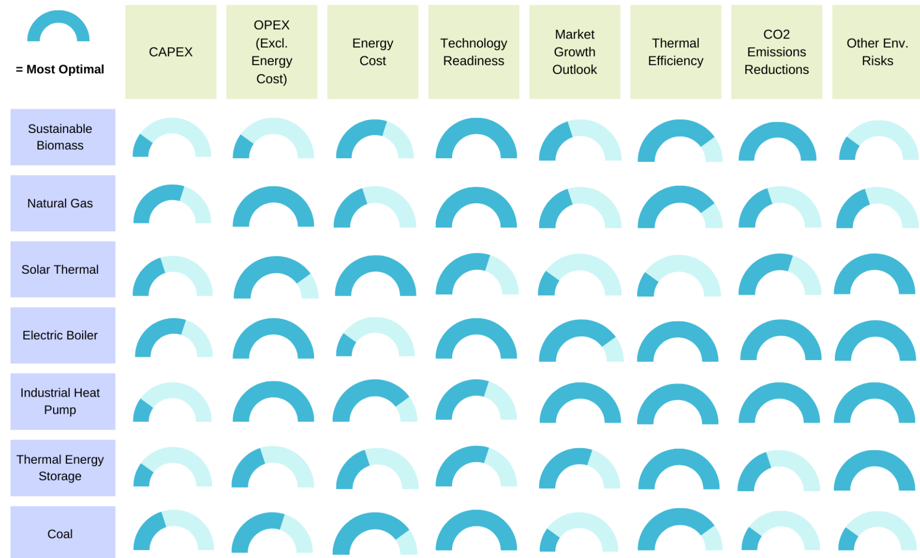
6. Low-Carbon Energy Source and Technology Evaluation

Following the country readiness evaluation, we evaluated each energy source and technology based on a number of indicators to allow cross-technology comparison regarding the overall maturity and applicability of each technology for the textile industry. The indicators we used were capital expenditures (CAPEX), operational expenditures (OPEX), energy costs, technological readiness, market growth outlook, thermal efficiency, CO_2 emissions, and other environmental risks. Each of these indicators was assigned a score from 1 to 5 based on a combination of qualitative and quantitative data, with 5 representing a feature that makes the energy source or technology most attractive for adoption. For example, sustainable biomass that is carbon neutral has a CO_2 emissions indicator score of 5, which does not represent that emissions are high, but rather that the technology is optimal from an emissions perspective and is a zero-carbon source of energy. It is important to note that this is a general assessment and conditions at the facility level will be highly context-specific.

Table 9 below summarizes the studied energy sources and technologies with their rating for each technological indicator. A full bar means the most optimal rating for each indicator. Across the indicators, electric boilers and industrial heat pumps rank highly in the most indicators, due to their low OPEX, high market growth outlook, high efficiency, CO_2 emissions reduction potential when paired with renewable energy, and low environmental risks. While we did not specifically analyze unsustainable biomass or natural gas plus leaked methane, those energy sources would have low scores for CO_2 emissions reduction and technology readiness since adequate leakage prevention technologies are still emerging for natural gas while sustainable biomass supply chains are unstable in many places. Sourcing these fuels sustainably could also add to overall energy costs.

TABLE 9: LOW-CARBON ENERGY SOURCES/TECHNOLOGIES EVALUATION MATRIX Source: this study

