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Electrification of Heating in the Textile Industry

A Techno-Economic Analysis for China, Japan, and Taiwan

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Executive Summary

The textile and apparel industry currently accounts for approximately 2% of global anthropogenic greenhouse gas (GHG) emissions. The sector has been growing rapidly in recent years, due to increasing demand from both developed and developing countries and world population growth, which will increase its environmental and climate impacts unless effective steps are taken to abate them. For these reasons, the textile and apparel sector is keenly interested in identifying and implementing opportunities to reduce its carbon and environmental footprint.

As is the case in many other industrial sectors, a key challenge for the textile industry in lowering its carbon footprint is its heavy reliance on thermal energy – steam and hot water – for its industrial processes; heating typically represents over half of total energy demand in the textile industry in China, Japan, and Taiwan, which are the economies studied in this report. In textile plants, this heat is often delivered as steam that is primarily generated by combustion boilers using fossil fuels. A significant amount of thermal energy is lost during steam generation and distribution (around 25%-30%).

There is a significant opportunity to decarbonize the textile and apparel industry by electrification of process heating where low- or zero-carbon electricity is used.

There is a significant opportunity to decarbonize the textile and apparel sector by shifting heat production away from inefficient and carbon-intensive fossil fuels to more efficient, clean electrified processes where low- or zero-carbon electricity is used. Based on careful investigation of the different heat demand profiles in the textile processes and the electrification technologies available in the marketplace to meet those heating needs, this report identifies and analyzes four separate electrification pathways with the ability to lower the CO_2 footprint of the textile industry. We quantify the potential energy savings, CO_2 emissions reductions, and costs of each technology pathway in each of the three economies studied.

The four electrification technology pathways analyzed are:

1) Industrial heat pumps (only for the textile wet-processing industry)
2) Electric steam boilers (for the entire textile industry)
3) Electric thermal oil boilers (for the entire textile industry)
4) Electric processing equipment (only for seven textile wet-processing processes)

Our results show that electrification can substantially decrease the total annual final energy demand in the textile industry in these three economies under all four electrification technology pathways. For example, the total technical annual energy saving potential through the application of industrial heat pumps in textile wet-processing plants (assuming a 100% adoption rate) is estimated to be around 270, 7.0, and 7.3 petajoules (PJ) per year in China, Japan, and Taiwan, respectively. This is equal to around one-third of total fuel used in the textile industry in these three economies. The substantial reduction in annual final energy demand is due to the increase in energy efficiency with electrified heating systems and reduction in energy losses that happen in conventional combustion heating systems.

The CO_2 emissions impact resulting from the electrification is highly dependent on the carbon intensity of the electricity used with the electrified process. Figure ES1 shows the CO_2 emissions reductions resulting from electrification under each of the four electrification technology pathways in 2050. For example, the total annual CO_2 emissions reduction potential from 100% adoption of electric steam boilers or industrial heat pumps in the Chinese textile industry is around 29.8 and 24.9 million tonnes (Mt) CO_2 per year in 2050, respectively. These are equal to approximately 59% and 49% of total fuel-related annual CO_2 emissions from the textile industry in China in 2021.

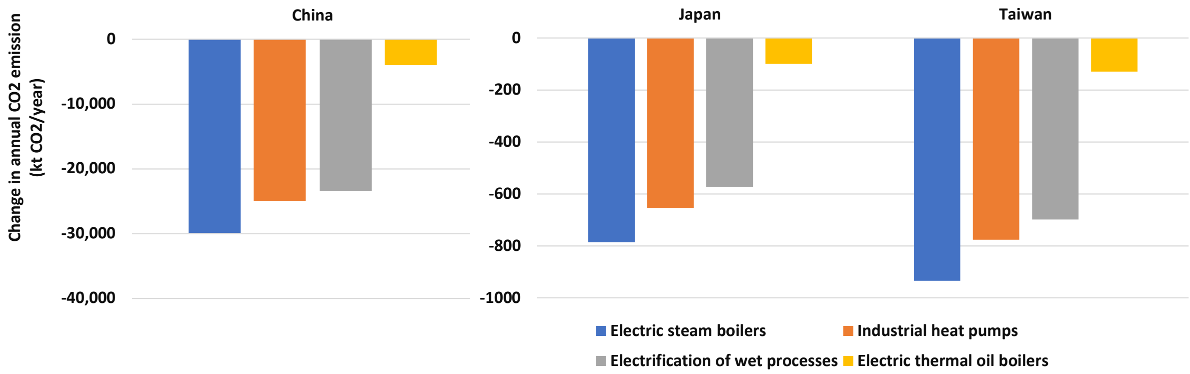

Figure ES1. The change in annual CO_2 emissions after electrification of the textile industry in 2050
(Notes: Figure shows the technical potential assuming a 100% adoption of industrial heat pump applications. Negative values imply a reduction in annual CO_2 emissions)

If the average national grid electricity is used, only electrification of the textile industry through industrial heat pumps can result in CO_2 emissions reduction in 2030 in all three economies. This is because of the substantial reduction in energy use that this heat pumps provide. Electrification of wet processes can result in CO_2 emissions reduction in 2030 in Taiwan and Japan, but not in China, a disparity which reflects the greater carbon intensity of the grid in China compared to the other two economies. Electrification of steam boilers and electric thermal oil boilers could initially lead to an increase in annual CO_2 emissions in all three economies in 2030. This is because the assumed average electricity grid emission intensity for these three economies in 2030 will be high and the grid is not decarbonized enough to result in CO_2 emissions reduction from the electrification of boilers despite the reduction in final energy use. However, electrification is projected to result in a substantial reduction in annual CO_2 emissions in 2040 and 2050 under all electrification technology pathways as the grid decarbonizes and becomes carbon neutral in 2050.

Our analysis for electrification through textile end-use processes shows that around 75% of the CO_2 emissions reduction potential in 2050 comes from electrification of three processes: drying, dyeing, and heat-setting (stenter) (Figure ES2). Around half of the emissions reduction potential comes from electrification of drying and heat-setting processes. The equipment with electrified heating for these two processes are already commercially available and they can be good candidates to start with for end-use process electrification in textile plants.

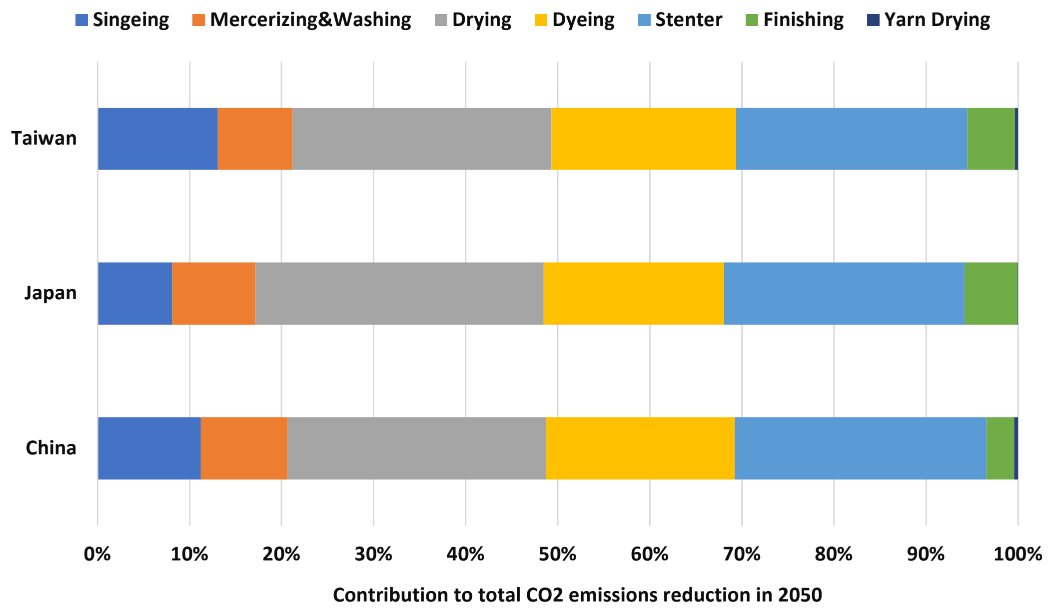

Figure ES2. Contribution of each textile wet processes electrification (in end-use electrification scenario) to total CO_2 emissions reduction in 2050 .

It should be noted, however, that in practice, electrification projects will happen at the plant level. If a given textile plant in any country electrifies its process heating demand today and purchases renewable electricity (e.g., through a power purchase agreement (PPA)) to supply the electricity demand of the electrified process heating, the CO_2 emissions reductions from electrification can be achieved immediately. Therefore, our country-level results should not be interpreted in a way that electrification cannot be beneficial now and we should wait until the electricity grid is decarbonized.

Plant-level emissions reductions can be achieved today through electrification projects, particularly when a renewable electricity supply is available.

Our analysis also evaluated the cost of the electrification of the four technology pathways; these cost calculations focus only on energy costs and do not include the capital costs associated with purchasing new equipment. Only in the case of industrial heat pumps, the energy cost per unit of production of electrified systems is lower than the conventional systems by 2030. based on assumed energy prices in the three countries analyzed. This outcome again reflects the fact that heat pumps substantially reduce energy use compared to conventional systems. For the other three electrification technology pathways, the electrified processes have higher energy costs per unit of production compared to the conventional process in the near term. But under all pathways, the electrified process has a lower energy cost in 2050 compared to conventional systems. In the best case, the price of renewable electricity may decrease even more rapidly than we have assumed, and/or the price of fossil fuels may increase more substantially, which would accelerate electrification of heating.

It should be noted that the energy cost is only a small portion (5%-15%) of the total manufacturing cost in the textile industry. A moderate increase in energy cost per unit of the product resulting from electrification will have a minimal impact on the price of the final textile and apparel products.

We also provide some key recommendations that can be taken by the textile industry, policymakers, and others to scale up electrification in the textile and apparel industry and accelerate CO_2 emissions reductions.

1. **Increase renewable electricity generation**

   Top priority should be given to increasing renewable electricity generation capacity and the decarbonization of the electric grid in the three economies studied in this report and the rest of the world, so that CO_2 emissions reductions go hand in hand with electrification initiatives undertaken by textile manufacturers and apparel brands. To achieve that aim, governments should consider financial incentives that reduce renewable energy costs and carbon taxes that increase the costs of fossil fuels. To be successful, it is also essential that governments develop a coherent power sector strategy that pays attention to the potential rapid increase in demand and competition for renewable electricity across many sectors and end uses, and the subsequent need for additional renewable electricity generation, additional energy storage, and demand response programs. The strategy to increase renewable electricity should incentivize the development of distributed renewable energy generation at industrial sites as well as the central grid.

   Apparel brands can work with their textile suppliers in China, Japan, and Taiwan to increase investment in on- and offsite renewable electricity generation projects and/or work with governments and power utilities through industry groups to communicate private sector demand for increased access to renewable electricity supply.

2. **Enhance and modernize the electric grid**

   As more renewable electricity is generated, it is important to ensure that these additional renewable resources can connect to the transmission and distribution system. This will require grid upgrades that can manage the overall increased clean electricity volume as well as distributed renewable generation. Enhancements should also include resiliency measures to protect against severe weather threats to the grid.

3. **Promote electrification technology development and adoption in the textile sector**

   Governments and utilities should take steps to promote the electrification pathways featured in this report through tax incentives, reduced permitting costs, and grants for switching to electric technologies. Utility rates should be structured to incentivize electrification as appropriate to each economy. Apparel brands can also provide financial incentives to their textile suppliers in China, Japan, and Taiwan to encourage electrification of process heating in their plants.

4. **Promote pilot and demonstration projects**

   Working in partnership with various stakeholders, textile brands and manufacturers should prioritize the further development, demonstration, and scaling of the four electrification pathways featured in this report, focusing first where reduction potentials are greatest and most immediate – i.e., heat pumps and drying and heat setting equipment. Governments, utilities, brands, and financial institutions should provide grants and other incentives for pilot and demonstration projects to encourage early adoption and demonstrate success of electrification strategies for the textile sector.

5. **Create and distribute educational information**

   Many textile engineers, plant managers, apparel brands, financial community, and other important stakeholders are unaware of the potential for the electrification pathways featured in this report to reduce textile and apparel industry's carbon emissions. Educational materials to educate these stakeholders can play an important role in improving policy and investment decisions that deliver real CO_2 emissions reduction.

6. **Workforce development**

Although fully commercialized, because these technologies are relatively new, there are few in the textile industry with experience to install or operate them or troubleshoot when problems arise. Training on installation, operation and maintenance, and other key technical features are critical to the short- and long-term success of increasing reliance on electrification to reduce textile and apparel industry's carbon footprint.

It should be noted that in addition to electrification, other decarbonization options such as energy efficiency, fuel switching to low-carbon fuels and adoption of low-carbon emerging technologies should also be pursued in order to achieve deep decarbonization in the textile industry.

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1 Introduction

The textile and apparel industry has undergone significant changes over the years. In the past, most textile production was based in developed countries and focused on providing goods for their domestic markets. However, the rise of global trade and the globalization of production has led to a shift in the textile industry. Today, textile production is increasingly occurring in developing countries, where labor and resource costs are lower. This has allowed textile companies to remain competitive in the global marketplace. In addition, new technologies have also played a role in the evolution of the textile industry. The textile industry is now more globalized and complex than ever before.

The textile and apparel industry is a major source of employment in many developing countries. In China, for example, the textile and apparel industry employs over 15 million people, mainly young women. The industry is also an important source of employment in other developing countries.

China is by far the world's top textile exporter followed by the European Union and India (Figure 1). Japan and Taiwan, which are the two other economies included in our study, are also among the top 10 textile exporters. The ranking of top exporters is slightly different when only considering the clothing export. China is also the top exporter of clothing followed by the EU, Vietnam, Bangladesh, and Turkey (WTO 2021). These top exporter regions are also among the top textile producing regions and substantial amount of their total production is also used for domestic consumption, especially in countries with large population like China and India.

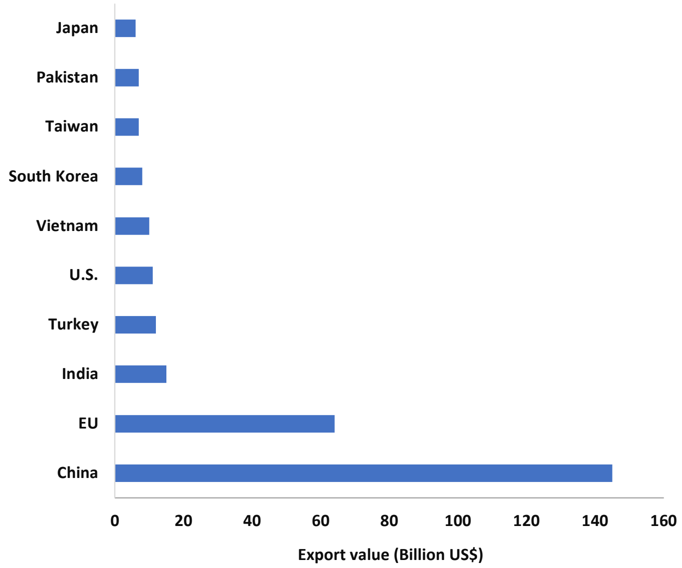


Figure 1. Top 10 exporters of textile in 2020 (WTO 2021)

The textile and apparel industry has been growing rapidly in recent years, due to increasing demand from both developed and developing countries and world population growth. In particular, the rise of online shopping has created a significant market for textile and apparel products. However, the textile and apparel industry faces challenges. One key challenge is to reduce its environmental and climate impact.

The textile and apparel industry accounts for around 2% of global anthropogenic greenhouse gas (GHG) emissions (Sadowski et al. 2021). As the effects of climate change become more apparent and as the world's population continues to grow and consume more textile products, the textile and apparel industry must take serious actions to reduce its impact on the climate and environment. There are several ways to reduce the climate impact of the textile and apparel industry, from using more environmentally friendly materials to deploying more efficient- and low-carbon manufacturing processes.

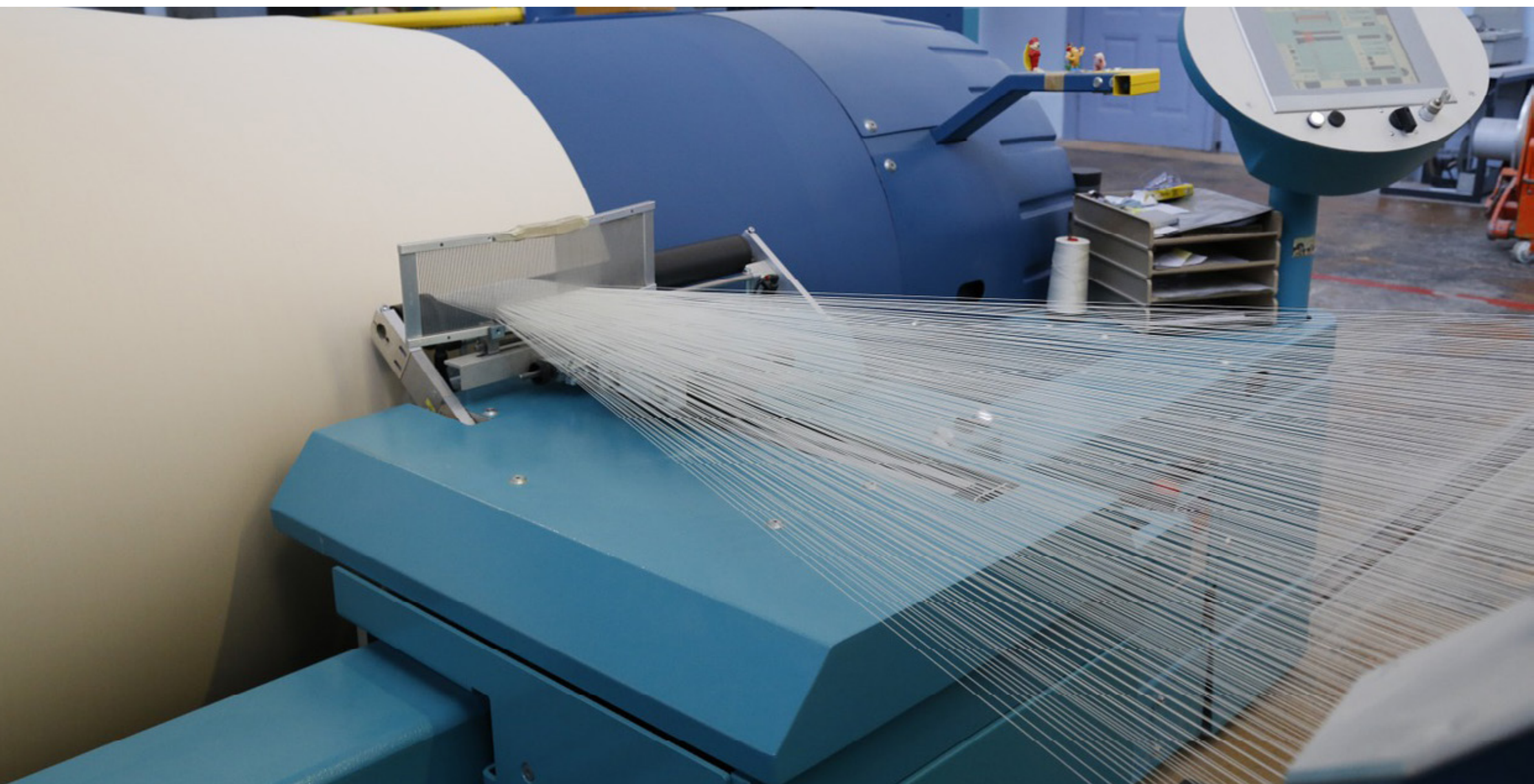
Thermal energy needs especially for heating processes are a significant challenge for climate change mitigation efforts in the textile industry. Heating often represents over half of the total energy demand in the textile industry (see next sections). Almost all of this heat is currently provided by fossil fuels in most countries including China, Japan, and Taiwan, the three economies we have focused on in this report.

There is a significant opportunity to decarbonize the textile and apparel sector by shifting heat production away from carbon-intensive fossil fuels to clean sources such as electrification where low- or zero-carbon electricity is used. This report aims to fill the information gap for the textile industry by examining profiles of heat consumption in this industry and the potential for electrification based on different heat demand profiles and electrification technologies available to meet those heating needs. There is substantial unrealized potential to electrify thermal processes in the textile industry as is shown later in this report.

This report is comprised of a bottom-up system and technology-level techno-economic analysis for electrification of the textile industry in three major textile producing and exporting economies: China, Japan, and Taiwan. The technical assessment provides an analysis of the current state of energy use in the textile industry in these three economies, the technologies available, and the potential for electrification in this sector. We have developed and analyzed four technological pathways for the electrification of the textile industry:

1) Electrification through industrial heat pumps (only for the textile wet-processing industry)
2) Electrification through electric steam boilers (for the entire textile industry)
3) Electrification through electric thermal oil boilers (for the entire textile industry)
4) Electrification through textile end-use processes (for 7 textile wet-processing processes)

Finally, we provide several recommendations that can be taken by industry, policymakers, and others to scale up electrification in the textile industry.



2 Profile of Energy Use in the Textile Industry

2.1. Profile of energy use and CO_2 emissions in the textile industry in China

In China, the textile and apparel industry consumed around 1,500 Petajoules (PJ) of energy in 2019 (IEA 2021) (Figure 2). To put this in context, this is almost equal to the entire electricity consumption of France which itself is the 10th largest electricity consuming country in the world. This energy use resulted in total energy-related CO_2 emissions in the textile and apparel industry in China of around 183 million tonnes (Mt) of CO_2 in 2019.

Around 51% of the total energy used in the Chinese textile industry is electricity (Figure 2). The rest is different types of fuels that are used in thermal processes to deliver heat mainly in textile wet processing (Figure 3). Surprisingly, according to the IEA, coal has a smaller share in the direct fuel used in the Chinese textile industry compared to natural gas. There is a large category of "other fuels" which is mainly the heat purchased by textile plants from other facilities. This purchased heat is often generated from fossil fuels.

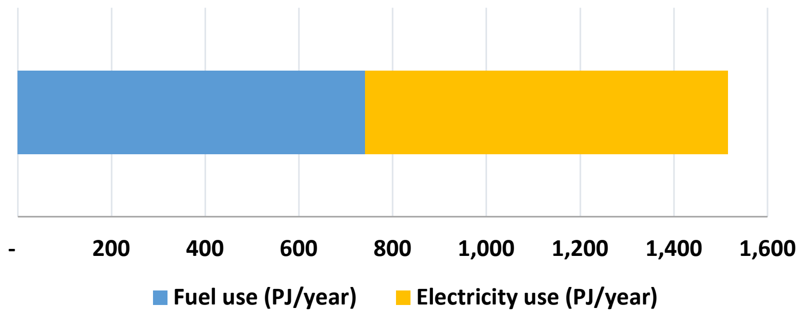


Figure 2. Fuel and electricity used in the textile industry in China in 2019 (IEA 2021).

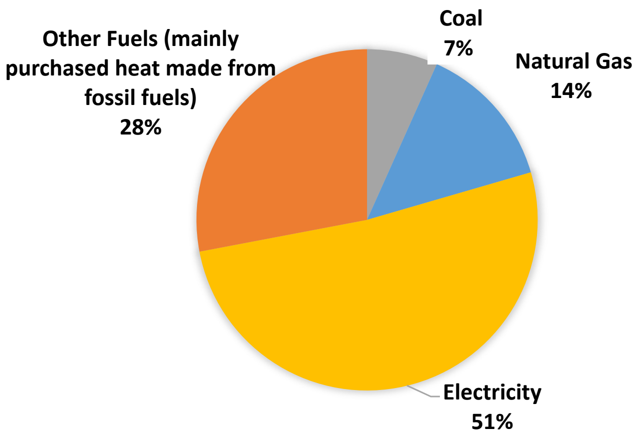


Figure 3. Energy mix in the textile industry in China in 2019 (IEA 2021).

2.2. Profile of energy use and CO_2 emissions in the textile industry in Japan

In Japan, the textile and apparel industry consumed around 33 PJ of energy in 2019 (IEA 2021) (Figure 4). In Japan, electricity has a smaller share (42%) in the total energy mix as opposed to 51% in China's textile industry. Among the fossil fuels used, natural gas has the highest share, 33% of the total energy mix (Figure 5). The total energy-related CO_2 emissions in the textile and apparel industry in Japan were around 3.1 Mt CO_2 in 2019.

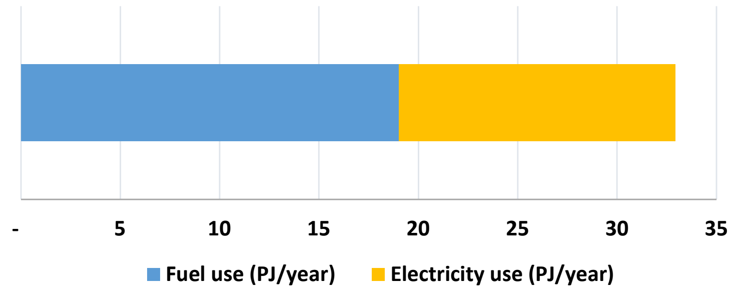


Figure 4. Fuel and electricity used in the textile industry in Japan in 2019 (IEA 2021).

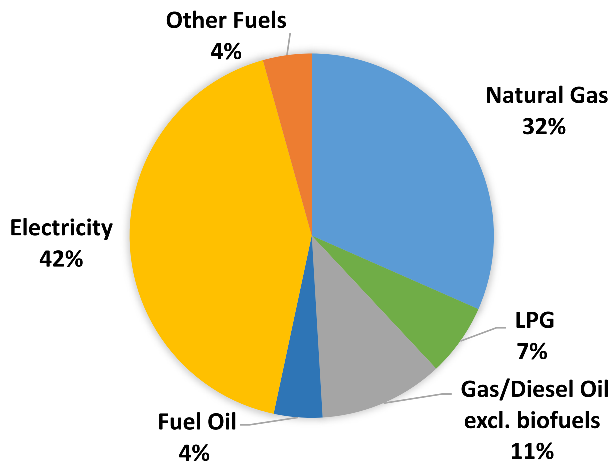


Figure 5. Energy mix in the textile industry in Japan in 2019 (IEA 2021).

2.3. Profile of energy use and CO_2 emissions in the textile industry in Taiwan

The Taiwanese textile and apparel industry consumed around 46 PJ of energy in 2019 (IEA 2021) (Figure 6). Electricity accounted for 47% of the total energy mix. Among the fossil fuels used, coal has the highest share, 24% of the total energy mix followed by natural gas (Figure 7). The total energy-related CO_2 emissions in the textile and apparel industry in Taiwan were around 5.2 Mt CO_2 in 2019.

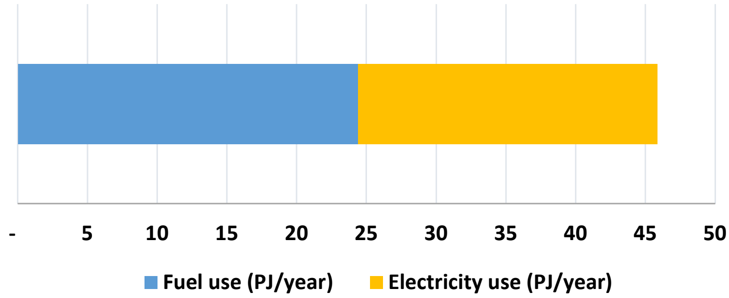


Figure 6. Fuel and electricity used in the textile industry in Taiwan in 2019 (IEA 2021).

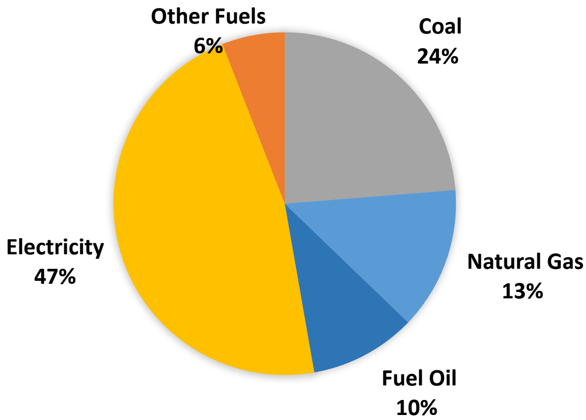


Figure 7. Energy mix in the textile industry in Taiwan in 2019 (IEA 2021).

2.4. Breakdown of energy use by end-use

In a textile plant, energy is used in different end-uses for different purposes. Figure 8 shows the breakdown of final energy use by end use in the U.S. textile industry (US DOE, 2021). Unfortunately, a similar breakdown was not available for the textile industry in China, Japan, and Taiwan. Although the shares shown in the graph can vary from one country to another, this figure gives an indication of final energy by end-use in the textile industry. As is shown in the figure below, in the U.S. textile industry machine drive systems (pumps, fans, compressed air, material handling, material processing, etc.), boilers, and process heating (direct fire systems and thermal oil boilers) have the highest share of the end-use energy consumption in the U.S. textile industry. The end-user systems that use fuel such as boilers, process heating, and cogeneration can be impacted by electrification.

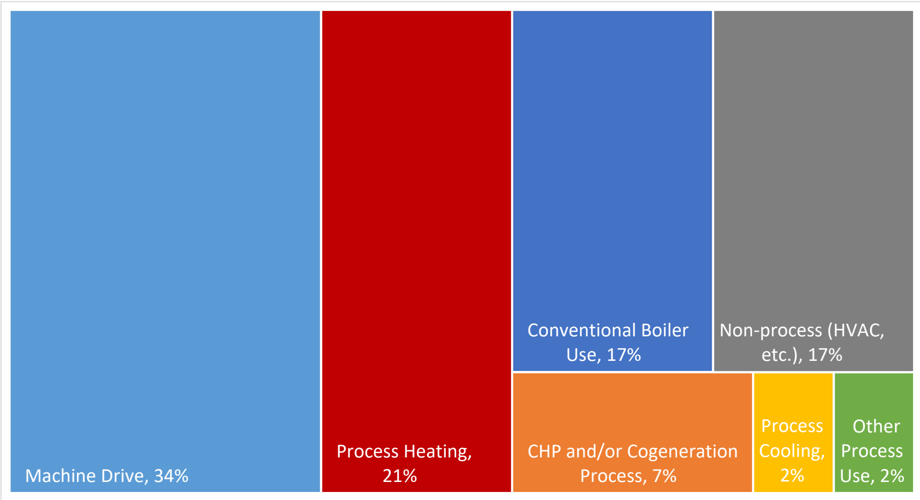


Figure 8. Textile and apparel industry's energy use by end-users in the U.S. in 2018 (US DOE, 2021).

A composite textile plant is a plant that has spinning, weaving/knitting, and wet-processing (preparation, dyeing/printing, finishing) at the same site. Figure 9 shows the breakdown of the typical electricity and thermal energy use in a composite textile plant (Hasanbeigi 2010). As can be seen, spinning consumes the greatest share of electricity (41%) followed by weaving (weaving preparation and weaving) (18%). Wet-processing 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 also lost during steam generation and distribution (35%). Most steam is also used in wet processing. Therefore, electrification of heat supply and heating in wet processing has a large potential for reducing fossil fuel use and reducing GHG emissions in the textile industry.

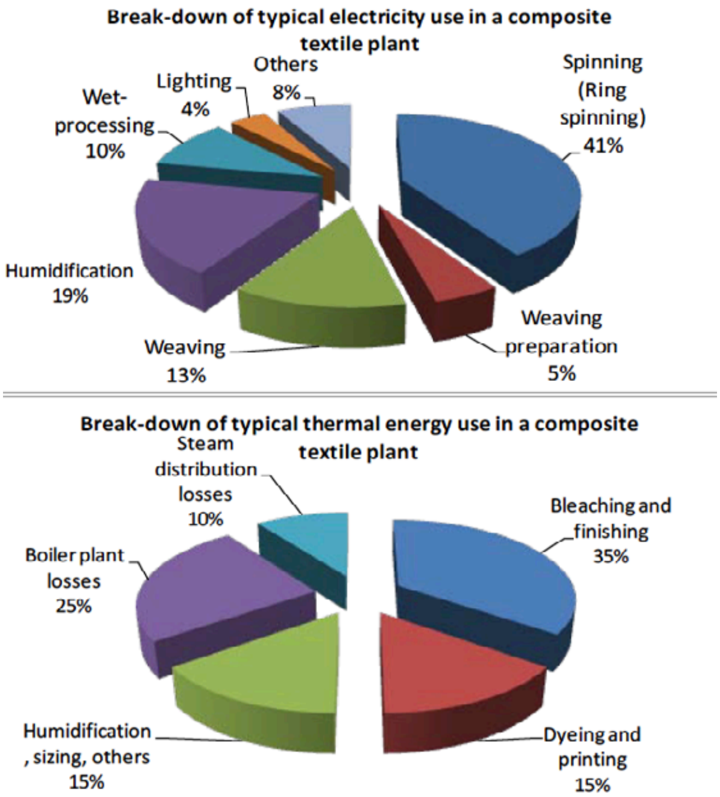


Figure 9. Breakdown of typical electricity and thermal energy used in a composite textile plant (Hasanbeigi 2010).

3 Methodology and Electrification Technologies Scenarios in This Study

In this study, we investigate the electrification of the textile industry in China, Japan, and Taiwan. To do this, we have developed and analyzed four separate technology pathways for the electrification of the textile industry. Our analysis attempts to quantify the potential application, energy savings, CO_2 emissions reductions, and cost for each of these four electrification technology pathways for the entire textile industry in these three economies. However, in practice, the electrification projects will happen at a textile plant level and a combination of these technologies might be used at one textile plant.

The four electrification technology pathways analyzed in this study are:

1) Electrification with industrial heat pumps (only for the textile wet-processing industry)
2) Electrification with electric steam boilers (for the entire textile industry)
3) Electrification with electric thermal oil boilers (for the entire textile industry)
4) Electrification through textile end-use processes (only for seven textile wet-processes)

The detailed analysis method for each of these electrification pathways is explained in the following subsections. The energy savings and CO_2 emissions reduction potentials shown later are total technical potentials assuming a 100% adoption rate of the given electrification technology. The cost analysis only focuses on energy cost per unit of production (finished fabric) and does not include capital cost and other costs associated with conventional and electrified technologies. We used 2021 as the base year and made projections up to 2050 in this analysis.

3.1. Methodology for industrial heat pumps analysis

Heat pumps drive heat from one or more heat sources at low temperatures to one or more heat sinks at high temperatures with the assistance of an external energy source (electricity). The thermodynamic working principle of an electric heat pump is illustrated in Figure 10a. In other words, heat pumps are designed to transfer thermal energy opposite to the direction of natural heat flow by absorbing heat from a cold reservoir and discharging it to a hot one (U.S. DOE, 2003). The external energy or work required to drive a heat pump depends on how much the temperature of the low-quality heat is to be raised.

Heat pumps employ refrigerants as transitional fluids to absorb heat and vaporize in an evaporator. Refrigerants have low boiling points and evaporate even at sub-zero temperatures. Despite the evaporation, the refrigerant is not hot enough to warm the process fluid. Hence a compressor is used to further raise the temperature and pressure of the refrigerant through volume reduction and forces the high temperature and 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 (Gagneja and Pundhir, 2016). Figure 10b presents the heat pump cycle. The most common examples of heat pumps are refrigerators and air conditioners.

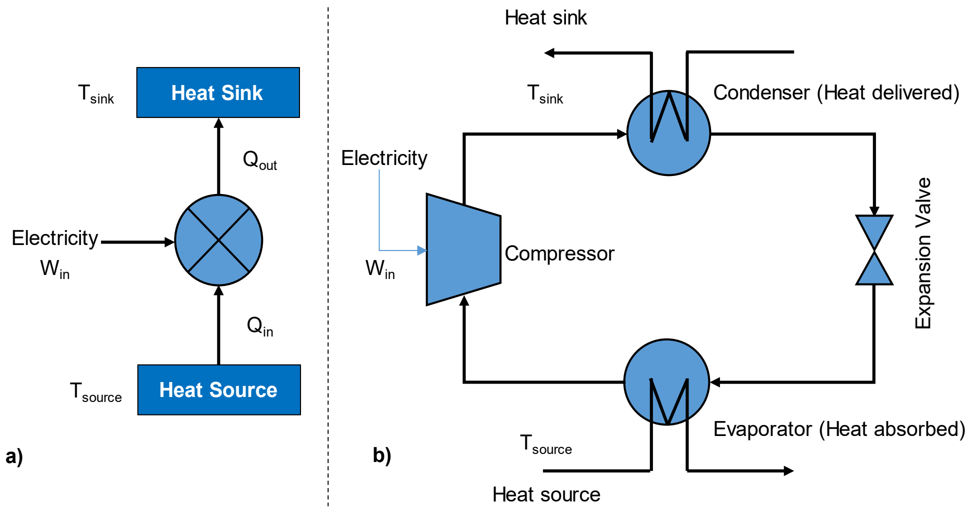


Figure 10. Thermodynamic representation and cycle of a heat pump.
Note: heat is transferred from heat sources (Qin) at low temperatures (Tsource) to heat sinks (Qout) at high temperatures (Tsink).

Heat pumps are very efficient because they only transfer heat, instead of burning fuels to generate it. The performance of a heat pump is expressed as the coefficient of performance (COP) which is the ratio of thermal energy output to external energy input, refer to Eq. 1.

$$COP_{real} = \left(\frac{Q_{out}}{W_{in}}\right) \quad (1)$$

Based on the ideal Carnot cycle, heat pumps operate between two heat reservoirs in the heating mode, having absolute temperatures i.e. T_{source} (heat source) and T_{sink} (heat sink). The maximum theoretical COP can be calculated by Eq. 2. Temperature lift (ΔT_{lift}) is the difference between the heat source and sink temperatures. Due to the losses in thermodynamic processes, the real COP of a heat pump is lower than the maximum theoretical COP. An efficiency term, also called second law efficiency (η_{HP}), that relates the real COP (COP_{real}) to the maximum theoretical COP (COP_{carnot}) is given by Eq. 3. The second law efficiency (η_{HP}) typically ranges between 40% and 60% (Schlosser et al., 2019). We are assuming a conservative value of 45% for our analysis. The COP of a heat pump is always greater than 1 as it transfers more heat than the electricity used.

$$COP_{carnot} = \left(\frac{T_{sink}}{T_{sink} - T_{source}}\right) = \left(\frac{T_{sink}}{\Delta T_{lift}}\right) \quad (2)$$

$$\eta_{HP} = \left(\frac{COP_{real}}{COP_{carnot}}\right) \quad (3)$$

The higher the temperature lift of a heat pump, the lower its COP and the higher its investment and operational costs (Rightor et al., 2022). Hence it is essential to assess the available waste heat sources that can potentially be utilized for optimal heat pump integration into a process. The amount of waste heat resources existing in a textile plant is site-specific and the level of heat pump integration depends on several variables including waste heat volumes, temperature levels, and plant complexity, to name a few. Based on our analysis of the data collected for 40 textile mills in China, Taiwan, and Japan, we assumed that enough waste heat would be available at 60°C to be utilized by heat pumps for textile manufacturing.

However, the proposed heat pump designs in this study may not necessarily be optimal for all relevant textile plants given the site-specific characteristics.
Furthermore, the ranges of industrial heat pump capacities and sink temperatures have significantly progressed over the years. Industrial heat pumps with capacities as high as 100 MW and heat sink temperatures of up to 165°C are now commercially available at scale (Marina et al. 2021; Zuberi et al. 2022). Finally, the potential energy savings (ES) due to the electrification of industrial process heat demand through heat pumps can be estimated by Eq. 4. Energy savings are calculated as the difference between temperature-specific heat demand by current processes (heat sink) and potential electricity demand by a heat pump as a replacement of combustion boilers for the same energy service. Similarly, potential CO_2 abatement (CA) due to a heat pump application and simultaneous electricity grid decarbonization can be determined by Eq. 5.

$$ES = Q_{out} - W_{in} \quad (4)$$

Where;
Q_{out}= Current heat demand at a certain temperature by a process step
W_{in}= Electricity demand by a heat pump for the same energy service

$$CA = (Q_{out} \times f_w) - (W_{in} \times f_{grid}) \quad (5)$$

Where;
f_w = Weighted average fuel emission factor
f_{grid} = National average electricity grid emission factor

In this study, the analysis of the potential application of industrial heat pumps and their impact only focuses on the textile wet-processing industry in these three economies (not the entire textile industry). As shown earlier in the report, textile wet-processing accounts for a large share of fuel used in the textile industry.

We collected the energy intensity and temperature levels of a typical textile wet-processing facility, disaggregated by direct and indirect fuel and electricity demand in each process step. The data was generalized based on the information collected from 40 different textile mills in China, Japan, and Taiwan. The process heat demand at temperatures suitable for industrial heat pump applications was then identified. Table 1 shows the process steam or water temperatures suitable for industrial heat pump applications, which are included in this analysis.

Table 1. Typical process steam temperatures suitable for industrial heat pump applications.

Process	Steam temperature (°C)
Desizing	120
Scouring	120
Mercerizing & Washing	120
Bleach & Wash/rinse	120
Drying	150
Dyeing & Washing	150
Printing	150
Finishing (Pad-dry-cure)	120
Dry & frame	150

Figure 11 shows the schematic of industrial heat pump applications and their corresponding COPs. A high-temperature heat pump (HTHP) can be installed to preheat the makeup feed water to 82°C before it enters the condensate tank for steam generation. The total required heating capacities of HTHPs for the textile wet-processing industry in China, Taiwan, and Japan are estimated at 152 MW, 4.6 MW, and 3.4 MW, respectively. This is relatively low heat capacity demand compared to SGHP (see below) because HTHP is used only to preheat make up feed water from 25 °C to 82 °C. A larger heat demand is needed for SGHP as shown below.

Moreover, most of the processes in Table 1 require hot water at various temperatures which can be supplied by HTHPs directly. However, textile process equipment often has different water retention rates and times of operation. For example, a washing machine may have multiple sections needing hot water in different timeframes and at different temperatures. This may require several small-scale HTHPs only for the washing machine which is techno-economically not feasible. Hence, the process heat to relevant unit operations is provided as steam which can be generated by the steam-generating heat pumps (SGHPs).

Two separate SGHPs can be installed to produce process steam: (1) at 120°C for de-sizing, scouring, mercerizing, washing, bleaching, and finishing (pad-dry-cure), and (2) at 150°C for steam drying, dyeing, and printing. The total required heating capacities of SGHPs in China, Taiwan, and Japan are estimated at 12 GW, 0.32 GW, and 0.31 GW, respectively. It should be noted that the utilization of heat sources possibly available at a temperature higher than 60°C that is assumed in this study may result in a COP higher than currently estimated and consequently the lower electricity demand by industrial heat pumps.

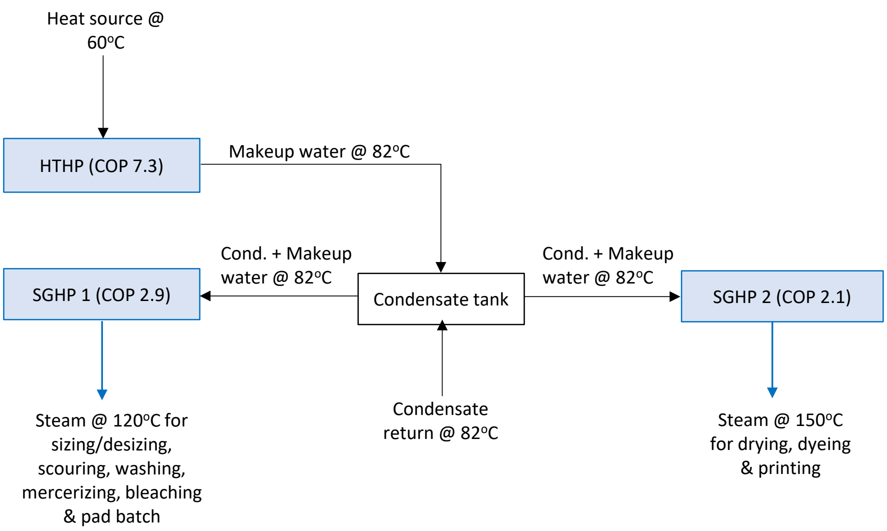


Figure 11. Industrial heat pump applications for textile wet-processing.