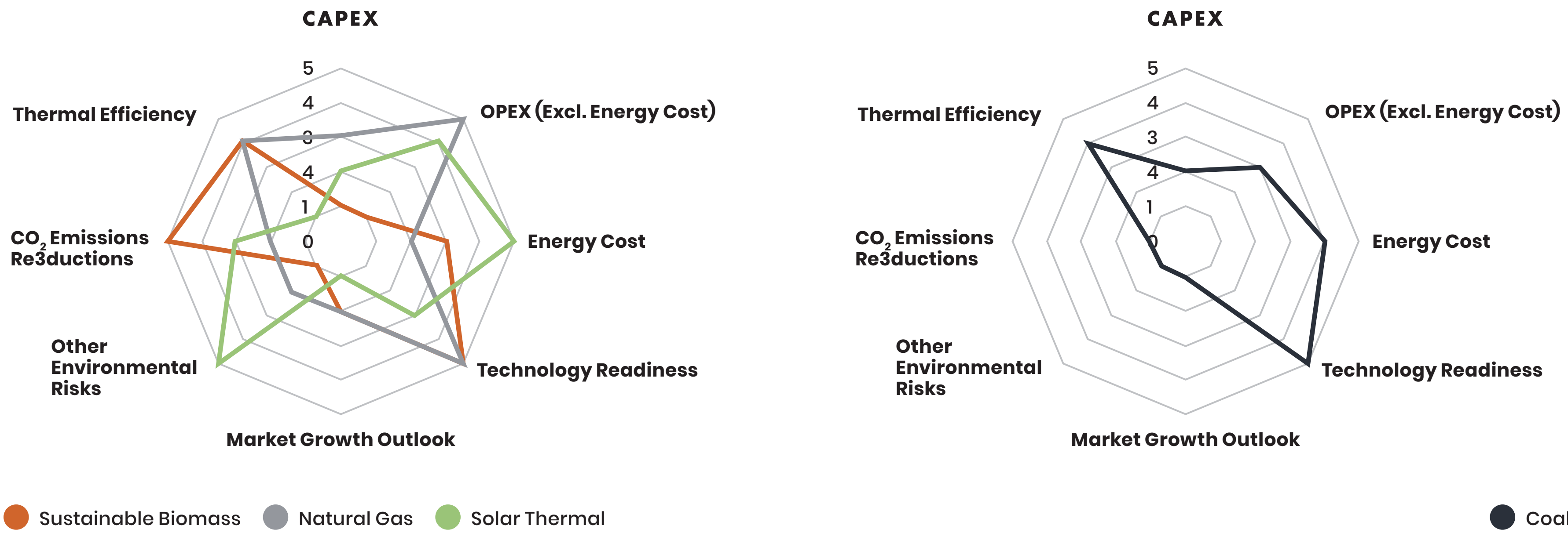
Note: A full bar means the most optimal rating for each indicator.



Note: For CO_2 emissions reductions, it is assumed that biomass is sustainably sourced and is carbon neutral, and renewable electricity is used in electric boilers, heat pumps, and thermal energy storage.

Figure 47 below compares the alternative lower-carbon fuel sources of sustainable biomass, solar thermal, and natural gas with coal. The larger the area encompassed by the polygon representing each energy source, the more optimal the energy source is for adoption in the textile industry across all indicators.

FIGURE 47: CROSS-INDICATOR COMPARISON OF FOUR ENERGY SOURCES FOR PROCESS HEATING IN THE TEXTILE INDUSTRY



Coal is technologically mature but has the worst emissions and environmental risks of the considered energy sources. It has high capital costs, although it is important to note that these costs are already sunk in many facilities. Operational costs and energy costs are medium-low.