HTHPs that can deliver heat at up to 90 °C are more established on the market compared to those that can deliver temperatures higher than 90 °C (e.g. SGHPs). However, SGHPs are also commercial on the market. There are several vendors providing SGHPs and they have also been implemented in the industry (Zuberi et al. 2022). Nevertheless, SGHPs' market is currently smaller and is continuously evolving.

We also used projections for the production of dyed and finished fabric as well as projections of grid emissions factor and unit price of energy to project the energy use, GHG emissions, and energy cost implications of electrification. The electricity grid emissions factor and

average unit price of fuels such as natural gas, coal, and fuel oil used in our analysis are shown in Appendix 1.
It should be noted that the energy savings and change in CO_2 emissions estimated for each process in the following sections are the total technical potentials assuming a 100% adoption rate. The actual adoption of electrification technologies in industry will be gradual over time. The change in energy use results in final energy terms, which means electricity is not converted to primary energy using average electricity generation efficiency and transmission and distribution losses.

The results of our cost per unit of production comparisons are highly sensitive to the unit price of energy (electricity and fossil fuels). The projections of energy prices are highly uncertain. In addition, renewable electricity prices could decrease more substantially than what we have assumed up to 2050, making electrification technologies more competitive. To address this scenario, we included a sensitivity analysis concerning the unit price of electricity in the form of error bars on our price graphs. The error bars show the energy cost per unit of production when the unit price of electricity is reduced by up to 50%.

3.2. Methodology for industrial steam boilers electrification analysis

Combustion boilers that use fossil fuels to generate steam, which provide heating for processes, are dominant in the global textile industry. Water-tube boilers and fire-tube boilers are the most common types of combustion boilers deployed in the industry sector. Electric boilers, which are a mature technology, have a small market share for heat and steam generation in the textile industry due to several techno-economic reasons. Given the high efficiency of electric boilers (97%-99% efficiency) they can have a large contribution to decarbonizing the textile industry.

Electric boilers use electricity to heat water and generate steam. A thermostat is used to control the flow of electric current and the in-turn heating. The most common types of electric boilers are electric resistance boilers and electrode boilers. In electric resistance boilers, an electric-powered resistive element transfers heat to the water, raising its temperature to the process level. In electrode boilers, the electric current passes directly through the water to boil the water. Electric resistance boilers possess lower thermal capacities, typically up to 5 MW_e). On the other hand, electrode boilers have capacities ranging between 3 MW_e and 70 MW_e. (Zuberi et al. 2021).

Compared to fossil fuel combustion boilers with an efficiency of 70-80%, electric boilers are also very efficient (i.e. 97-99% efficiency) with only minimal radiation losses from the exposed boiler surfaces. In addition, electric boilers possess many non-energy benefits such as lower criteria air pollution (depending on electricity grid fuel mix), lower permitting hurdles, and faster ramp-up times compared to combustion boilers (Rightor et al., 2020).

With today's technology, electric boilers (resistance/electrode) are capable of producing hot water and superheated steam at very high temperatures and pressures, unlike industrial heat pumps which cannot go beyond temperatures of 165°C. Figure 12 presents the textile industry's boiler size distribution in the three economies adapted based on Zuberi et al. (2021). This study employs a bottom-up approach to investigate the techno-enviro-economic potentials of deploying electric steam boilers for heat and steam generation in the entire textile industry in China, Japan, and Taiwan up to 2050.

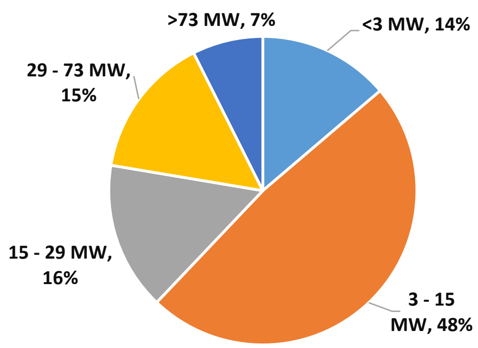


Figure 12. Current combustion steam boiler size distribution assumed for the textile industry in China, Japan, and Taiwan .

The efficiency of combustion boilers (η_{CB}) in the Chinese, Taiwanese and Japanese textile industries is assumed as 80%, while the efficiency of an electric boiler (η_{EB}) is taken as 99% (Zuberi et al. 2021). Similarly, the efficiencies of thermal oil boilers and their alternative electric boilers are taken as 85% and 98% respectively (Sitong boiler n.d.; Leway boiler n.d.). These efficiency levels are used to estimate the potential electricity demand in the future (E_{EB}; estimated using Eq. 6) due to the electrification of steam, hot water, and thermal oil supply in textile manufacturing.

$$E_{EB} = \left(\frac{E_{CB} \times \eta_{CB}}{\eta_{EB}}\right) \quad (6)$$

Where;
E_{CB} = Energy demand by combustion boilers
E_{EB} = Electricity demand by electric boilers

Potential energy savings (ES) due to the electrification of industrial process heat supply through electric boilers can be estimated by Eq. 7. Similarly, potential CO_2 abatement (CA) due to boilers' electrification and simultaneous electricity grid decarbonization can be calculated by Eq. 8.

$$ES = E_{CB} - E_{EB} \quad (7)$$

$$CA = (E_{CB} \times f_w) - (E_{EB} \times f_{grid}) \quad (8)$$

Where;
f_w = Weighted average fuel emission factor
f_{grid} = National average electricity grid emission factor

3.3. Methodology for thermal oil boilers electrification analysis

Thermal oil boilers (also known as thermal fluid heaters or hot oil boilers) are heaters that 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, such as natural gas, fuel oil, coal, etc. These boilers have the advantage of working at high temperatures in the liquid phase, maintaining low working pressures. The heat in the thermal oil will reach the consumer using a circulation pump. Thermal oil heaters are used in many different industrial sectors such as textile, petrochemical, food, automotive, timber, etc. They are applied to processes where a medium and high-temperature range is required, up to 400°C, avoiding the high pressures that the use of steam would imply (Sugimat 2022).

Electric-driven thermal oil boilers which mainly provide heat for the fabric heat setting machines (stenter) are also available on market. This study employs a bottom-up approach to investigate the techno-economic potential of deploying electric thermal oil boilers for heat generation in the entire textile industry in China, Japan, and Taiwan. The same analysis and equations explained above for the electrification of steam boilers are also used for the electrification of thermal oil boilers.

3.4. Methodology for analyzing electrification of different textile processes

Wet-processing accounts for the largest share of fuel used in the textile industry. Wet-processing includes several steps that involve adding colors to fiber, yarn, or fabric or imparting patterns to the fabric, along with a variety of finishing steps that provide certain desired characteristics to the end product. These finishing steps are important mainly in cotton and synthetic textile production. For most wool products and some man-made and cotton products, the yarn is dyed before weaving and the pattern is woven on the fabric. As an example, Figure 13 shows a schematic of typical woven fabric wet-processing operations.

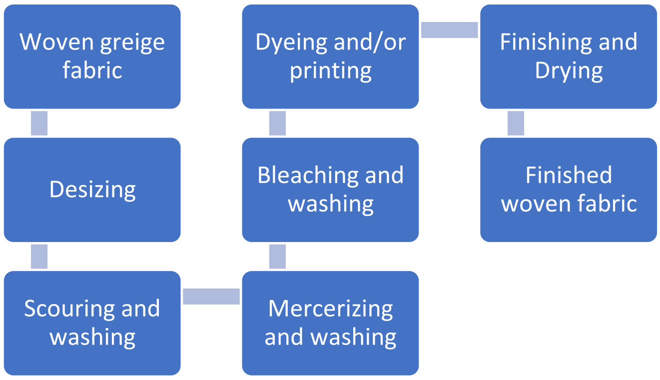


Figure 13. Schematic of Typical Woven Fabric Wet-Processing Operations (Hasanbeigi 2010) .

The seven wet-processing processes that are included in our electrification analysis are presented in Table 2 and explained in more detail in the following subsections. The process-specific electrification analysis focuses on electrifying the heating system at the end-use technologies/machines as opposed to electrifying steam boilers or thermal oil boilers. In most textile processes, steam is used as a heat carrier, and steam itself is not needed in the process. Therefore, instead of using steam, we can consider using end-use electrification technologies (such as the ones described in the following sections) to provide the heat for the process. The electrification of end-use processes has the advantage of increasing efficiency by removing energy losses during steam generation and distribution.

Table 2. Textile wet-processes processes that are analyzed in this study

No.	Process
1	Singeing
2	Mercerizing and Washing
3	Dyeing
4	Drying
5	Heat Setting (Stenter)
6	Finishing (pad-dry-cure)
7	Yarn Drying

To conduct this bottom-up technology-level electrification analysis for each textile wet-processing, we followed four steps as shown in Figure 14. We analyzed the existing heating systems used in the main processes for each process, including the heat demand and temperature profile. Then we identified suitable electrification technologies that can provide the same heat and function for each thermal process. Almost all of the electrification technologies we identified and assigned to wet processes are commercially available. Given the energy intensity of technologies for conventional and electrified processes, the energy use, CO_2 emissions, and energy cost implications of electrification in each process can be calculated.

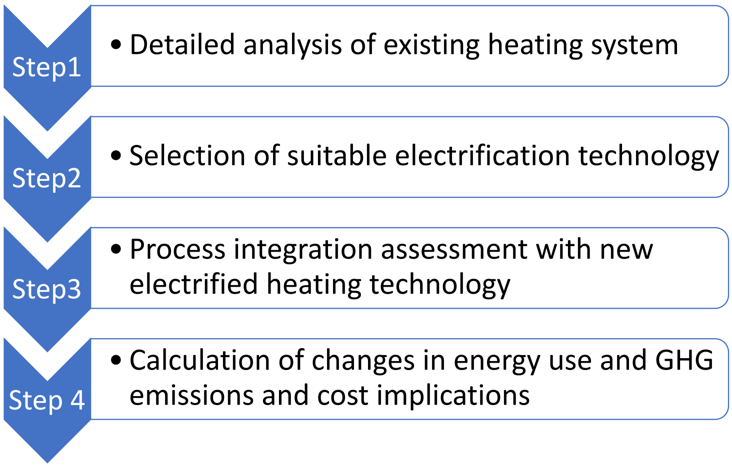


Figure 14. Methodology steps to estimate electrification potential in textile processes .

It should also be noted that the electrification technologies we considered in our analysis for each process or system may not be the only electrification options. Other electrified heating technologies might be available and applicable to the processes analyzed. In addition, other processes within the textile industry might have electrification potential but are not considered in this study. In summary, the energy savings and CO_2 reduction potentials as shown in our study are only a portion of the total savings potential that can be achieved by full electrification of the textile industry.

4 Electrifying the Textile Industry with Industrial Heat Pumps

As explained earlier, in this study, the analysis of the potential application of industrial heat pumps and their impact only focuses on the textile *wet-processing* industry in China, Japan, and Taiwan (not the entire textile industry). Textile wet-processing accounts for the largest share of fuel used in a typical composite textile plant.

The change in annual final energy demand due to industrial heat pump applications in textile wet-processing in the three economies in different timeframes is shown in Figures 15-17. The figures conclude that industrial heat pump applications can substantially decrease the total annual final energy demand. Since the production of finished textiles in these economies is projected to be at the same level until 2050 (see later discussion), the technical potential assuming the 100% adoption of industrial heat pump applications is estimated to be the same. More precisely, it is estimated that nearly 270, 7.0, and 7.3 PJ of the annual final energy can be saved for textile wet-processing in China, Japan, and Taiwan, respectively. The substantial reduction in annual final energy demand is due to the increase in the efficiency (measured in terms of COPs of the heat pumps) for steam generation.

The annual final energy demand in the textile wet-processing industry shown in Figures 15-17 for each economy remain at the same level because we assumed the finished fabric production will remain the same during 2021-2050, and we did not assume any incremental improvement in the efficiency of boilers or heat pumps in the future compared with the base year. It is less likely that the efficiency of conventional boilers will have any substantial improvement in the future since conventional boilers are matured technologies. However, likely, the efficiency of industrial heat pumps will substantially improve in the future up to 2050 since they are emerging technologies and have room for improvement.

Given the uncertainty and lack of data on the overall rate of improvement of efficiency of industrial heat pumps in the future, we made a conservative assumption and assumed the efficiency will remain at the 2021 level in the future in this analysis. However, it should be noted that the difference in temperature levels of heat source and heat sink has the larger impact on the COP of heat pumps. In Figures 15-17, the annual energy saving in 2030 and 2050 is the same because we assumed the same level of production in 2030 and 2050 and similar level of efficiency for technologies in 2030 and 2050.

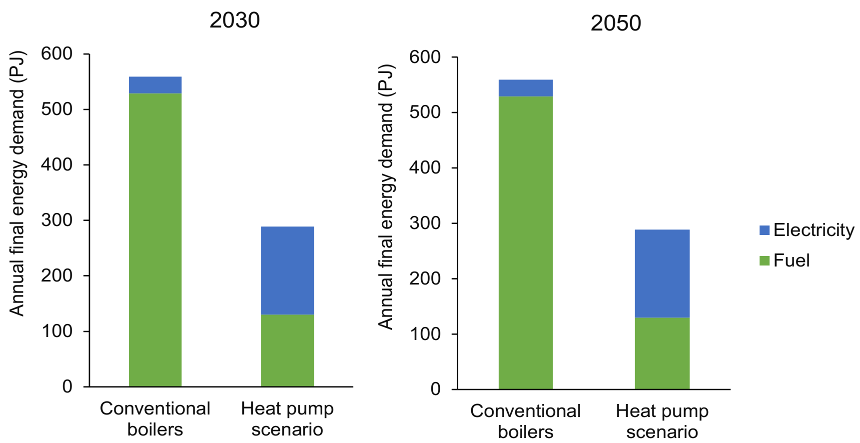


Figure 15. Annual final energy demand in the textile wet-processing industry in **China** (technical potential assuming a 100% adoption of industrial heat pump applications).

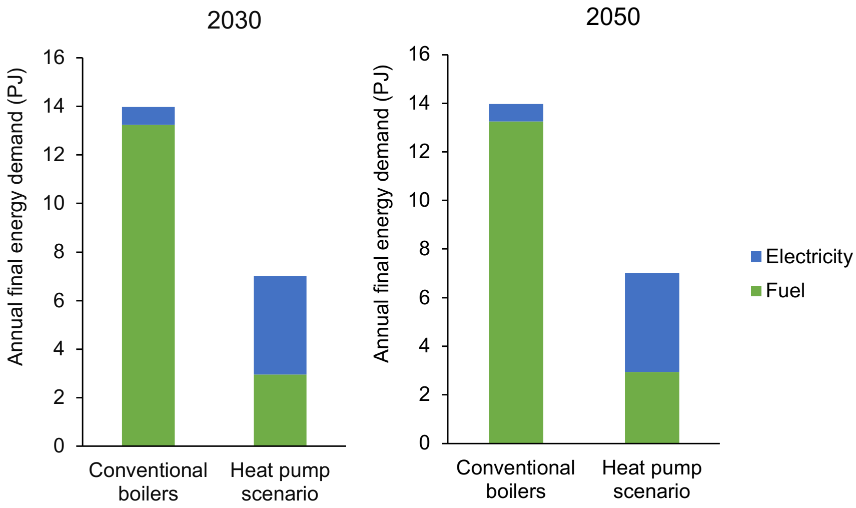


Figure 16. Annual final energy demand in the textile wet-processing industry in **Japan** (technical potential assuming a 100% adoption of industrial heat pump applications).

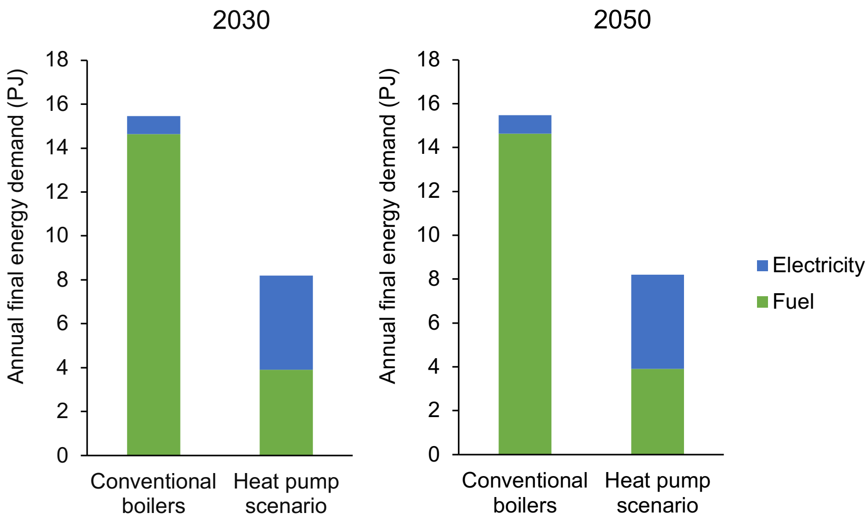


Figure 17. Annual final energy demand in the textile wet-processing industry in **Taiwan** (technical potential assuming a 100% adoption of industrial heat pump applications).

The change in annual CO_2 emissions from the textile wet-processing industry due to industrial heat pump applications in different years is presented in Figures 18-20. The figures show up to 12, 0.4, and 0.5 Mt CO_2/year emissions reduction potential in 2030 for textile wet-processing in China, Japan, and Taiwan, respectively, assuming a 100% adoption of industrial heat pumps in the textile industry. This is despite the increase in electricity demand from industrial heat pumps. The CO_2 reduction potential further increases to 25, 0.7, and 0.8 Mt CO_2/year in 2050, in China, Japan, and Taiwan, respectively, due to the projected rate of electricity grid decarbonization between now and 2050 in these economies (We assumed the electricity grid will be carbon neutral in 2050). The results in 2030, 2040, and 2050 for the heat pump scenario shows the annual CO_2 emissions when the electricity grid's CO_2 emissions intensity ($KgCO_2$/kWh) drops by 33%, 67%, and 100% compared to 2021 level, respectively.

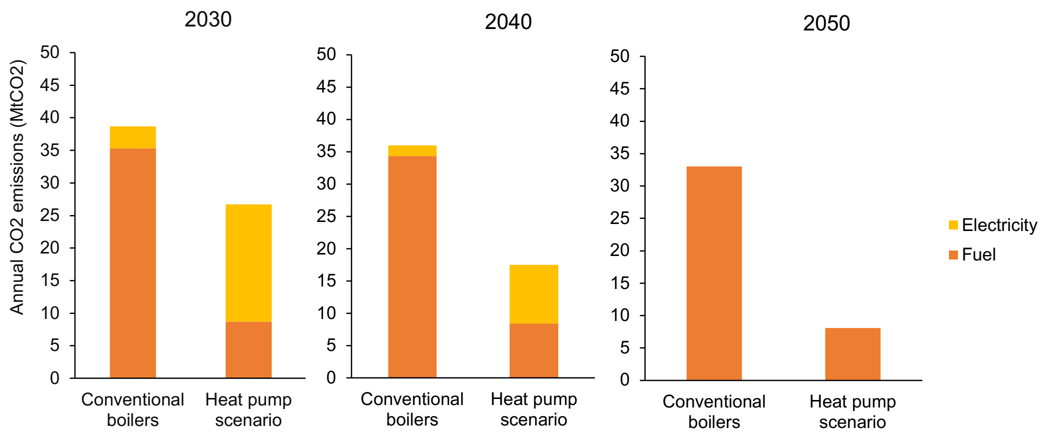


Figure 18. Annual CO_2 emissions from textile wet-processing industry in **China** (technical potential assuming a 100% adoption of industrial heat pump applications).

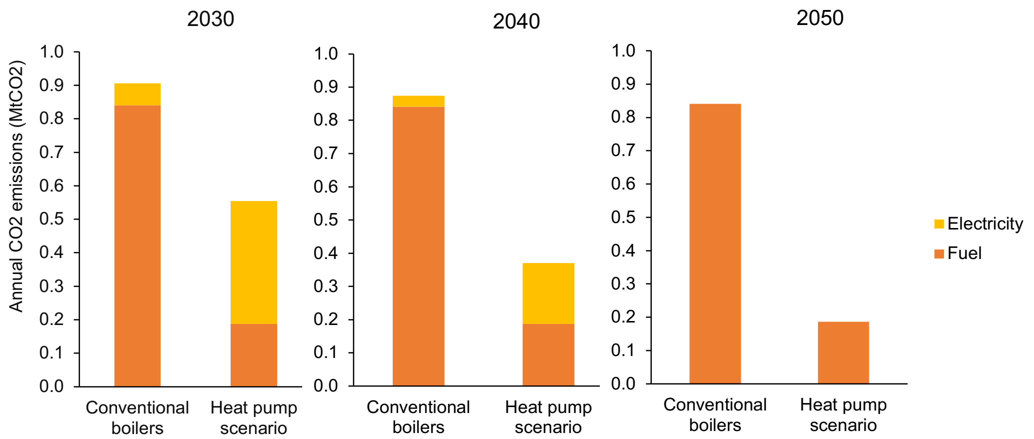


Figure 19. Annual CO_2 emissions from textile wet-processing industry in **Japan** (technical potential assuming a 100% adoption of industrial heat pump applications).