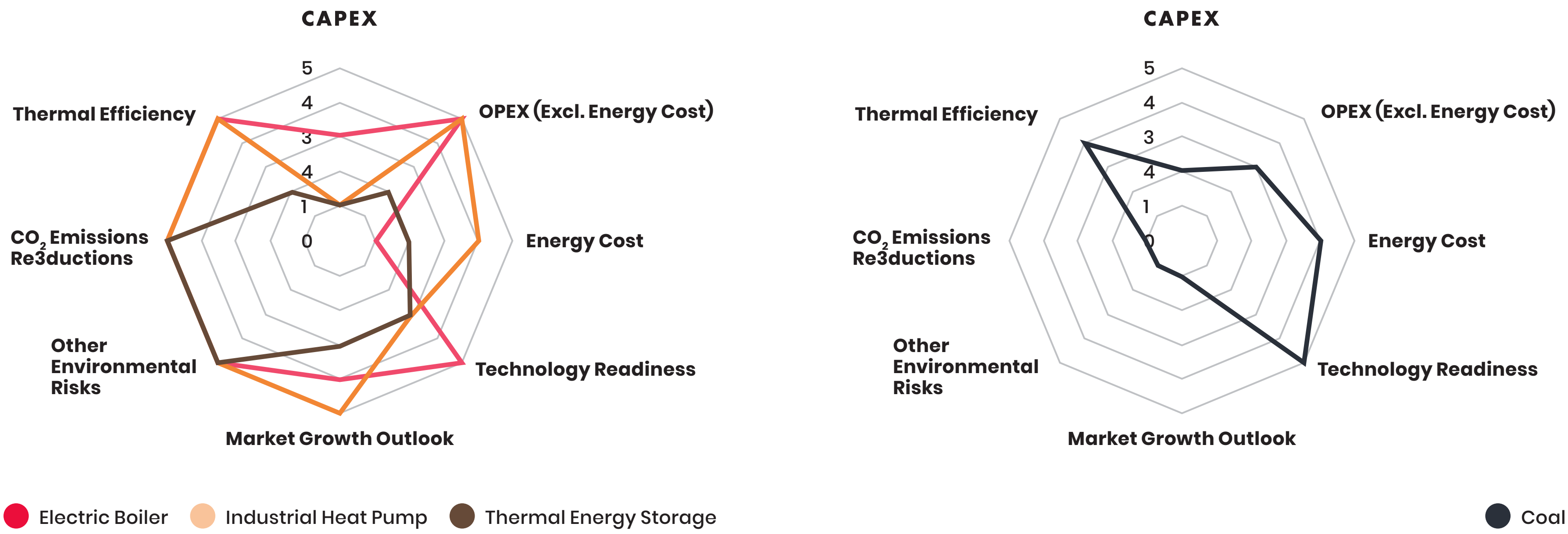
For biomass, CO_2 emissions reduction is a positive aspect of biomass adoption, assuming that carbon-neutral sources of biomass can be procured. However, other environmental risks are a concern, especially with regard to deforestation and land use change. Biomass fuel may also potentially be costly. CAPEX and OPEX may also be a deterrent to adoption.

For natural gas, CAPEX is middling and OPEX is expected to be low and a minor consideration. Energy costs could be a deterrent given the high and volatile gas prices in many countries. Gas boilers are a mature technology and are expected to have some uptake in global markets, though increasing concern about climate impacts and infrastructure challenges may impact market growth. Finally, CO_2 emissions and other environmental risks could pose barriers given methane leakage (see Section 5.3).

Finally, solar thermal technologies are the least technologically ready of the energy sources studied for applications in the textile industry, but they are expected to be zero-carbon with low environmental risk. CAPEX is a barrier, but energy costs would be minimal due to utilizing solar energy. However, overall efficiency for steam production is very low, leading to less overall energy savings and emissions benefits.

Next, we compared the electrification technologies covered in this study, with coal still visualized as a comparison point. Figure 48 shows the comparison of these technologies.

FIGURE 48: CROSS-INDICATOR COMPARISON OF ELECTRIFICATION TECHNOLOGIES FOR PROCESS HEATING IN THE TEXTILE INDUSTRY, PLUS COAL



Electric boilers are the most mature electrification technology, and they have low operating costs and middling capital costs. They are highly efficient and can significantly reduce emissions when paired with zero-carbon electricity (as with the other electrification technologies).