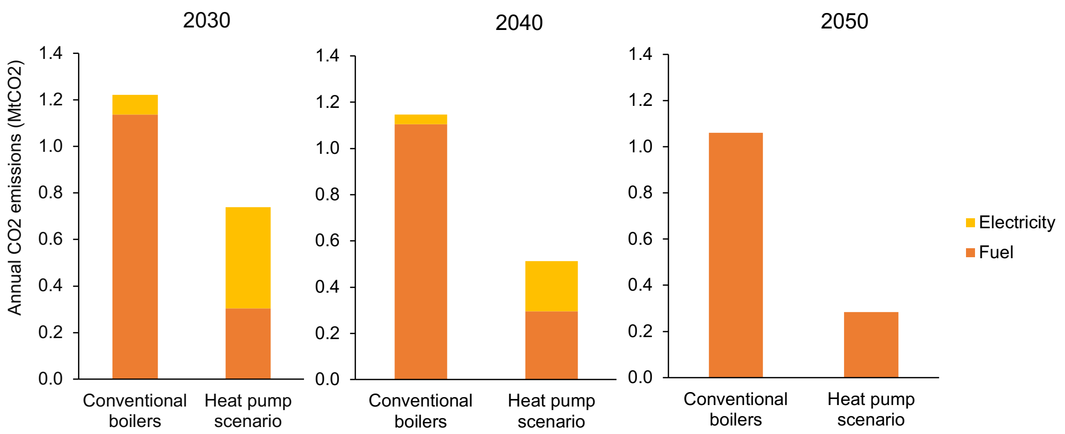


Figure 20. Annual CO_2 emissions from textile wet-processing industry in **Taiwan** (technical potential assuming a 100% adoption of industrial heat pump applications).

The transition from conventional boilers to industrial heat pumps in the textile industry will have a cost implication. We estimated the energy costs per unit of production (US$ per tonne of finished fabric) for the textile wet-processing industry in each economy (Figures 21-23). As can be seen, in all three economies, switching from combustion boilers to industrial heat pumps will result in lower energy costs per tonne of finished fabric produced even in the base year even though the electricity prices in all three economies are substantially higher than fossil fuel prices per unit of energy (kWh). This lower energy cost per unit of production by industrial heat pumps is primarily because heat pumps have high efficiency (as explained earlier) and will result in substantial overall energy saving shown above.

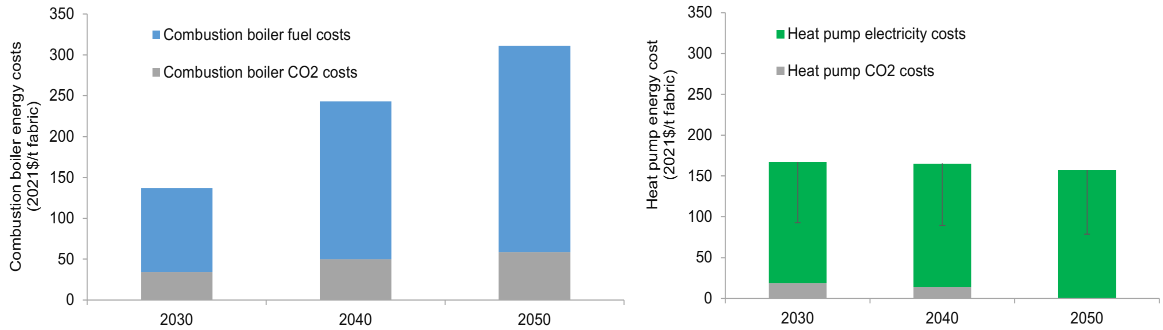


Figure 21. Energy costs per unit of production for the textile wet-processing industry in **China.**

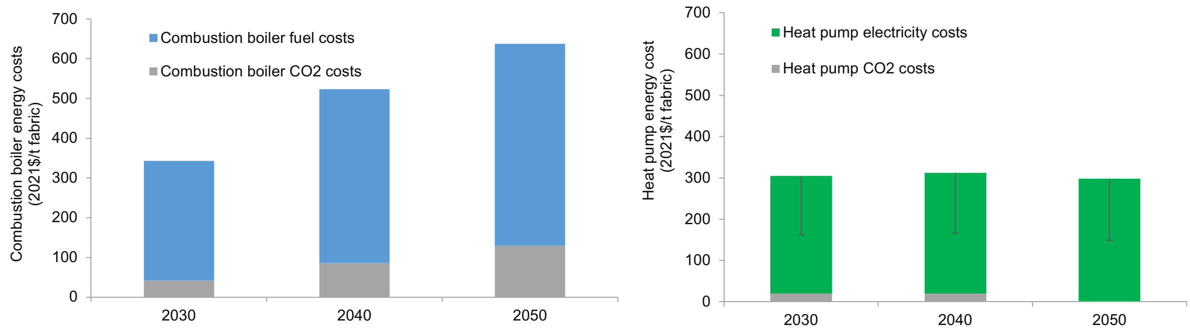


Figure 22. Energy costs per unit of production for the textile wet-processing industry in **Japan.**

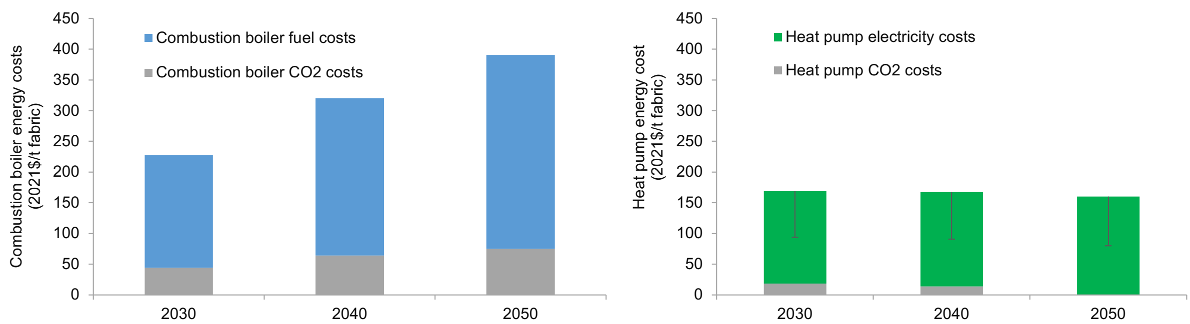


Figure 23. Energy costs per unit of production for the textile wet-processing industry in **Taiwan.**

5 Electrifying the Textile Industry with Electric Steam Boilers

In this study, the analysis of the potential application of electric steam boilers and their impact includes all the steam boilers in the textile industry in China, Japan, and Taiwan (not only the wet-processing industry).

Electrification of steam boilers could substantially reduce the annual energy demand for steam generation in the textile industry in these three economies up to 2050 (Figure 24). Approximately 92, 2.4, and 2.5 PJ/year of annual boiler energy demand in the textile industry in China, Japan, and Taiwan, respectively can be saved if the existing combustion boilers are electrified. This is equal to approximately 19% of the total boiler energy demand in the three economies. The annual energy saving potential shown in Figure 24 remains at the same level because we assumed that the amount of textile production and steam production in the textile industry in each economy will remain the same during 2021-2050.

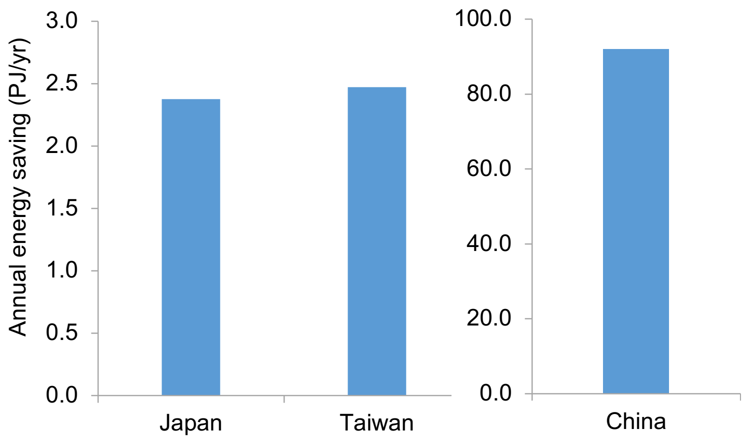


Figure 24. Total annual energy saving after electrification of steam boilers in the textile industry in China, Japan, and Taiwan up to 2050 (technical potential assuming a 100% adoption rate).

If the average national grid electricity is used, the electrification of combustion steam boilers in the textile industry in China, Taiwan, and Japan could initially lead to an increase in annual CO_2 emissions by around 12000, 116, and 55 kilo tonne CO_2 (kt CO_2) in 2030, respectively (assuming a 100% adoption rate) (Figures 25-27). This is because the estimated average electricity grid emission factors for these three economies in 2030 still are much higher than the weighted average emission factors of fuel used in combustion steam boilers. However, boiler electrification is projected to result in 30,000, 785, and 935 kt CO_2 of annual CO_2 abatement in 2050, as also shown in the same figures. This substantial decrease in future annual CO_2 emissions is projected as the consequence of electricity grid decarbonization up to 2050 (we assumed the electricity grid will be carbon neutral in 2050 in all three economies). The results in 2030, 2040, and 2050 for the heat pump scenario shows the annual CO_2 emissions when the electricity grid's CO_2 emissions intensity ($KgCO_2$/kWh) drops by 33%, 67%, and 100% compared to 2021 level, respectively.

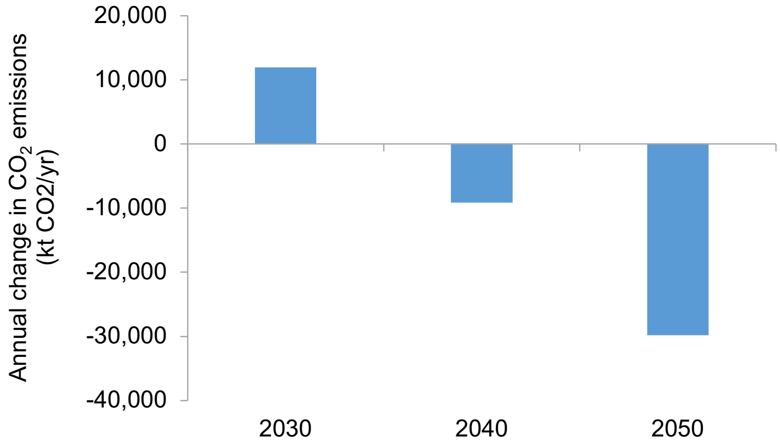


Figure 25. Potential change in steam boilers' annual CO_2 emissions after electrification in the textile industry in **China** (technical potential assuming a 100% adoption rate).

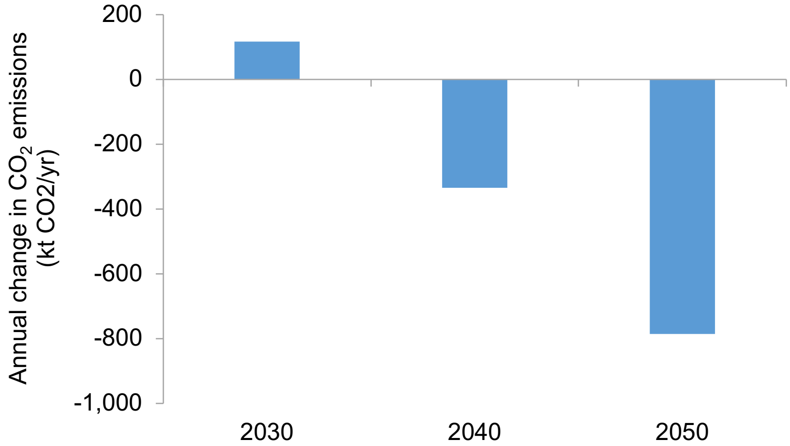


Figure 26. Potential change in steam boilers' annual CO_2 emissions after electrification in the textile industry in **Japan** (technical potential assuming a 100% adoption rate).

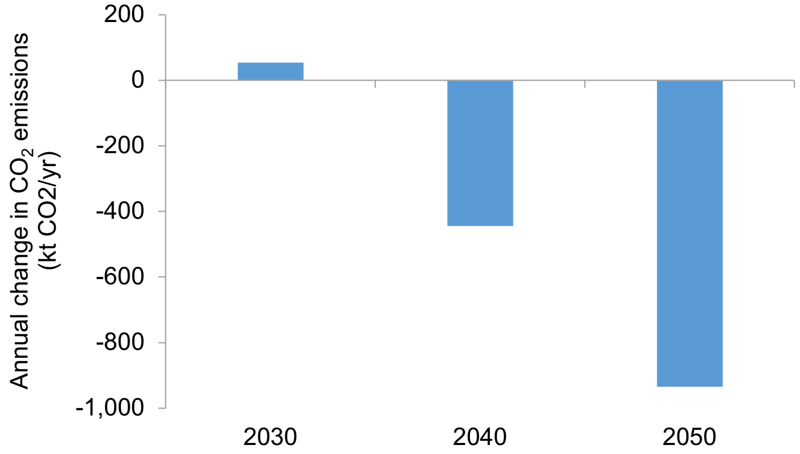


Figure 27. Potential change in steam boilers' annual CO_2 emissions after electrification in the textile industry in **Taiwan** (technical potential assuming a 100% adoption rate).

It should be noted that, in reality, the electrification projects will happen at the plant level. If a given textile plant in any country electrifies its steam boilers today and purchases renewable electricity (e.g. through a power purchase agreement (PPA)) to supply the electricity demand of the electric boiler, then the CO_2 emissions reductions from electrification can be achieved immediately. Therefore, our country-level results should not be interpreted in a way that electrification cannot be beneficial until the electricity grid is decarbonized.

We also estimated the energy costs per unit of production (US$ per tonne of finished fabric) for the textile wet-processing industry in each economy (Figure 28-30). Unlike industrial heat pumps results shown in the previous section, in all three economies, switching from combustion steam boilers to electric boilers will result in substantially higher energy cost per tonne of finished fabric produced in 2030 even though electric boilers result in 19% energy savings compared with combustion steam boilers. This is primarily because the electricity prices in all three economies are substantially higher than fossil fuel prices per unit of energy (kWh) (see Appendix 1). The energy cost for electric steam boilers become more competitive in 2050, but still higher than that of combustion steam boilers. This is partly because of our assumptions that fuel prices up to 2050 will increase at a higher rate than the electricity prices in these three economies, and partly because of an increase in assumed carbon price in the future (see Appendix 1). It should be noted that the energy cost is only a small portion (5%-15%) of the total manufacturing cost in the textile industry. A moderate increase in energy cost per unit of the product resulting from electrification will have a minimal impact on the price of the final textile and apparel product.

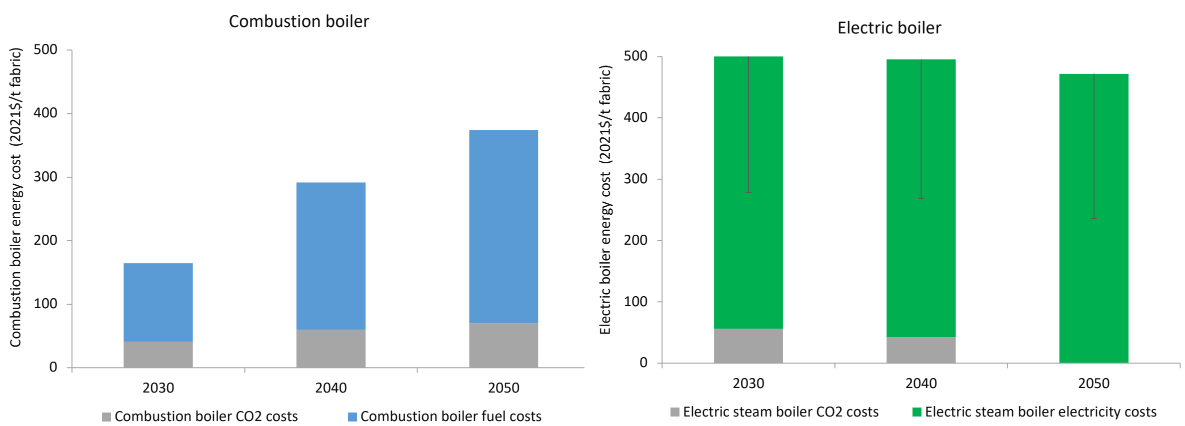


Figure 28. Energy costs per unit of production for combustion and electric steam boilers in the textile wet-processing industry in **China** .

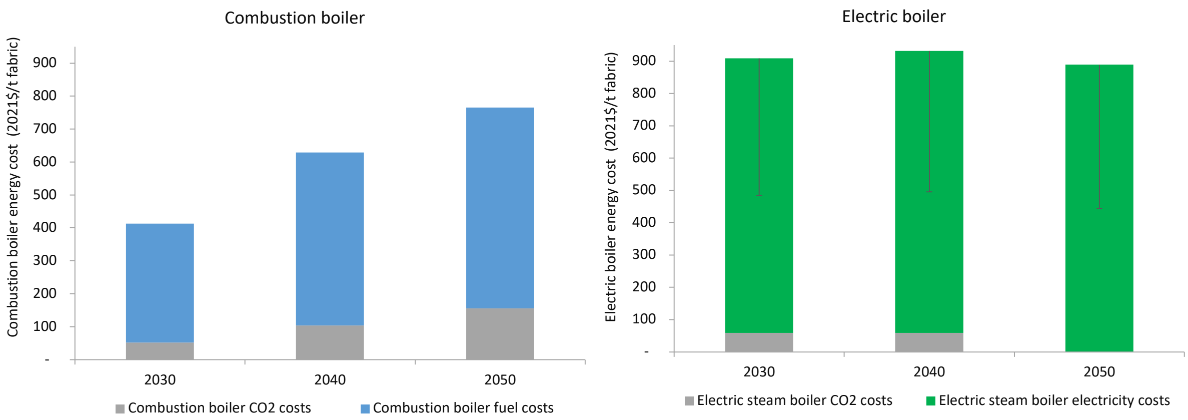


Figure 29. Energy costs per unit of production for combustion and electric steam boilers in the textile wet-processing industry in **Japan.**

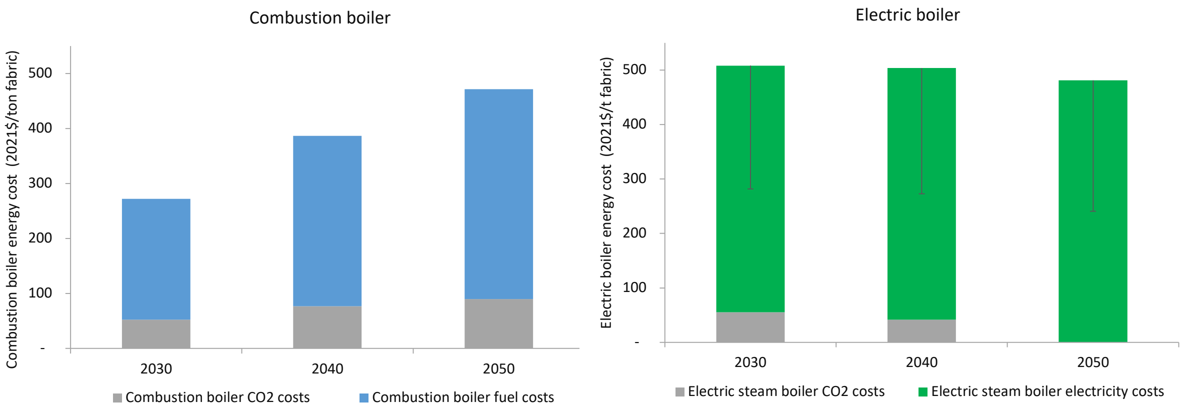


Figure 30. Energy costs per unit of production for combustion and electric steam boilers in the textile wet-processing industry in **Taiwan.**

We have shown the impact of a CO_2 price on the energy costs per unit of production separately, so it can be both included or excluded by readers in their assessment. Currently there is a small price on CO_2 in China and Japan but not applied to the textile industry. Taiwan currently does not have any price on CO_2 emissions. Since these economies have net-zero emissions targets, it is likely that their price on CO_2 will expand to apply to more industries and would increase over time as suggested in number of studies. Also, companies often have their own internal carbon price to be included in their cost-benefit analysis of energy and other capital investment.

6 Electrifying the Textile Industry with Electric Thermal Oil Boilers

In this study, the analysis of the potential application of electric thermal oil boilers and their impact includes all the thermal oil boilers in the textile industry in China, Japan, and Taiwan (not only the wet-processing industry).

Electrification could substantially reduce the annual energy demand for thermal oil boilers in the Chinese, Taiwanese, and Japanese textile industries up to 2050 (Figure 31). Approximately 13% of the annual thermal oil boiler energy demand in the textile industry can be saved if the existing fossil-fuel-fired thermal oil boilers are electrified. This results in an annual energy saving of 8.6, 0.21, and 0.24 PJ in China, Japan, and Taiwan, respectively. The annual energy saving potential shown in Figure 31 remains at the same level because we assumed that the heat demand provided by thermal oil boilers in the textile industry in each economy will remain the same during 2021-2050.

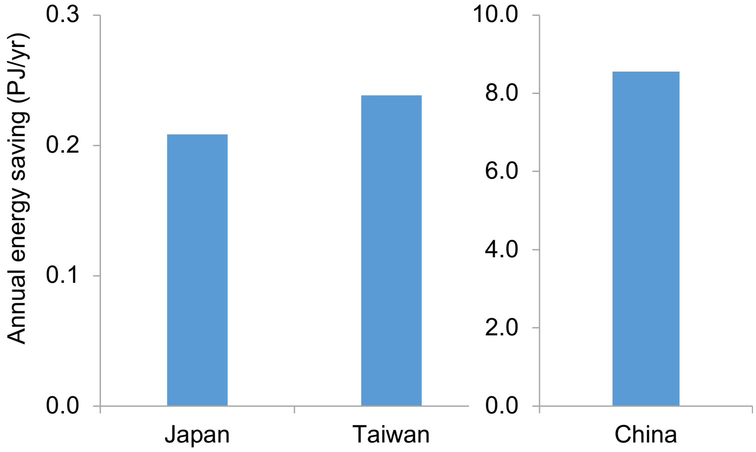


Figure 31. Total annual energy saving after electrification of thermal oil boilers in the textile industry in China, Japan, and Taiwan up to 2050 (technical potential assuming a 100% adoption rate).

With average national grid electricity, the electrification of thermal oil boilers in the textile industry in China, Taiwan, and Japan could initially lead to an increase in annual CO_2 emissions by around 2000, 23, and 18 kt CO_2, respectively (assuming a 100% adoption rate). (Figures 32-34). This is because the electricity grid in the three economies still will not be decarbonized enough in 2030 based on our assumptions. However, thermal oil boiler electrification will result in 4000, 100, and 130 kt CO_2 of annual CO_2 abatement in 2050. This substantial decrease in future annual CO_2 emissions is projected as the consequence of electricity grid decarbonization between 2021 and 2050.