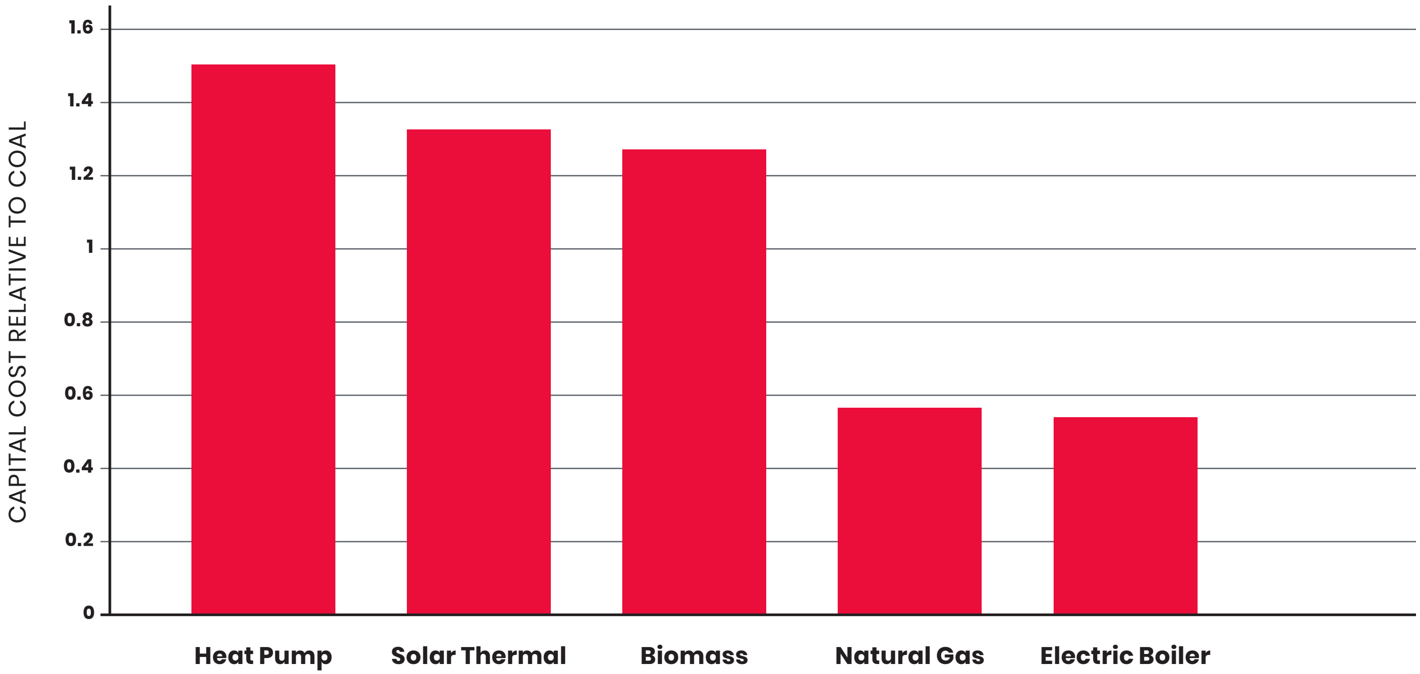
Industrial heat pumps currently face barriers with regard to capital costs, but they are highly efficient and are expected to enjoy significant market growth due to increasing awareness and demand. Due to their efficiency, energy costs are expected to be fairly optimal despite using electricity, which is usually more expensive than traditional fossil fuels currently.

Finally, thermal energy storage systems are less technologically mature and their growth for textile industry applications is more uncertain. CAPEX and OPEX could be significant barriers, although their environmental benefits would be large.

Figure 49 below presents CAPEX estimates based on costs per unit of capacity (e.g. $/MW) for each alternative energy source and two electrification technologies relative to new coal boilers. We used data from multiple studies to assess average estimates relative to coal (IRENA 2023) (Han et al. 2017) (EECA 2023) (Zuberi et al. 2021) (Zuberi et al. 2022). CAPEX for electric boilers and natural gas boilers are expected to be lower than for a new coal boiler (it is important to note that capital costs for existing coal-fired boilers are already sunk costs). Heat pumps are expected to have the highest relative CAPEX per unit of capacity, with solar thermal and biomass boilers also more costly than new coal boilers, potentially requiring CAPEX support to achieve commercial viability.

FIGURE 49: CAPITAL COSTS OF ELECTRIC, BIOMASS, AND NATURAL GAS BOILERS RELATIVE TO COAL-FIRED BOILERS

Source: Han et al. 2017



7. Conclusion and Recommendations

In this report, we have provided a comprehensive overview and analysis of six low-carbon energy sources and technologies for process heating in the textile industry: sustainable biomass, solar thermal, electric boilers, industrial heat pumps, thermal energy storage systems, and natural gas (as a potential transition fuel). One key takeaway is that electrification technologies, including electric boilers, industrial heat pumps, and thermal energy storage systems, are gaining traction as a major decarbonization lever for textile companies.

From a technology readiness level (TRL) perspective, all of the energy sources and technologies covered are commercially available. However, readiness and ability to adopt the technologies and leverage them for decarbonization varies across major textile-producing countries.

We have also summarized the opportunities and challenges for adopting low-carbon energy sources and technologies for process heating in the textile industry, highlighting the special potential of electrification technologies. In addressing these challenges and leveraging these opportunities, several key actions are recommended for apparel companies and textile suppliers. These actions are tailored to support the increased adoption of low-carbon energy sources and electrification technologies within the textile industry.

8.1 Recommendations Regarding Biomass Adoption in the Textile Industry

Biomass use has been increasing in Asia. However, the carbon benefits of biomass are questionable if agriculture or biomass harvesting displaces primary forests, which are major carbon sinks and sources of biodiversity and other environmental services. The use of biomass may not bring clear carbon benefits, and it could pose additional social and environmental risks that may also create reputational issues for textile suppliers and brands.

In light of the growing interest in biomass as an alternative fuel source within the textile industry, it is critical to ensure that the adoption of biomass contributes to genuine CO_2 reductions and sustainable development goals. To this end, several recommendations are proposed to guide the responsible and effective use of biomass:

Prioritize Waste and Residue Biomass: Agricultural residues and waste biomass are the least likely to contribute to land-use change that might exacerbate the carbon footprint of biomass sources. Therefore, they are the only realistic sustainable biomass options for textile facilities to consider. Textile facilities should work with other stakeholders to develop shortlists of preferred sources of biomass that are appropriate to local conditions.

Assess Local Biomass Supply Chains: Encourage and prioritize the use of biomass sourced from suppliers that have extensively mapped their biomass supply chains and assessed risks. Adopters of biomass should confirm that the biomass does not contribute to deforestation, degrade natural habitats, or disrupt local biodiversity. Facilities should also emphasize biomass production that supports social welfare, including respecting land rights and providing fair working conditions.

Implement Robust Monitoring, Reporting, and Verification (MRV) Systems: Support the establishment of comprehensive MRV systems to accurately track the carbon footprint of biomass from production through utilization. These systems should assess the lifecycle emissions of biomass to ensure that its use indeed results in net carbon benefits. MRV frameworks should include methodologies for calculating emissions savings from biomass use, taking into account factors such as carbon sequestration potential lost due to land-use change, emissions from biomass production, and transportation.

Promote the Use of Agricultural Residues: Use agricultural residues as the primary source of biomass, rather than virgin timber or crops grown specifically for energy purposes. Agricultural residues, such as rice husks, bagasse, and other crop by-products, represent a sustainable and underutilized resource that can provide energy without necessitating additional land-use change or water consumption. Although supply may be limited in many places, this approach minimizes competition with food production and helps to manage agricultural waste more effectively.

Develop Clear Guidelines for Biomass Sourcing: Create and disseminate clear guidelines for sourcing biomass for suppliers in the textile industry, emphasizing the importance of using residues and waste materials over timber or crops grown on land with high carbon stock or conservation value, which MRV protocols and certifications to adhere to, etc. These guidelines should also address the social implications of biomass sourcing, ensuring that it does not adversely affect local communities' access to resources.