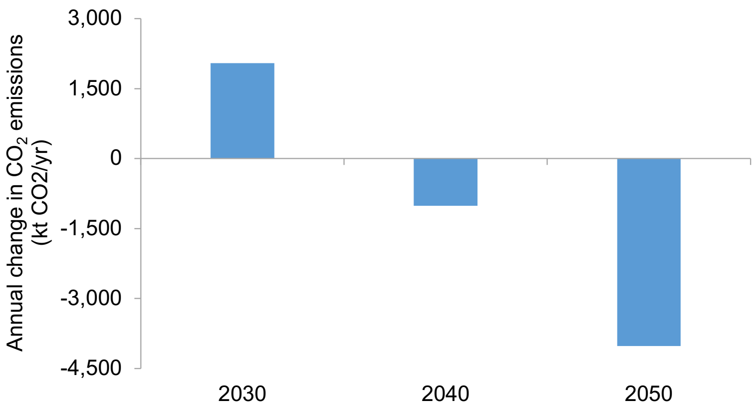


Figure 32. Potential change in thermal oil boilers' annual CO_2 emissions after electrification in the textile industry in **China** (technical potential assuming a 100% adoption rate).

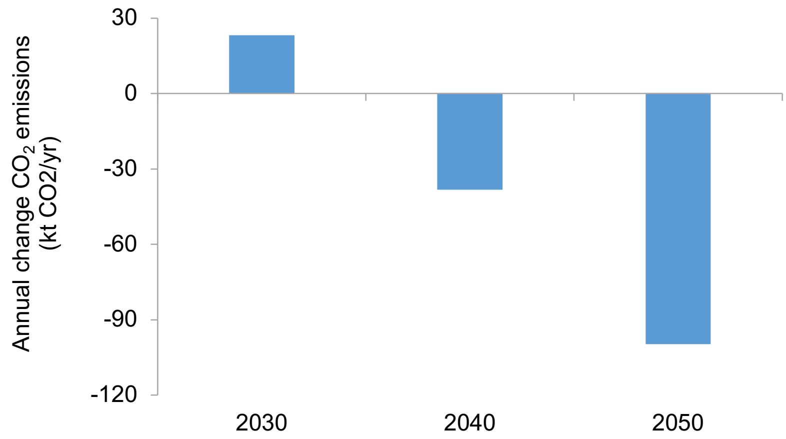


Figure 33. Potential change in thermal oil boilers' annual CO_2 emissions after electrification in the textile industry in **Japan** (technical potential assuming a 100% adoption rate).

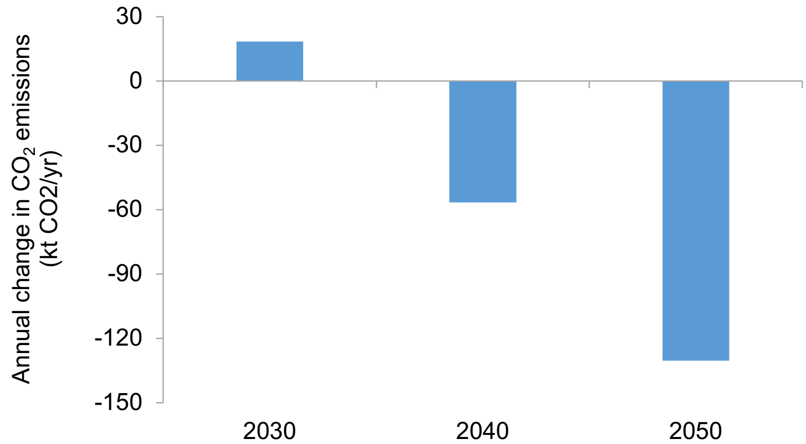


Figure 34. Potential change in thermal oil boilers' annual CO_2 emissions after electrification in the textile industry in **Taiwan** (technical potential assuming a 100% adoption rate).

Like the case for the electric steam boiler discussed earlier, if a given textile plant in any country electrifies its thermal oil boilers today and purchases renewable electricity to supply the electricity demand of the electric thermal oil boiler, then the CO_2 emissions reductions from electrification can be achieved immediately.

We also estimated the energy costs per unit of production (US$ per tonne of finished fabric) for the textile wet-processing industry in each economy (Figure 35-37). Like the electric steam boilers, in all three economies, switching from combustion thermal oil boilers to electric thermal oil boilers will result in substantially higher energy cost per tonne of finished fabric produced in 2030 even though electric boilers result in 13% energy savings compared with combustion steam boilers. This is primarily because the electricity prices in all three economies are substantially higher than fossil fuel prices per unit of energy (kWh) (see Appendix 1). The energy cost for electric thermal oil boilers become more competitive in 2050, but still higher than that of combustion thermal oil boilers (see Appendix 1).

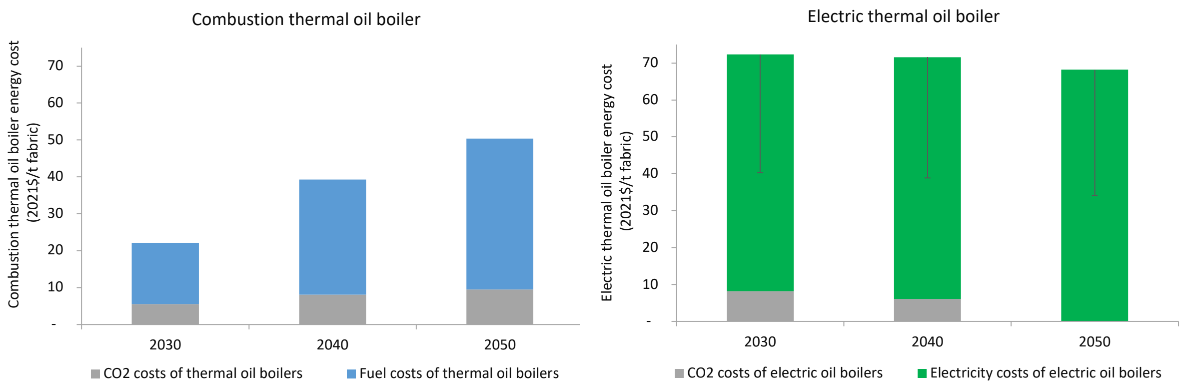


Figure 35. Energy costs per unit of production for combustion and electric thermal oil boilers in the textile wet-processing industry in **China .**

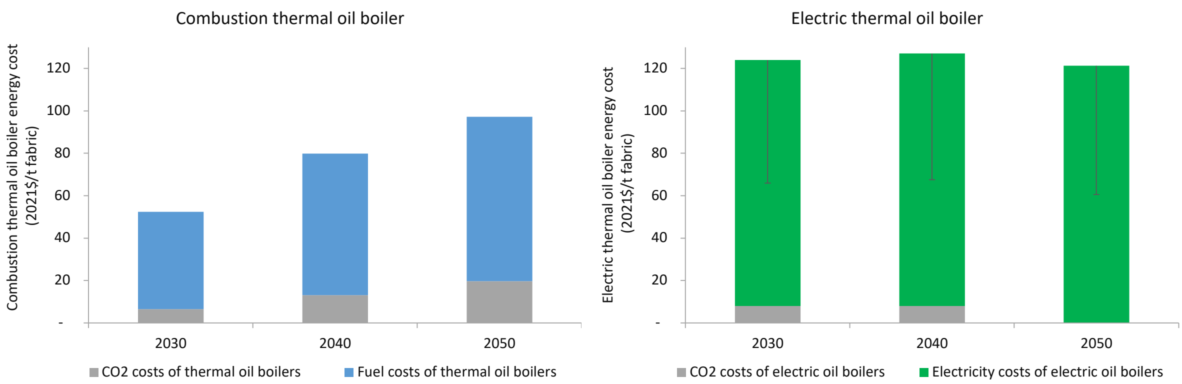


Figure 36. Energy costs per unit of production for combustion and electric thermal oil boilers in the textile wet-processing industry in **Japan .**

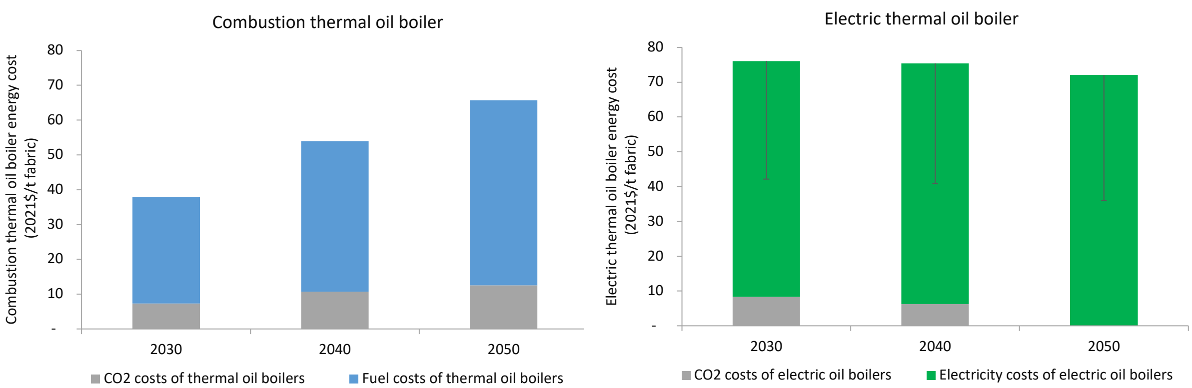


Figure 37. Energy costs per unit of production for combustion and electric thermal oil boilers in the textile wet-processing industry in **Taiwan** .

7 Electrifying the Textile Industry through Electrification of Wet Processes

This subsection discusses and shows the potential for electrification of seven individual processes in the textile wet-processing industry in China, Japan, and Taiwan.

7.1. Electrification of singeing process

Fabrics from the weaving and knitting section contain some loose fibers protruding or struck out from the surface. Singeing removes those loose hairy fibers by burning them off. This is typically the first process in the wet-processing unit. The objective is to generate an even surface without a fuzzy appearance, which will not tend to pill. Singeing of fabric can be achieved in various arrangements. Plate singeing machine uses heated plates, roller singeing machine uses rotating cylinders, and the most commonly used gas singeing machine uses gas burners. As a result, a smooth surface appears. This also helps to achieve uniform dyeing afterward (Nassif, 2019; Tusief et al., 2014).

Electrified singeing process

Conventional singeing machines use heat from fuel combustion to remove fluff. However, this heat can also be provided through electrical energy. Electric cylinder singeing machines use high-temperature industrial electrical heating elements (such as silicon carbide rods) as heating sources. Silicon carbide heating rods are high-temperature non-metal electrical heating elements that have many advantages over other metal elements, such as a high working temperature, oxidation resistance, longer life, and corrosion resistance (Ma Lei 2004; Samaterials, 2022).

The electrical singeing machine is equipped with a heat preservation box under the cylinder to keep the temperature of the cylinder body at a set process temperature for a long time during work. This results in energy savings. Since in these electric singeing machines there is no wasted heat through exhaust gases and the heat distribution is balanced and controlled, in this study, around 30% saving in total energy consumption is assumed compared to conventional singeing machines.

Some of the advantages of an electrical singeing machine over the conventional ones are lower energy consumption, higher surface temperature, smaller temperature difference, higher singeing grade, no local air pollution, etc. Table 3 shows the estimated CO_2 intensity of the conventional and electrified singeing process in the textile industry in each economy.

Table 3. The CO_2 intensity of the conventional and electrified singeing process.

	CO_2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	2030	2040	2050	2030	2040	2050
China	376	353	331	305	388	184	0
Japan	342	332	321	311	308	146	0
Taiwan	427	404	381	355	346	164	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies.

Figure 38 shows that electrifying the singeing process results in a substantial annual energy saving between 2030 and 2050. Electrification could lead to annual energy savings of about 17,000, 300, and 500 TJ per year for China, Japan, and Taiwan, respectively in 2050. This annual energy saving results from higher efficiency (lower energy intensity) of electrified singeing compared with the conventional singeing process.

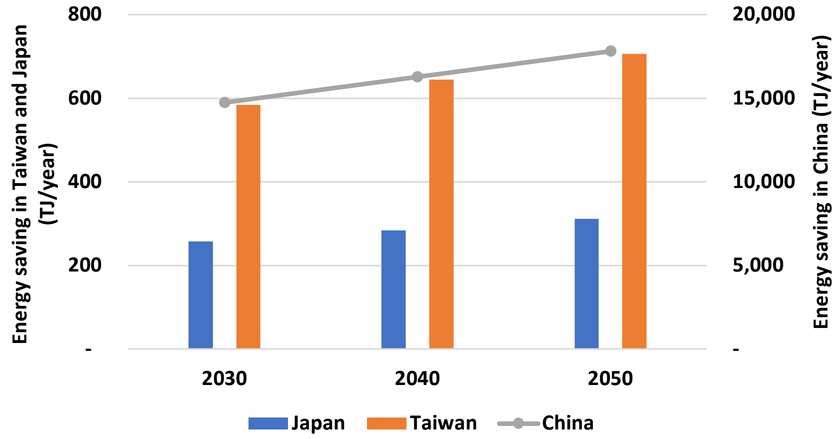


Figure 38. Total annual energy saving after electrification of singeing process (This is the technical potential assuming a 100% adoption rate.)

In 2030, there is still a slight increase in CO_2 emissions after the electrification of singeing process in China if the grid electricity is used, but the electrification of singeing process could result in a reduction in CO_2 emissions in Japan and Taiwan in 2030 (Figure 39). There is a substantial reduction in CO_2 emissions in all three economies in 2040 and 2050 which is the result of a decline in the electricity grid's CO_2 emissions factor (grid decarbonization), and energy efficiency improvement between 2021 and 2050. The annual reduction of CO_2 emission after electrification of singeing process in 2050 is around 2,600, 47, and 120, kt CO_2/year in China, Japan, and Taiwan, respectively.

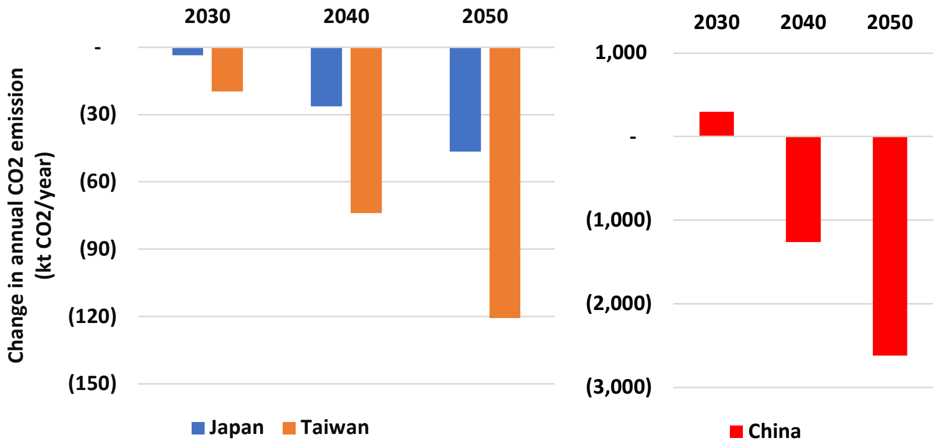


Figure 39. Total change in annual CO_2 emission after electrification of singeing process (This is the technical potential assuming 100% adoption rate.)

Figures 40-42 show the energy cost per unit of production (in 2021US$/tonne fabric processed) in China, Japan, and Taiwan singeing process for the conventional process and electrified process from 2030 to 2050. The energy cost for the electrified singeing process is substantially higher than that for the conventional process in 2030. However, as the price of fossil fuels increases over time and considering the carbon price (see the methodology section for more detail) the energy cost for the electrified process can be lower than that of the conventional process in 2050. In addition, the error bar on the graph shows that the energy cost per unit of production for the electrified process can be lower than the conventional process even in 2030 when lower unit price of electricity is used in the analysis. The error bars on cost figures show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.

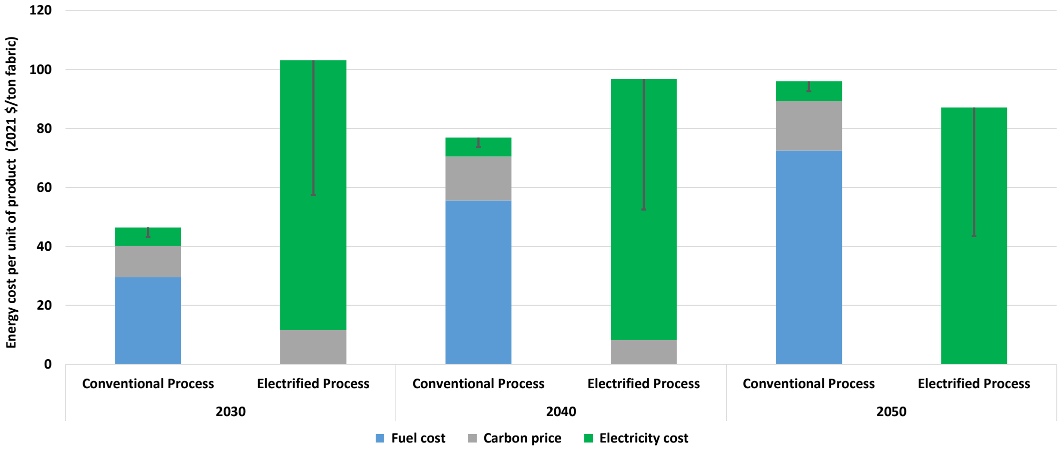


Figure 40. Energy cost per unit of production for conventional and electrified singeing process in **China**

(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

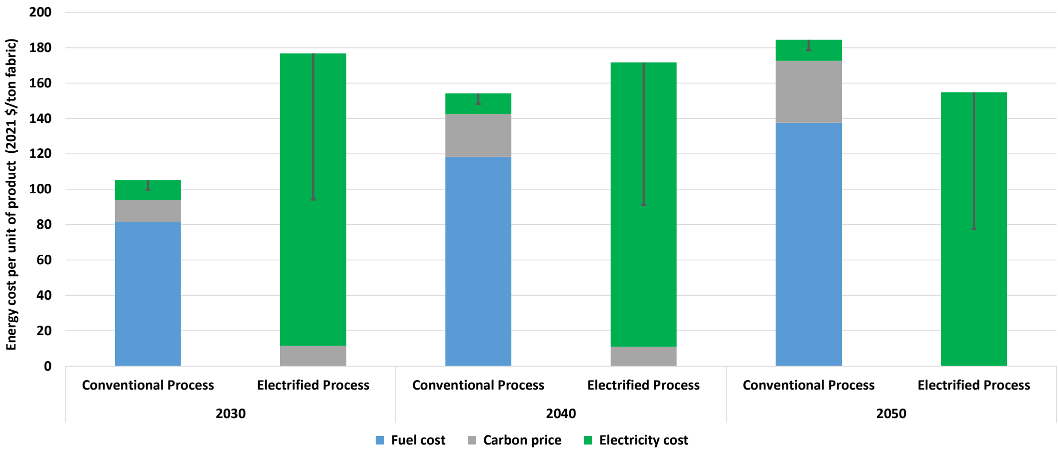


Figure 41. Energy cost per unit of production for conventional and electrified singeing process in **Japan.**

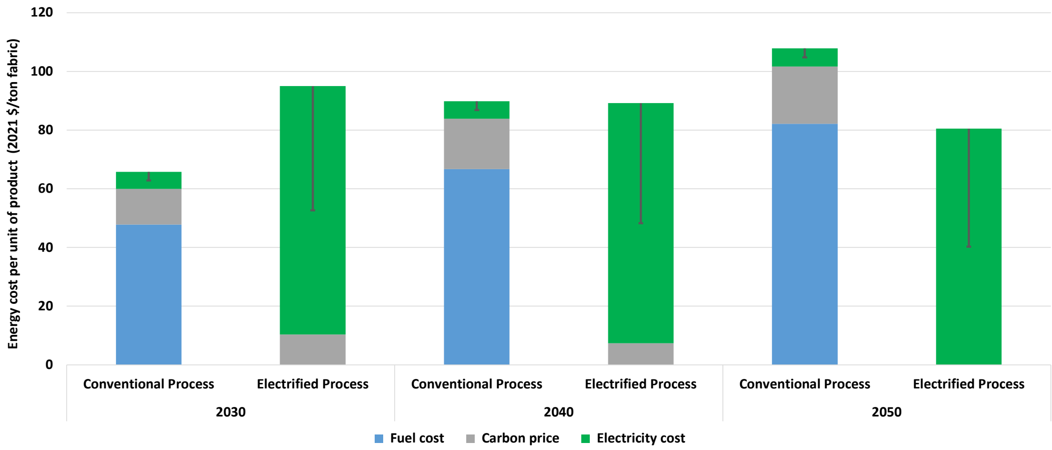


Figure 42. Energy cost per unit of production for conventional and electrified singeing process in **Taiwan.**

7.2. Electrification of mercerizing and washing process

Mercerization is a chemical treatment applied to cotton fibers or fabrics to improve their dyeing properties, tensile strength, absorbency, and luster. The treatment consists of immersing the yarn or fiber in a solution of sodium hydroxide for short periods (usually less than four minutes) and then treating it with water or acid to neutralize the sodium hydroxide. If the material is held under tension during this stage, it will be less likely to shrink. Higher-quality cotton goods are usually mercerized; mercerized cloths take brighter, longer-lasting colors while using lower amount of dye (Hasanbeigi, 2010; Lin et al., 2022).

Electrified mercerizing and washing process

In mercerizing and washing processes, steam coils are usually used to supply the required heat. In an electrified process, instead of steam coils, direct heating electric resistance elements can be used. Washing is needed after the chemical treatment. Technologies such as ultrasonic washing machines are an emerging electrified alternative. They can replace several baths of traditional, high-temperature systems. These washing machines use ultrasound to clean the fabric, which reduces water and energy consumption as well as the use of chemicals (Sonotronic 2022). Further research and development are still needed to make these machines more commercially available .

If electrical processes (resistive elements or ultrasonic systems) are used, the usual losses related to the steam generation and distribution systems will be eliminated. Therefore, in this study, it is assumed that electrical processes consume at least 30% less energy. Table 4 shows the estimated CO_2 intensity of the conventional and electrified mercerizing and washing process in the textile industry in each economy.