Invest in Local Biomass Supply Chains: Support the development of local biomass supply chains where available to reduce transportation emissions and bolster local economies. Investing in local agricultural residue processing can enhance the economic value of agricultural waste, providing additional income for farmers and reducing the environmental impact associated with long-distance transportation of biomass or other biomass sources.

Facilitate Research and Innovation: Encourage research and development efforts aimed at improving the efficiency of biomass conversion technologies and expanding the types of residues that can be utilized effectively. Innovations in biomass processing and conversion can unlock the energy potential of a wider range of agricultural residues, further reducing reliance on non-renewable energy sources.

8.2 Recommendations Regarding Solar Thermal Adoption in the Textile Industry

Solar thermal technologies have been used for decades for residential water heating, but their application for the textile industry is limited and faces key challenges. Solar thermal technology can readily produce warm water, but industrial applications typically require steam. In addition, solar thermal technologies must be co-located with the textile facility and may require significant amounts of land. Many countries important to global textile production have less solar irradiation and may be land-constrained. Thus, we recommend that solar thermal technologies should not be a priority for the textile industry's decarbonization efforts.

8.3 Recommendations for Adopting Electrification Technologies in the Textile Industry

Our analysis shows that the electrification technologies covered in this report are highly efficient, require minimal additional onsite infrastructure, and are poised to deliver low/no-carbon heating when paired with renewable electricity. Below are recommendations for textile and apparel companies and other stakeholders to advance the adoption of electrification technologies in the textile industry; the first two are critical for electrification technologies to lower this industry's carbon footprint.

Consider Availability of Renewable Electricity in Sourcing Strategies: Apparel brands can evaluate the local landscape for renewable energy and low-carbon electricity availability, the PPA market, and the policy environment when considering sourcing strategies and supplier qualifications. This can determine whether electrification will be viable in the near term.

Advocate for Increased Renewable Electricity Generation: Apparel brands should leverage their influence to advocate for increased renewable electricity generation in countries where their suppliers are located. Collaborating with governments, industry groups, and power utilities to communicate the industry's demand for clean renewable electricity is crucial. Brands can support their suppliers in investing in on-site and off-site renewable energy projects, ensuring clean power supply for electrification technologies.

Support Electric Grid Modernization: To accommodate the shift towards electrification, the modernization of the electric grid is essential. Apparel companies should engage in dialogues with policymakers and energy providers to emphasize the need for grid enhancements, including the integration of distributed renewable generation.

Promote Pilot and Demonstration Projects: Apparel companies can collaborate with suppliers, governments, and research institutions to sponsor pilot and demonstration projects for electrification. Given across-the-board benefits from electrification with heat pumps (Chapter 6), industrial heat pumps should be a priority in these projects. Pilot and demonstration projects can showcase the feasibility and benefits of electrification technologies in textile plants. Success stories from these projects can serve as powerful examples to encourage the widespread adoption of electrification technologies in the textile industry.

Educate and Disseminate Information: There is a critical need to improve awareness among textile engineers, plant managers, and financial stakeholders about electrification technologies and their potential to reduce emissions, especially for the newly commercial technologies (heat pumps and TES). Apparel brands should invest in the creation and distribution of educational materials and organize workshops and seminars to educate their supply chain partners about the benefits and implementation strategies of electrification technologies.

Workforce Development and Training: Given the relative novelty of electrification technologies in the textile industry, cultivating a skilled workforce capable of installing, operating, and maintaining these systems is imperative. Apparel brands should support training programs and initiatives that equip workers with the necessary skills. Collaboration with technical institutions and industry associations to develop standardized training curricula can help ensure a consistent level of expertise across the industry.

Expand Financial Incentives for Electrification Projects: Enhance financial support mechanisms, such as grants, low-interest loans, and tax incentives, for textile companies willing to adopt electrification technologies. Special attention should be given to SMEs in the textile industry, which might face more significant financial barriers to adoption. Encourage banks and financial institutions to offer green financing options for textile companies investing in electrification and renewable energy projects. Green bonds and sustainability-linked loans can provide the necessary capital at favorable terms. International and regional development banks such as the World Bank and Asian Development Bank might also have financing mechanisms to support electrification projects.

Develop Tailored Electrification Policies for the Textile Industry: Implement policies that specifically address the unique challenges and opportunities of electrifying the textile industry. This could include specific targets for renewable energy usage in textile production or encouragement of Energy Service Companies (ESCOs) that specialize in electrification. ESCOs can help textile companies implement electrification technologies with minimized upfront costs, sharing the financial risks and benefits.

Advance R&D for Electrification as a Decarbonization Strategy in Textile Industry: Promote interdisciplinary research and development by sponsoring collaborative projects that unite textile engineers, energy experts, and environmental scientists to create holistic electrification solutions. Encourage innovation through competitions and awards that drive the creation of new, scalable electrification technologies tailored to textile manufacturing needs. Facilitate collaboration and knowledge sharing among textile manufacturers, technology providers, and researchers.

8.4 Recommendations Regarding Natural Gas Fuel Switching in the Textile Industry

Our analysis shows that many countries are constrained by reliance on natural gas imports and may have limited ability to devote and transport supply to textile facilities. In addition, the climate benefits of natural gas relative to coal have come into question as data increasingly shows the impact of methane leaks in the natural gas supply and distribution systems. That is why textile and apparel companies must look beyond natural gas as a transition fuel and actively explore and invest in other low-carbon and renewable energy technologies. These technologies, such as electrification tied with renewable electricity, can provide truly low-carbon heat solutions that align with the pathway to net zero.

Nonetheless, to navigate the complexities associated with natural gas adoption in the textile industry, while also addressing the environmental impacts, particularly methane emissions, the following recommendations are proposed:

Support Policy and Regulation Development: Advocate for the creation and enforcement of stringent regulations on methane emissions from the natural gas industry. Support policies that incentivize the reduction of methane leaks and promote the use of low-emission technologies throughout the natural gas supply chain. For apparel brands, evaluate the regulatory landscape for methane leakage in different countries as an important criterion for sourcing strategies.

Implement Leak Detection and Repair Programs: Encourage textile facilities to adopt advanced leak detection and repair (LDAR) technologies and practices. Regular monitoring and maintenance can significantly reduce methane emissions from natural gas systems. Adopting best practices in pipeline integrity and equipment maintenance can minimize leaks. Where possible, evaluate upstream leaks and whether leaks have been monitored during production and transport to the facility.

Lifecycle Analysis and Carbon Footprint Assessment: Encourage textile companies to conduct comprehensive lifecycle analyses and carbon footprint assessments of their natural gas usage. Understanding the full environmental impact can help in making more informed decisions about energy sources.

Diversification of Energy Sources: Encourage textile facilities to diversify their energy mix by integrating renewable energy sources with natural gas. Hybrid systems can reduce reliance on natural gas imports and enhance energy security while contributing to emissions reduction goals.

In summary, to implement these recommendations effectively across alternative energy sources and electrification technologies, a collaborative approach involving multiple stakeholders is essential. Apparel brands, being at the forefront of the supply chain, can play a strategic role in driving change by:

- Establishing clear goals and timelines for the adoption of low-carbon energy sources and electrification technologies within their supply chains.
- Creating incentives for early adopters and recognizing suppliers who demonstrate leadership in implementing low-carbon heating technologies.
- Engaging in policy advocacy to support the development of favorable regulatory environments for renewable energy, low-carbon energy sources, and electrification.
- Facilitating access to financing options for both CAPEX and OPEX and technical expertise for suppliers looking to invest in electrification technologies.
- Monitoring progress and evaluating the impact of low-carbon energy sources and electrification initiatives on reducing CO_2 emissions within the textile industry.

By taking a proactive stance on decarbonization, apparel companies and brands can not only contribute to reducing the climate impact of their supply chains but also position themselves as leaders in the transition towards a net-zero textile industry.

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