Table 4. The CO_2 intensity of the conventional and electrified mercerizing and washing process

	CO2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	2030	2040	2050	2030	2040	2050
China	125	119	113	106	132	63	0
Japan	114	112	110	108	105	50	0
Taiwan	143	137	131	123	118	56	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies

The electrification of the mercerizing and washing process could save a large amount of energy each year (Figure 43). This is because the electrified process is more efficient than the conventional process. In 2050, China, Japan, and Taiwan could save 15,000, 340, and 330 TJ per year, respectively from the electrification of mercerizing and washing process.

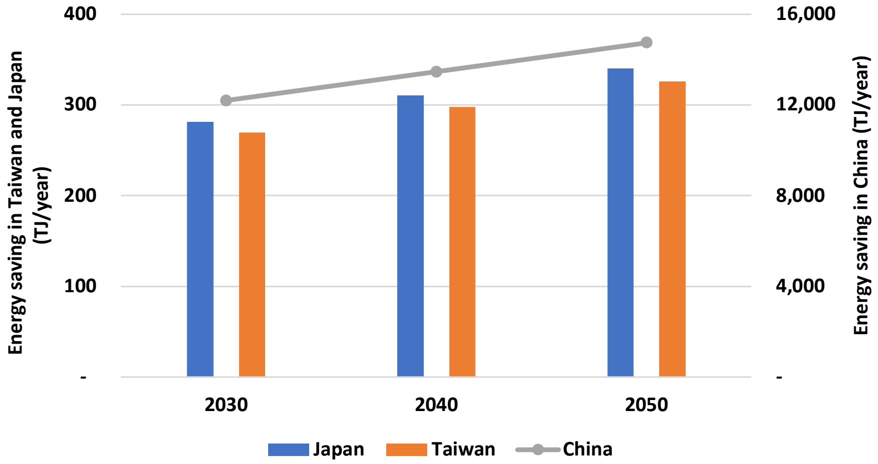


Figure 43. Total annual energy saving after electrification of mercerizing and washing process (This is the technical potential assuming a 100% adoption rate.)

The electrification of the mercerizing and washing process in the textile industry can result in a significant reduction in CO_2 emissions in the future years as the electricity grid decarbonizes in these three economies (Figure 44). In 2030, there is still a slight increase in CO_2 emissions after the electrification of this process in China, but by 2040 and 2050, there is a substantial reduction in emissions due to grid decarbonization and energy efficiency improvements. This could lead to an annual reduction of CO_2 emissions of around 2100, 55, and 51 kt CO_2/year in China, Japan, and Taiwan, respectively in 2050.

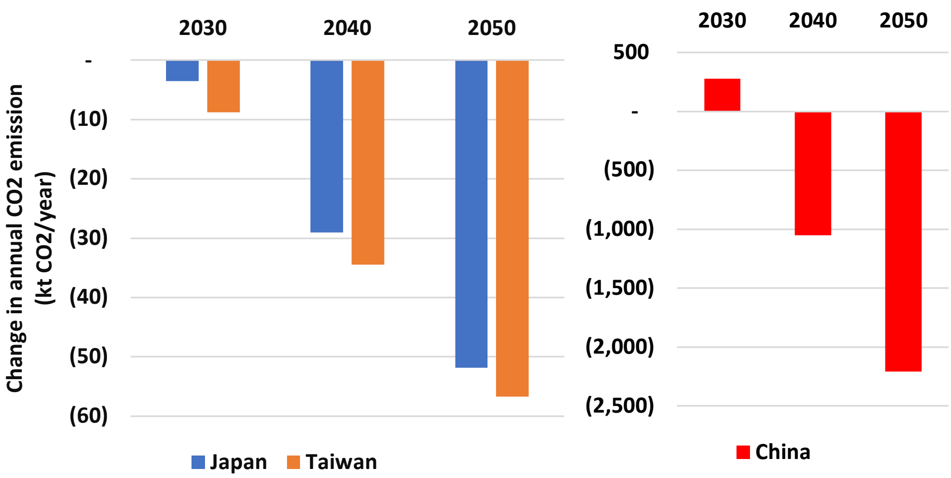


Figure 44. Total change in annual CO_2 emission after electrification of mercerizing and washing process (This is the technical potential assuming a 100% adoption rate.)

As shown in Figures 45-47 the energy cost for electrified mercerizing and washing process is substantially higher than that for the conventional process in 2030. However, the electrified process in the textile industry can be less expensive than the traditional process in the long term. This is due to the increasing price of fossil fuels and the carbon price, which make the energy cost for the electrified process less expensive.

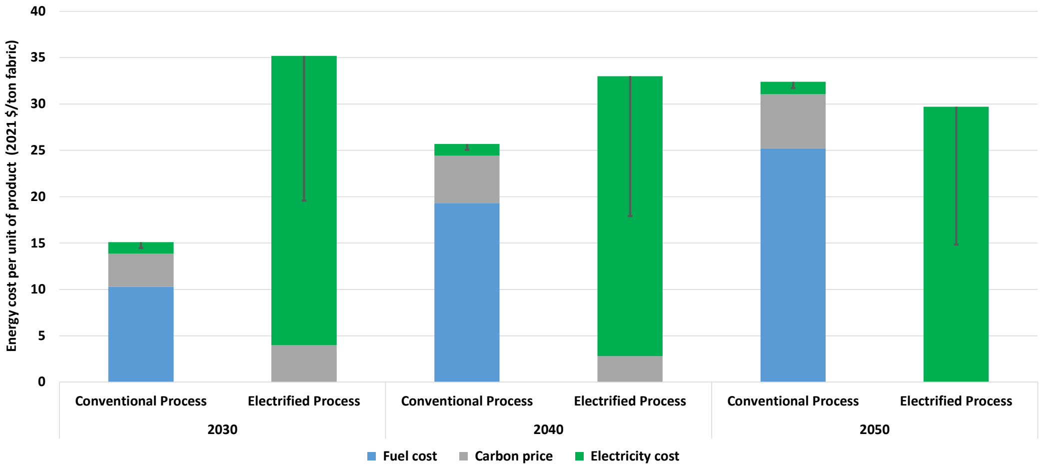


Figure 45. Energy cost per unit of production for conventional and electrified mercerizing and washing processes in **China.**

(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

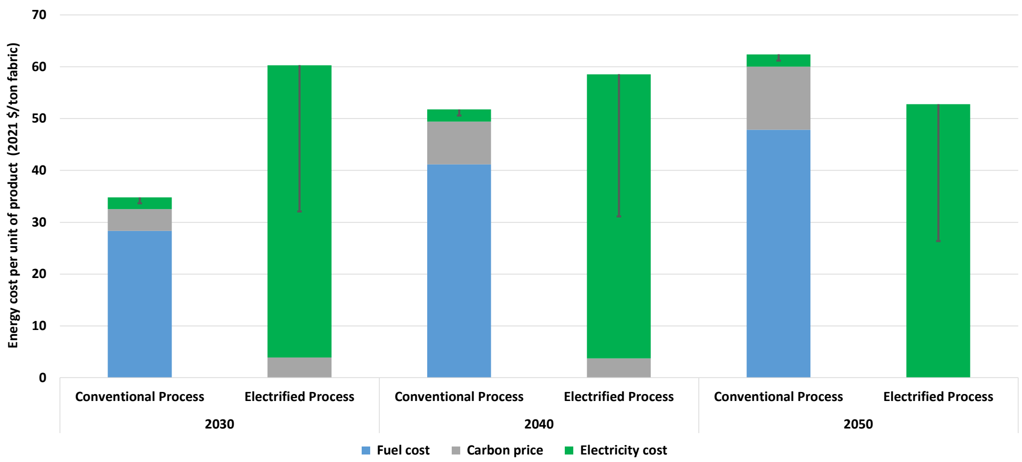


Figure 46. Energy cost per unit of production for conventional and electrified mercerizing and washing process in **Japan .**

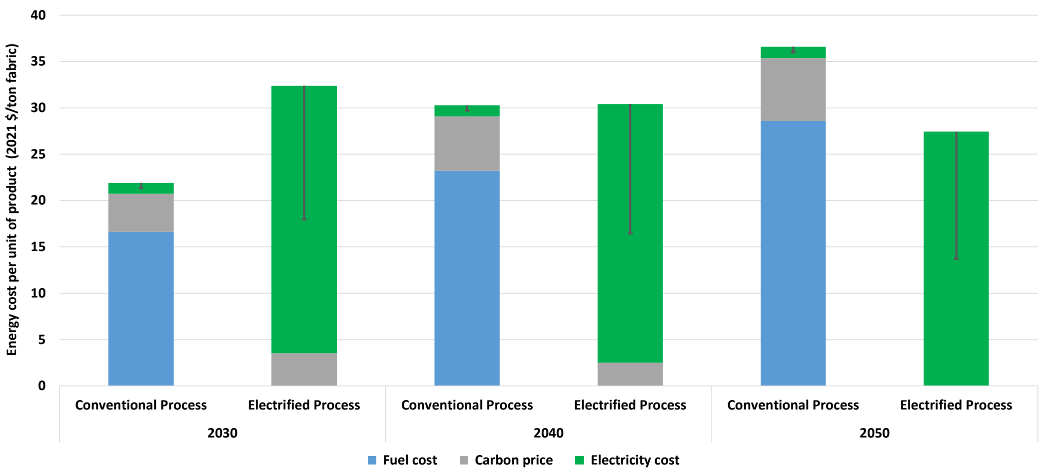


Figure 47. Energy cost per unit of production for conventional and electrified mercerizing and washing process in **Taiwan.**

7.3. Electrification of the dyeing process

Dyeing is the application of color to the whole body of textile material with some degree of colorfastness. Textiles are dyed using continuous and batch processes and dyeing may take place at any of several stages in the manufacturing process (i.e., before fiber extrusion, while the fiber is in staple form, to yarn, to fabrics, and garments). Various types of dyeing machines are used for both continuous and batch processes. Every dye system has different characteristics in terms of versatility, cost, the tension of the fabric, use of carriers, weight limitations, etc. Dyeing systems can be aqueous, non-aqueous (inorganic solvents), or use sublimation (thermosol, heat transfer). Hydrophilic fibers such as cotton, rayon, wool, and silk, are typically easier to dye as compared with hydrophobic fibers such as acetate, polyesters, polyamides, and polyacrylonitrile. Dyeing is an energy-intensive process since it requires heat which is provided by steam. The steam is usually generated in combustion steam boilers (Benkhaya et al., 2020; Hasanbeigi, 2010).

Electrified dyeing process

Electric fabric dyeing machines can be an alternative to conventional dyeing machines. In the electrified dyeing machine, the heat is provided by electric heating systems such as electric resistance heating. There is no heat loss through exhaust gases in the electrified process and temperature control is done better. Also, there are no losses related to the steam systems generation and distribution systems in the electrified process. Therefore, in this study, the energy intensity of the electric dyeing process is assumed to be around 30% lower than that of the conventional process. Table 5 shows the estimated CO_2 intensity of the conventional and electrified dyeing process in the textile industry in each economy.

Table 5. The CO_2 intensity of the conventional and electrified dyeing process

	CO_2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	2030	2040	2050	2030	2040	2050
China	487	449	410	368	483	229	0
Japan	440	418	396	375	383	181	0
Taiwan	546	508	470	428	431	204	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies .

Electrifying the dyeing process can result in large energy savings. In China, Japan, and Taiwan, annual energy savings of 33000, 780, and 730 TJ per year can be achieved in 2050 (Figure 48). This is because electrified dyeing is more efficient than the conventional process, resulting in less energy consumption.

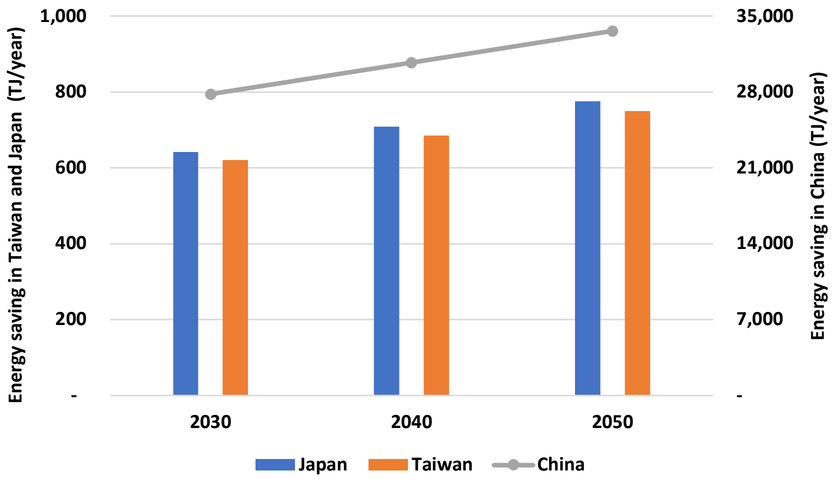


Figure 48. Total annual energy saving after electrification of dyeing process (This is the technical potential assuming a 100% adoption rate.)

Electrification of the dyeing process in China could result in an increase in annual CO_2 emissions in the short term if highly carbon-intensive grid electricity is used (Figure 49). The electrification of the dyeing process could lead to a decrease in CO_2 emissions in Japan and Taiwan in 2030. Between 2030 and 2050, there will be a substantial reduction in CO_2 emissions as a result of the decline in the electricity grid's CO_2 emissions factor and energy efficiency improvements. In 2050, the annual reduction of CO_2 emissions after electrification of the dyeing process will be around 4900, 115, and 125 kt CO_2 /year in China, Japan, and Taiwan, respectively.

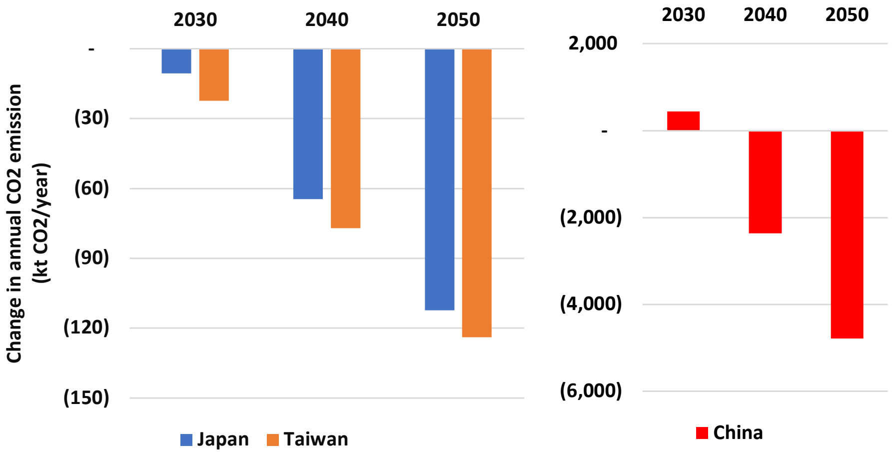


Figure 49. Total change in annual CO_2 emission after electrification of dyeing process (This is the technical potential assuming a 100% adoption rate.)

The energy cost per unit of production (in 2021 US$/tonne fabric processed) varies across the three economies for the conventional and electrified dyeing process (Figure 50-52). The energy cost for the electrified dyeing process is substantially higher than that for the conventional process in 2030. However, as the price of fossil fuels increases over time and considering the carbon price (see the methodology section for more details) the energy cost for the electrified process can be lower than that of the conventional process in 2050. The error bar on the graph shows that the energy cost per unit of production for the electrified process can be lower than the conventional process even earlier when a a lower price of electricity is used.

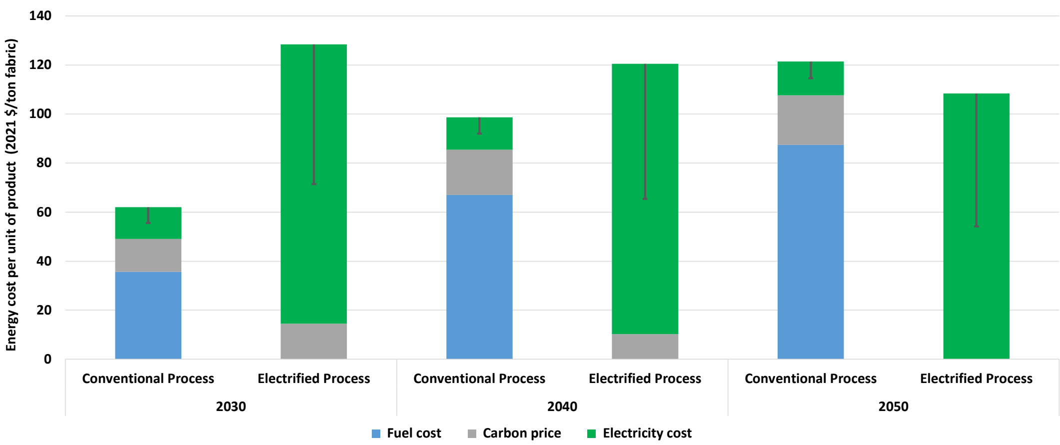


Figure 50. Energy cost per unit of production for conventional and electrified dyeing processes in **China**
(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

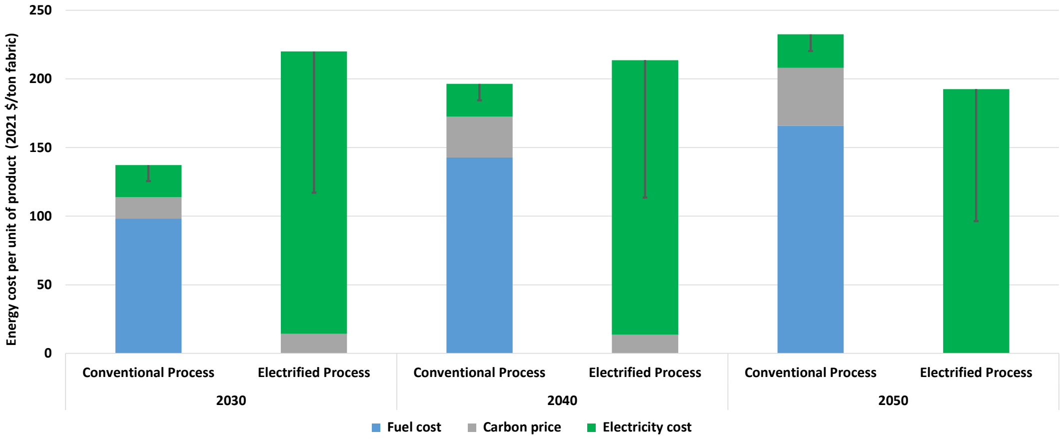


Figure 51. Energy cost per unit of production for conventional and electrified dyeing processes in **Japan**

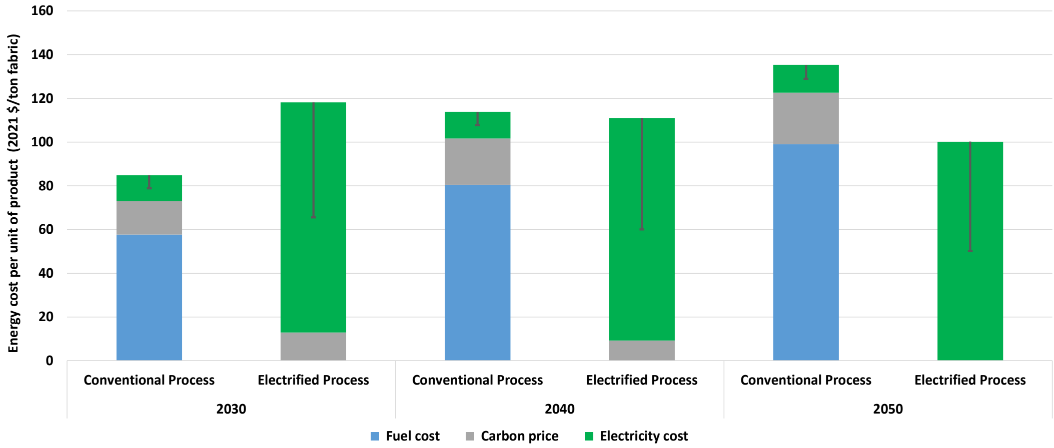


Figure 52. Energy cost per unit of production for conventional and electrified dyeing processes in **Taiwan.**

7.4. Electrification of the drying process

Fabric drying is done to get rid of moisture and impart a wrinkle-free smooth surface to the fabric. Contact drying using cylinder dryers is mainly used for intermediate drying, rather than final drying (since there is no way of controlling fabric width), and for pre-drying before stentering. Fabric is passed around a series of cylinders, which are heated by steam supplied at pressures. Cylinders can be used to dry a wide range of fabrics. However, since the surface of the fabric is compressed, the process is not suitable for fabrics with a raised surface effect. Cylinder dryers are heated by steam. Other types of dryers such as hot air dryers are also used for drying fabrics during wet processing. These conventional hot air dryers are also often heated by steam (Hasanbeigi 2010).

Electrified drying process

One of the most prominent electrification technologies for the drying process in the textile industry is infrared machines. Infrared heating is radiant heating and it differs from conduction and convection because it transfers heat to objects directly, without heating something else in between (air, water, metal, etc.). Infrared is a proven source of heat in textile processing, as infrared sends high heating power in extremely compact times. This helps to lessen energy consumption, to expand production speeds, and to lower production costs.

Currently, several companies around the world are producing infrared fabric dryers. Based on the collected information, these machines consume at least 25% less energy than the usual old methods (Kerone 2022, Ansal 2022). Table 7 shows the estimated CO_2 intensity of the conventional and electrified drying process in the textile industry in each economy.

Table 6. The CO_2 intensity of the conventional and electrified drying process

	CO_2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	2030	2040	2050	2030	2040	2050
China	254	240	226	210	284	134	0
Japan	232	226	220	214	225	107	0
Taiwan	290	275	261	244	253	120	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies

The electrification of the drying process could save a large amount of energy each year (Figure 53). This is because the electrified process is more efficient than the conventional process. In 2050, China, Japan, and Taiwan could save 40000, 1050, and 1000 TJ per year, respectively from the electrification of the drying process.

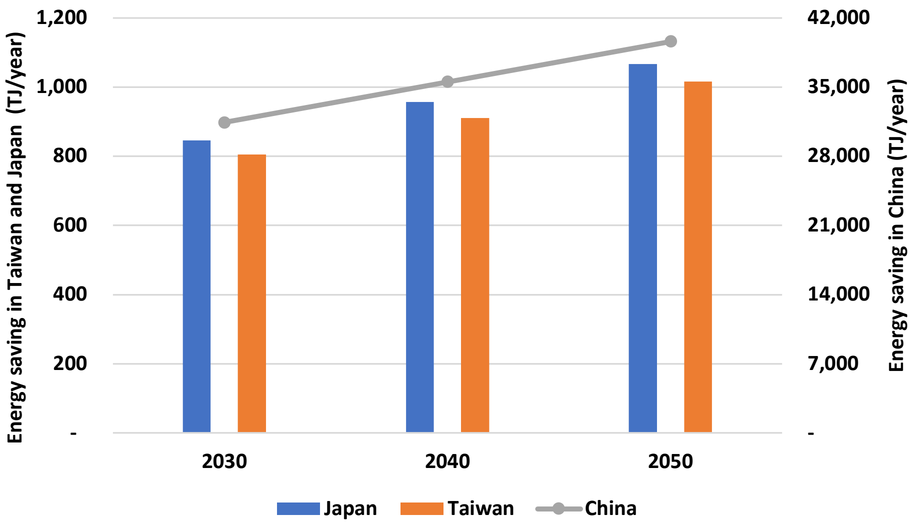


Figure 53. Total annual energy saving after electrification of the drying process (This is the technical potential assuming a 100% adoption rate.)

In 2030, there is still a slight increase in CO_2 emissions after the electrification of these processes in China, but by 2040 and 2050, there is a substantial reduction in emissions due to grid decarbonization and energy efficiency improvements (Figure 54). This could lead to an annual reduction of CO_2 emissions of around 6100, 180, and 190 kt CO_2/year in China, Japan, and Taiwan, respectively.

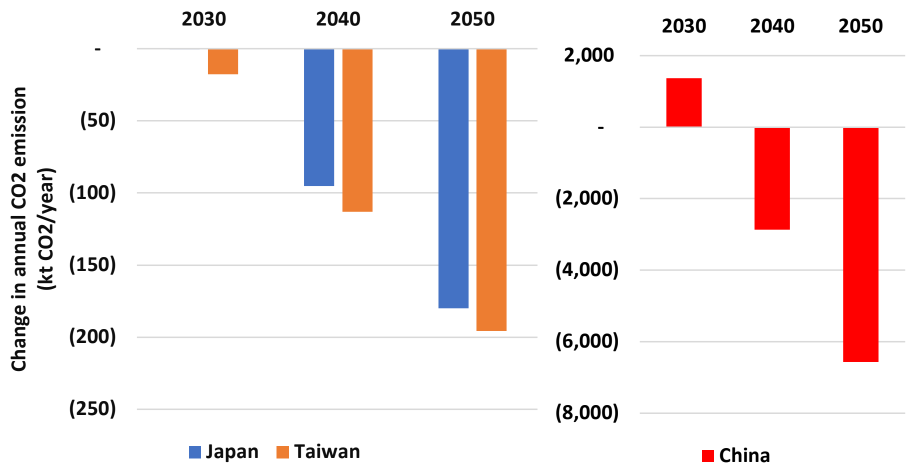


Figure 54. Total change in annual CO_2 emission after electrification of the drying process (This is the technical potential assuming a 100% adoption rate.)

As shown in Figures 55-57, the energy cost for the electrified drying process is higher than that for the conventional process in 2030. However, the electrified drying process in the textile industry can be less expensive than the traditional process in the long term. The energy cost per unit of production for the electrified process can be lower than the conventional process in Japan and Taiwan even in 2030 when lower unit price of electricity is used in the analysis.

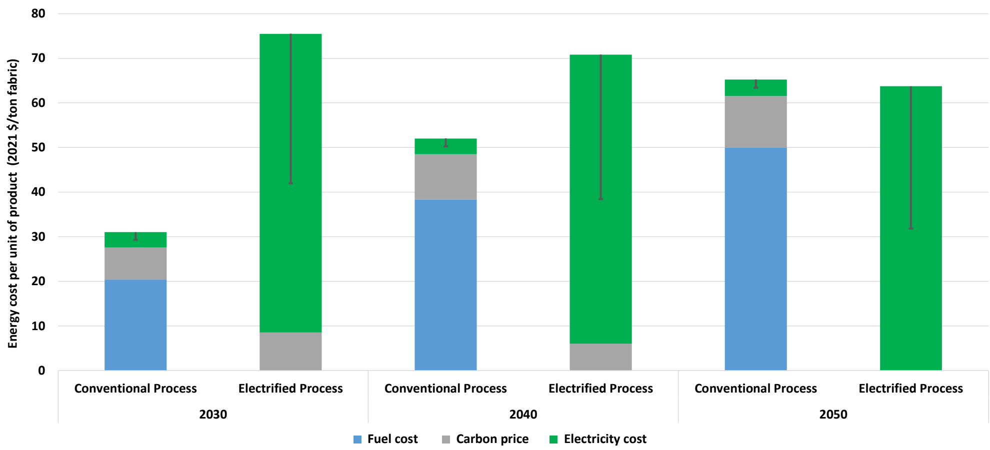


Figure 55. Energy cost per unit of production for conventional and electrified drying processes in **China**

(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

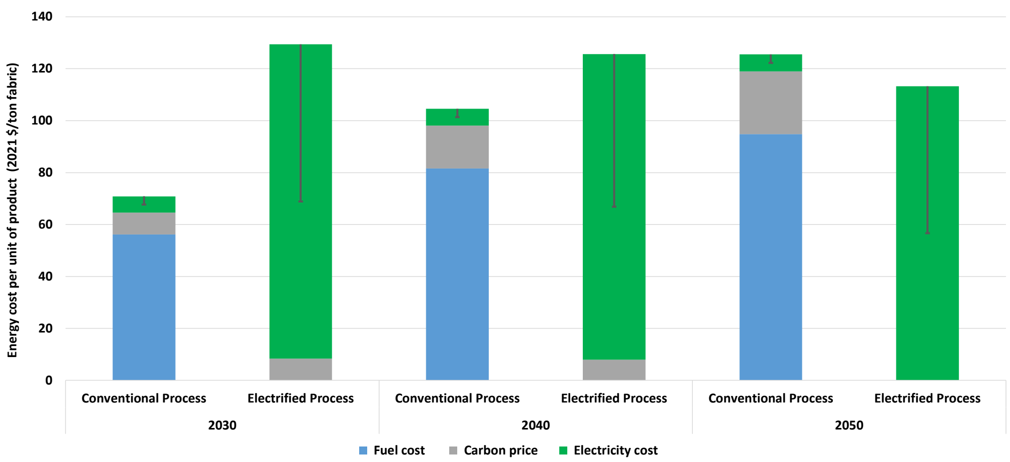


Figure 56. Energy cost per unit of production for conventional and electrified drying processes in **Japan**

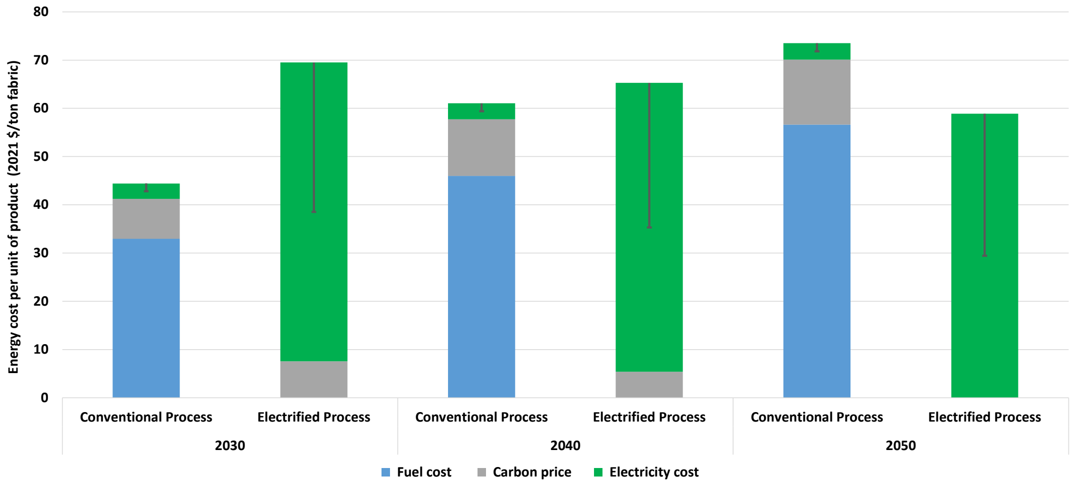


Figure 57. Energy cost per unit of production for conventional and electrified drying processes in **Taiwan.**

7.5. Electrification of heat setting process (Stenter machine)

After dyeing and printing, heat-setting of fabric is done to make sure that the fabric retains its shape afterward. The process is very important especially for the knit fabric to control the fabric shrinkage, It also helps to impart wrinkle/crease resistance to the fabric. A stenter machine is often used for heat setting (Istook, 2022).

Stenters are mainly used in textile finishing for heat-setting, drying, thermosol processes, and finishing. It can be roughly estimated that, in fabric finishing, the fabric is treated on average 2 – 3 times in a stenter. Fabric can be processed at speeds from 10 – 100 m/minute and temperatures of more than 200°C. Stenters can be heated in a variety of ways, such as direct gas firing and through the use of thermal oil systems. Gas-fired stenters are highly controllable over a wide range of process temperatures.

Thermal oil heating for stenters requires a small thermal oil boiler and its associated distribution pipeline. This system is less efficient than direct gas firing and has higher capital and running costs. Finally, there are several steam-heated stenters. Because of their low-temperature limits (usually up to a maximum of 160°C), these stenters can only be used for drying; they are not suitable for heat setting or thermo-fixing of fabrics (Hasanbeigi 2010).

Electrified heat setting (Stenter machine)
Currently, several stenter manufacturing companies offer choices for the type of heating system in the machine. Many stenter manufacturers offer machines with electric heating systems (Brueckner 2022, Zhejiang 2022, Yamuna 2022, Virock 2022). Also, using a stenter with electric heating instead of a direct gas-fired or the thermal oil stenter reduces the total energy consumption of the process because of a reduction in energy losses in the system (Elitex finishing 2022). In this study, we assumed a 25% lower energy intensity for the electric stenter compared with the conventional stenter. Table 6 shows the estimated CO_2 intensity of the conventional and electrified heat setting process in the textile industry in each economy.

Table 7. The CO_2 intensity of the conventional and electrified heat setting process (Stenter machine)

	CO_2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	2030	2040	2050	2030	2040	2050
China	281	270	259	246	346	164	0
Japan	258	255	253	250	274	130	0
Taiwan	324	312	300	285	308	146	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies

Figure 58 shows that electrifying the heat setting process results in a substantial annual energy saving between 2030 and 2050. Electrification could lead to annual energy savings of about 34,000, 780, and 730 TJ per year for China, Japan, and Taiwan, respectively in 2050. This annual energy saving results from higher efficiency (lower energy intensity) of electrified dyeing compared with the conventional process.

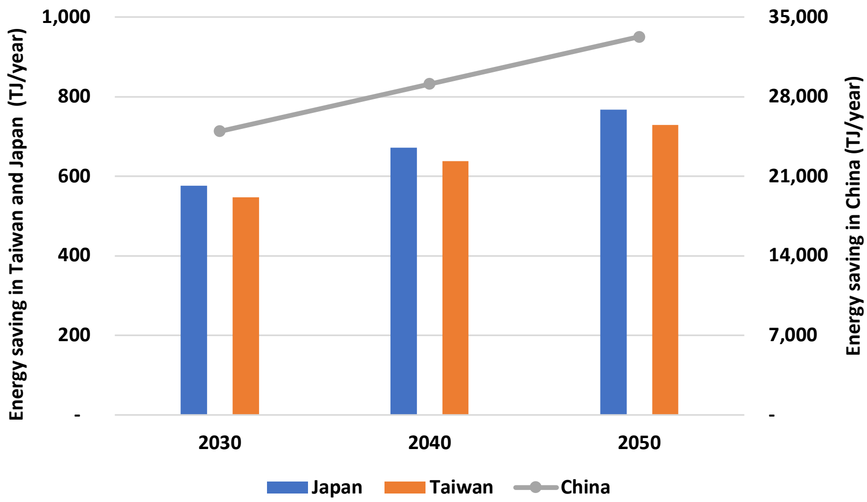


Figure 58. Total annual energy saving after electrification of heat setting process (This is the technical potential assuming a 100% adoption rate.)

In 2030, there is still a slight increase in CO_2 emissions after electrification of the heat setting process in China and Taiwan, but electrification of this process could result in a reduction in CO_2 emissions in Japan in 2030. There is a substantial reduction in CO_2 emissions in all three economies in 2040 and 2050 which is the result of grid decarbonization, and energy efficiency improvement up to 2050. The annual reduction of CO_2 emission after electrification of the heat setting process in 2050 is around 6100, 150, and 160 kt CO_2/year in China, Japan, and Taiwan, respectively.

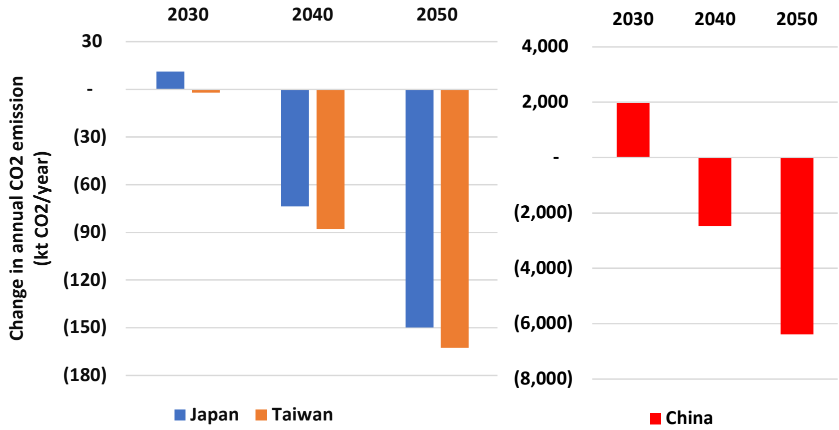


Figure 59. Total change in annual CO_2 emission after electrification of heat setting process (This is the technical potential assuming 1a 00% adoption rate.)

The energy cost for the electrified heat setting process is substantially higher than that for the conventional process in 2030 (Figures 60-62). However, as the price of fossil fuels increases over time and considering the carbon price the energy cost for the electrified process can be lower than that of the conventional process in 2050. The energy cost per unit of production for the electrified process can be lower than the conventional process when lower electricity prices are used in the analysis as shown by the error bars on the graphs.

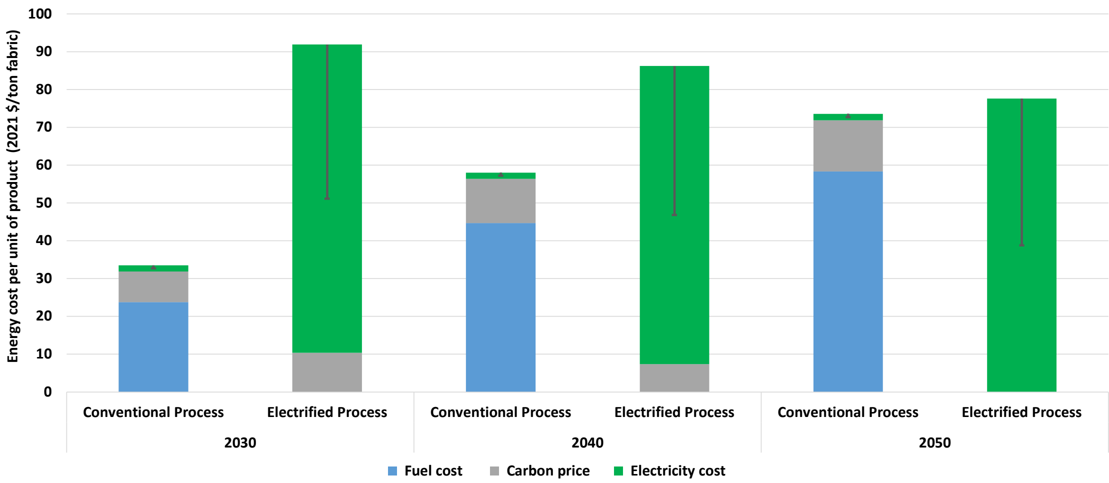


Figure 60. Energy cost per unit of production for conventional and electrified heat setting process in **China.**
(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

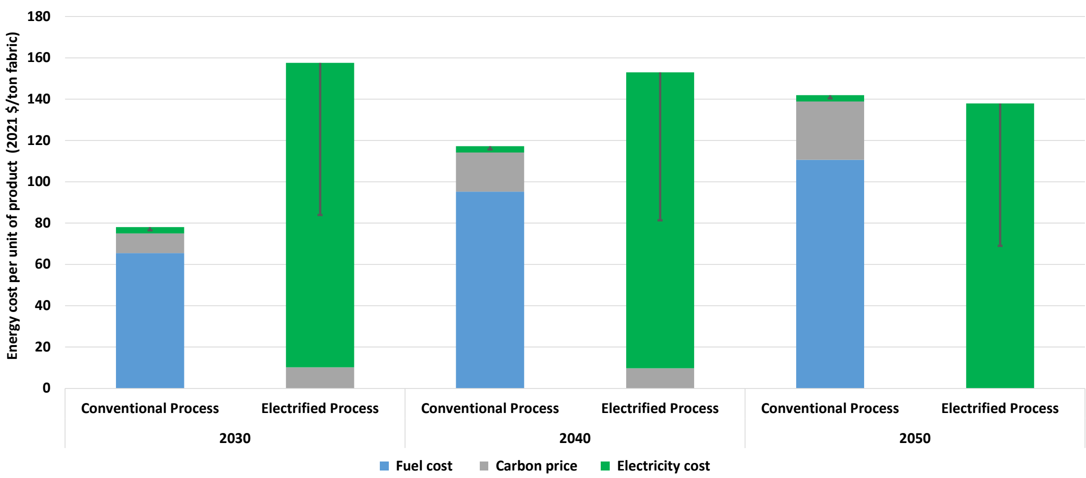


Figure 61. Energy cost per unit of production for conventional and electrified heat setting process in **Japan** .

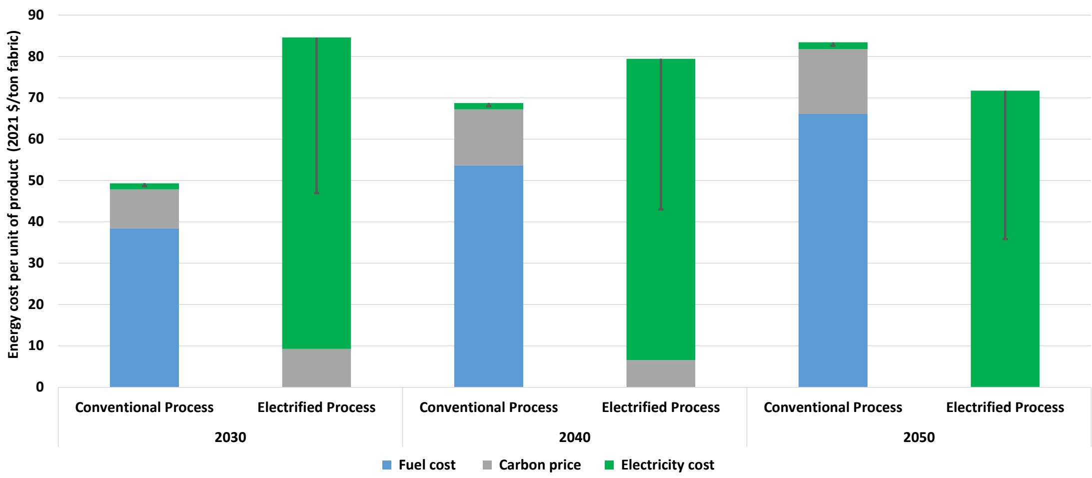


Figure 62. Energy cost per unit of production for conventional and electrified heat setting process in **Taiwan.**

7.6. Electrification of finishing process (pad-dry-cure)

Textile finishing can be defined as all processes (chemical and/or mechanical), employed after textile coloration which imparts additional functionality/superior aesthetics to the textile material. Chemicals that have strong affinities for fiber surfaces can be applied in batch/dis-continuous processes by exhaustion. Chemicals that have low/no affinity for fibers are applied by continuous processes that involve padding with a chemical solution, squeezing, drying at moderate temperature, and curing at an elevated temperature for fixation (pad-dry-cure). The drying is often in a cylinder dryer or hot air dryer and curing is done in a hot air dryer. These dryers often use a steam coil or thermal oil coil as a heat source.

Electrified finishing (pad-dry-cure) process

Same as the stenters and dryers, the electrified process for drying and curing the finishing process is now available. Electricidal resistance heating elements and/or infrared heating are used as the heating system in the electrified process (Monforts 2022). Since the electrified heating systems do not have the heat losses related to steam generation and distribution systems and have minimal exhaust losses, they can result in at least a 30% reduction in energy intensity of heating and curing processes in finishing. Table 8 shows the estimated CO_2 intensity of the conventional and electrified finishing (pad- dry-cure) process in the textile industry in each economy.

Table 8. The CO_2 intensity of the conventional and electrified finishing (pad-dry-cure) process

	CO_2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	**2030**	**2040**	**2050**	**2030**	**2040**	**2050**
China	175	162	150	135	176	83	0
Japan	159	152	145	138	139	66	0
Taiwan	197	184	172	157	157	74	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies

Electrifying the finishing (pad-dry-cure) process can result in large energy savings (Figure 63). In China, Japan, and Taiwan, annual energy savings of 5000, 225, and 210 TJ per year can be achieved in 2050, respectively. This is because electrified finishing is more efficient than the conventional process.

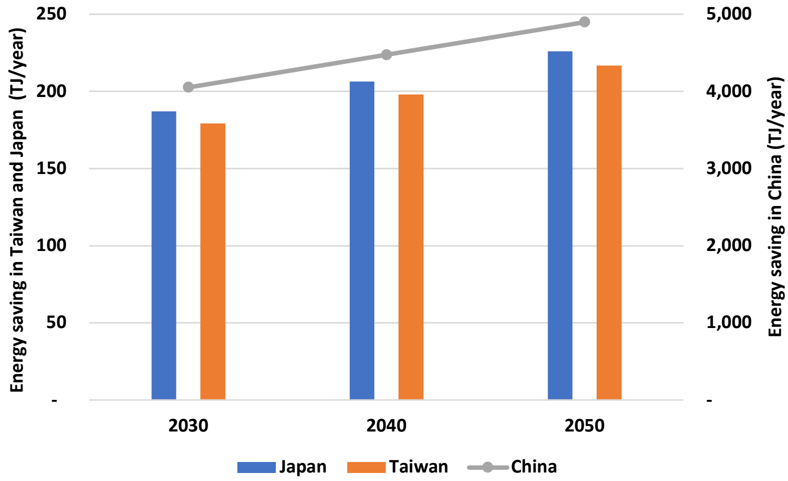


Figure 63. Total annual energy saving after electrification of finishing (pad-dry-cure) process (This is the technical potential assuming a 100% adoption rate.)

The electrification of the finishing process could lead to a decrease in CO_2 emissions in Japan and Taiwan and a slight increase CO_2 emissions in China in 2030. In 2050, the annual reduction of CO_2 emissions after electrification of the finishing process will be around 700, 32, and 35 kt CO_2 /year in China, Japan, and Taiwan, respectively.

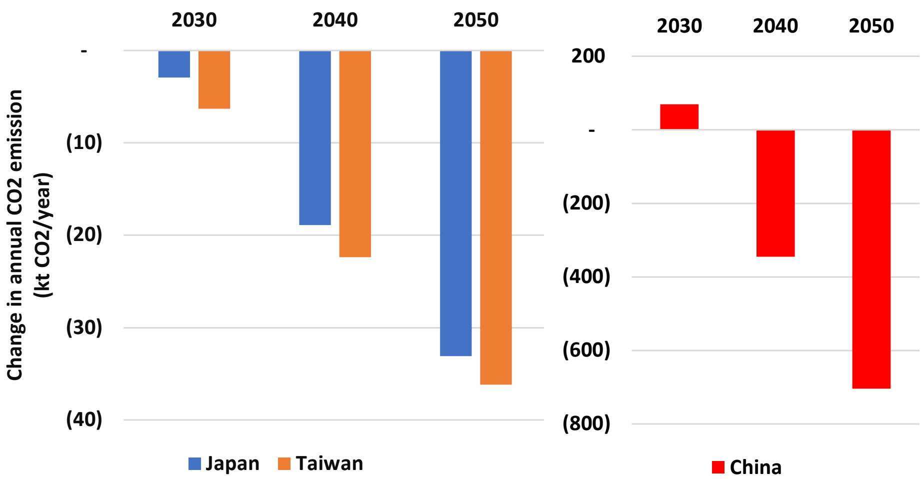


Figure 64. Total change in annual CO_2 emission after electrification of finishing (pad-dry-cure) process (This is the technical potential assuming a 100% adoption rate.)

The energy cost per unit of production varies across the three economies for the conventional and electrified finishing process (Figure 65-67). The energy cost for the electrified finishing process is higher than that for the conventional process in 2030. However, the energy cost for the electrified process can be lower than that of the conventional process in 2050. The sensitivity analysis on the graphs shows that the energy cost for the electrified finishing process can be lower than the conventional process even earlier when a lower price of electricity is used.

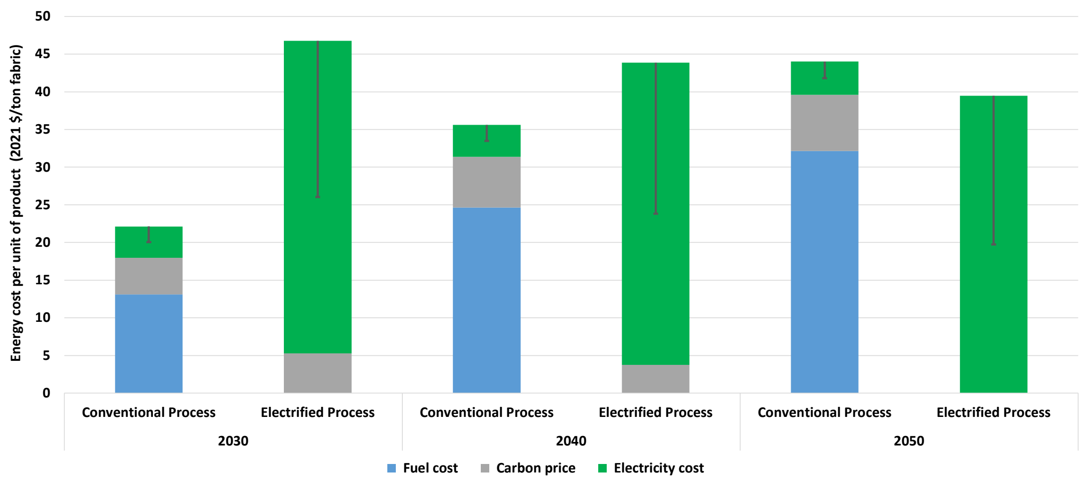


Figure 65. Energy cost per unit of production for conventional and electrified finishing (pad-dry-cure) process in **China** .

(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

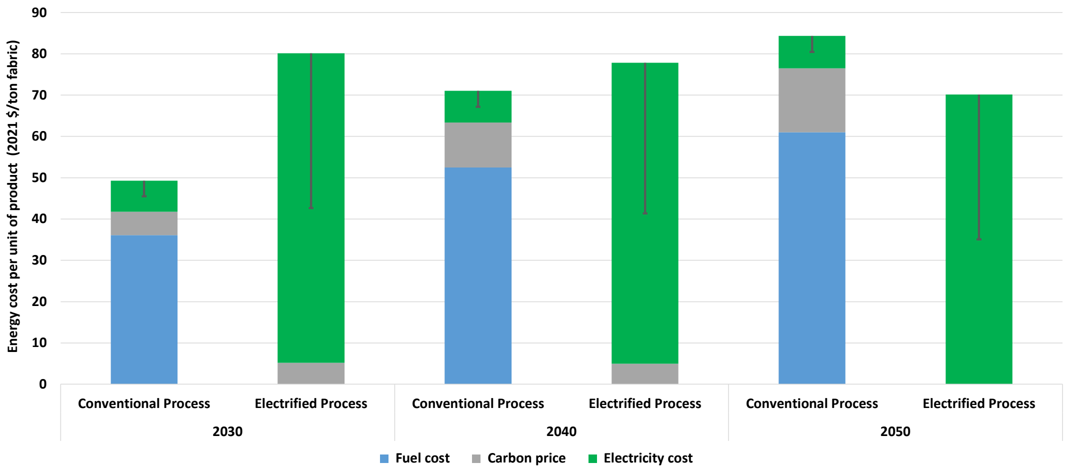


Figure 66. Energy cost per unit of production for conventional and electrified finishing (pad-dry-cure) process in **Japan .**

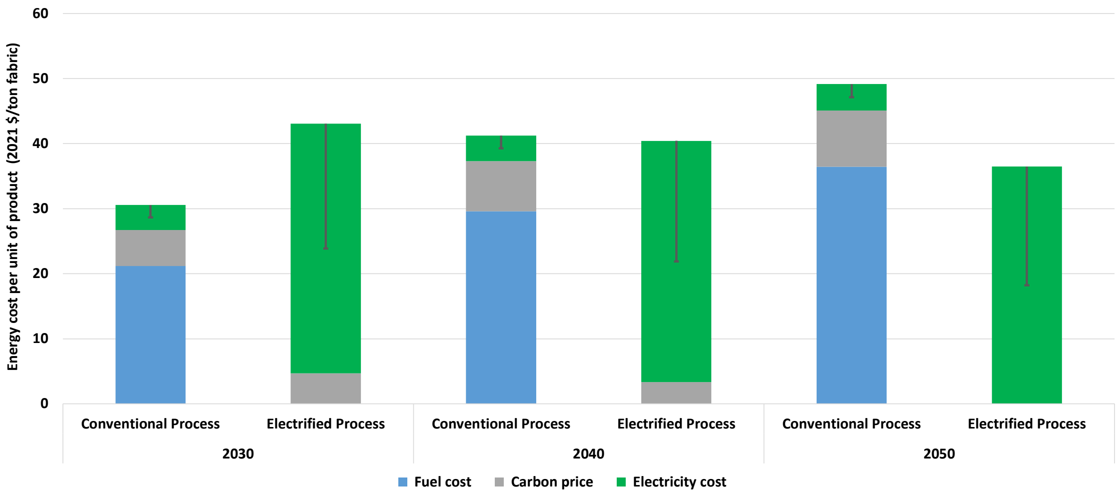


Figure 67. Energy cost per unit of production for conventional and electrified finishing (pad-dry-cure) process in **Taiwan .**

7.7. Electrification of the yarn drying process

The two main steps in drying textile yarns are the mechanical removal of water and the thermal removal of the remaining moisture. Mechanical processes use centrifugal force to extract water that is mechanically bound to the fiber. After the pre-drying, the remaining water is removed with a thermal process. This can be done through convection, contact, infrared or radiofrequency drying. The most common technique is convection drying, which involves passing a hot air stream through the material to be dried. The heat from the air transfers to the material and evaporates the water, which is then carried away (Galoppi et al. 2017).

Electrified yarn drying process
Radiofrequency (RF) dryers are well-known and already commercial electrified yarn dryers. The RF yarn drying machine is based on the direct transfer of electromagnetic energy to the water molecules contained in the wet fibers. Therefore, the energy is only delivered to the product in proportion to its moisture content with minimal losses in the surroundings, so the drying process can be carried out very efficiently. In this study, based on the information in the literature and the fact that RF dryers do not have the energy losses related to steam generation and distribution, we assumed the energy intensity of RF dryers is around 30% lower than that of a conventional yarn dryer (Stalam 2022, Fabern 2022, RF Systems 2022). Table 9 shows the estimated CO_2 intensity of the conventional and electrified yarn drying process in the textile industry in each economy.

Table 9. The CO_2 intensity of the conventional and electrified yarn dyeing process

	CO_2 Intensity (kg CO_2/t finished fabric)						
	Conventional				Electrified		
	2021	2030	2040	2050	2030	2040	2050
China	60	55	50	44	59	28	0
Japan	54	51	48	45	47	22	0
Taiwan	67	62	57	52	53	25	0

Note: We assumed the electricity grid will be carbon neutral in 2050 in all three economies

Electrification could lead to annual energy savings of about 750, 3, 14.5 TJ per year for China, Japan, and Taiwan, respectively in 2050 (Figure 68). This annual energy saving results from the higher efficiency (lower energy intensity) of electrified yarn drying compared with the conventional process.

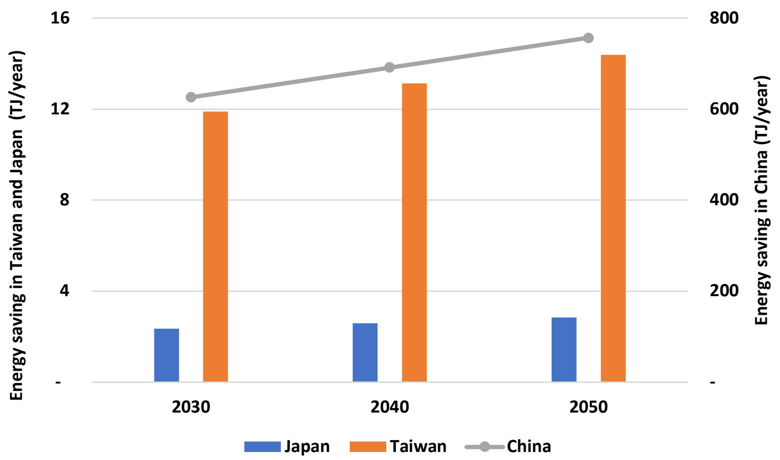


Figure 68. Total annual energy saving after electrification of yarn dyeing process (This is the technical potential assuming ing 100% adoption rate.)

In 2030, there is still a slight increase in CO_2 emissions after the electrification of the yarn drying process in China because of its relatively high grid CO_2 emissions factor, but electrification of this process could result in a reduction in CO_2 emissions in Japan and Taiwan in 2030. There is a substantial reduction in CO_2 emissions in all three economies in 2040 and 2050. The annual reduction of CO_2 emission after electrification of the yarn drying process in 2050 is around 110, 0.4, and 2.4 kt CO_2/year in China, Japan, and Taiwan, respectively.

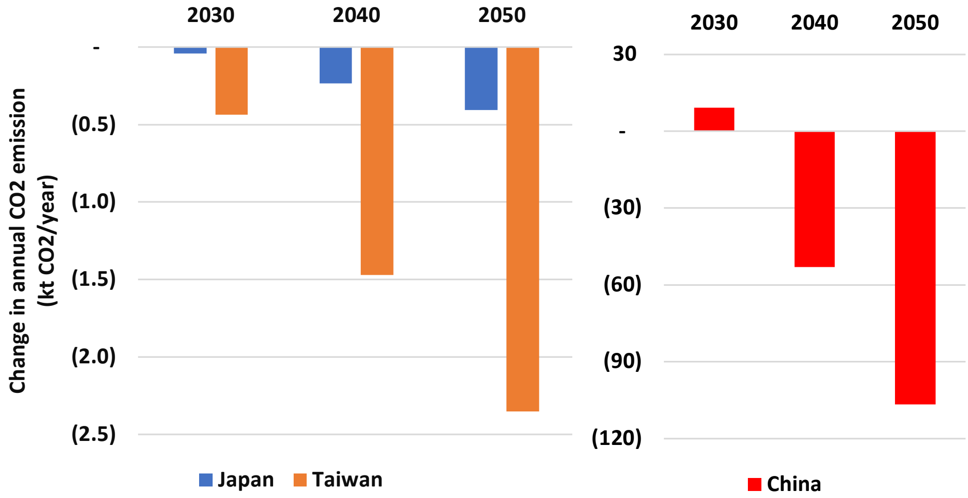


Figure 69. Total change in annual CO_2 emission after electrification of yarn dyeing process (This is the technical potential assuming a 100% adoption rate.)

Figures 70-72 show energy cost per unit of production in China, Japan, and Taiwan yarn drying process for the conventional process and electrified process up to 2050. The energy cost for the electrified yarn drying process is substantially higher than that for the conventional process in 2030. However, as the price of fossil fuels increases over time and considering the carbon price, the energy cost for the electrified process can be lower than that of the conventional process. In addition, the error bar on the graph shows that the energy cost per unit of production for the electrified process can be lower than the conventional process in Japan and Taiwan even in 2030 when the unit price of electricity is reduced.

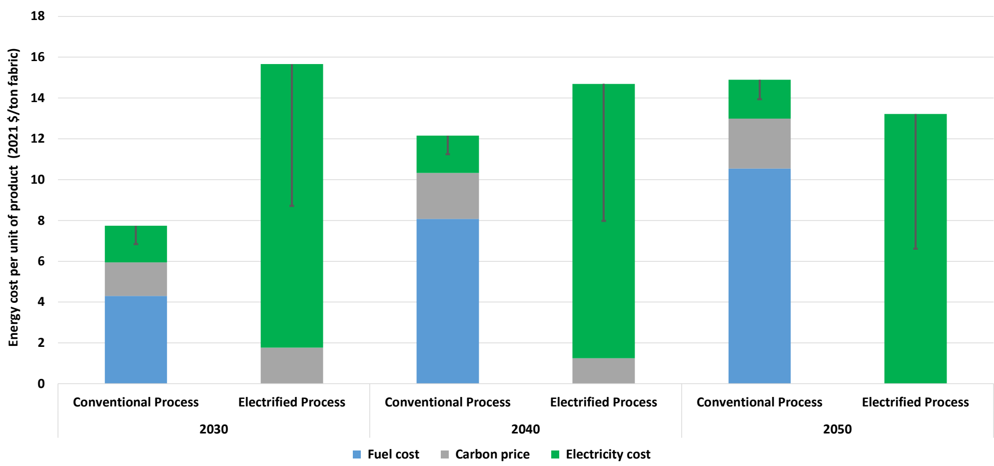


Figure 70. Energy cost per unit of production for conventional and electrified yarn dyeing process in **China** .
(Note: The error bars show the energy cost per unit of production when the unit price of electricity is reduced by 50 %.)

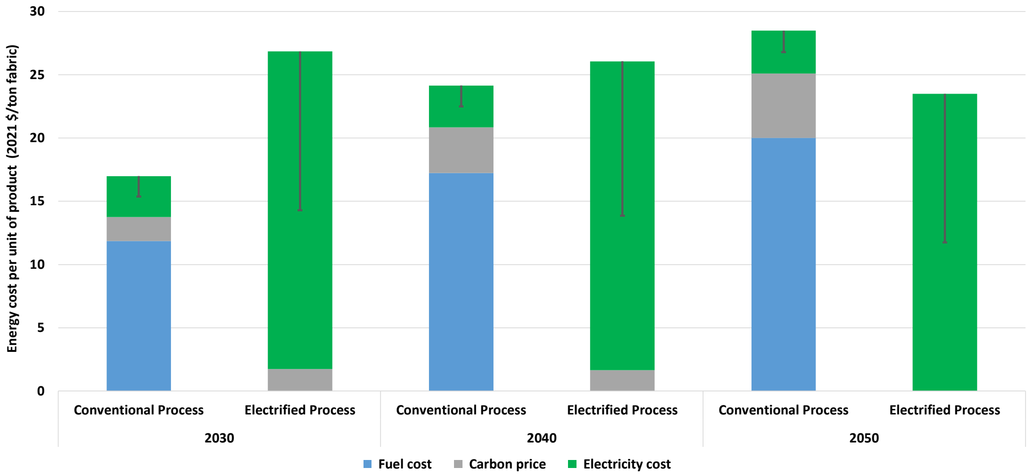


Figure 71. Energy cost per unit of production for conventional and electrified yarn dyeing process in **Japan** .

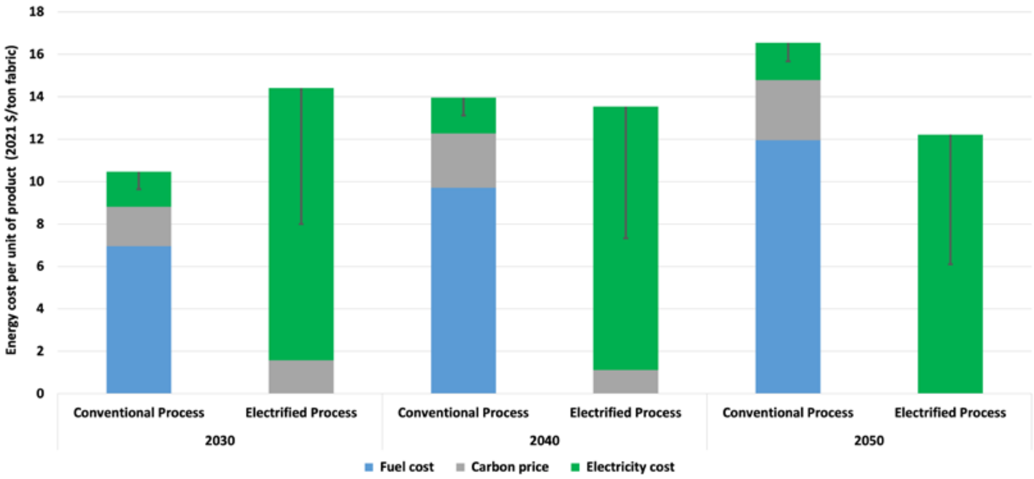


Figure 72. Energy cost per unit of production for conventional and electrified yarn dyeing process in **Taiwan .**

7.8. Total electrification potential in seven studied wet processes

This section presents the total combined annual energy saving and change in annual CO_2 emissions after electrification of all seven studied wet processes. Figure 73 shows that electrifying the studied processes results in a substantial annual energy saving up to 2050. Electrification could lead to annual energy savings of about 145000, 3500, and 3800 TJ/year in China, Japan, and Taiwan, respectively in 2050.

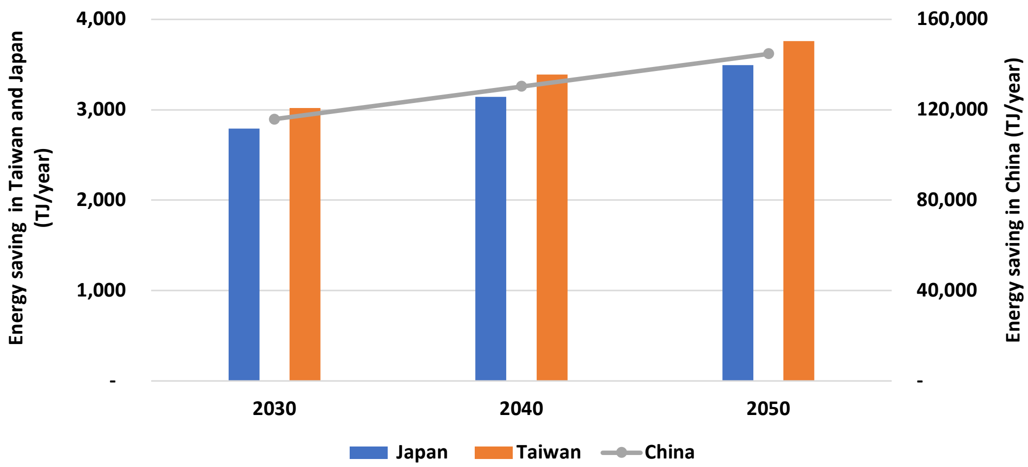


Figure 73. Total combined annual energy saving after electrification of all seven studied wet-processing processes (This is the technical potential assuming a 100% adoption rate.)

If the grid electricity is used, in 2030, there is still a slight increase in CO_2 emissions after the electrification of these processes in China, but by 2040 and 2050, there is a substantial reduction in emissions due to grid decarbonization and energy efficiency improvements. This could lead to an annual reduction of CO_2 emissions of around 23400, 570, and 700 kt CO_2/year in China, Japan, and Taiwan, respectively.

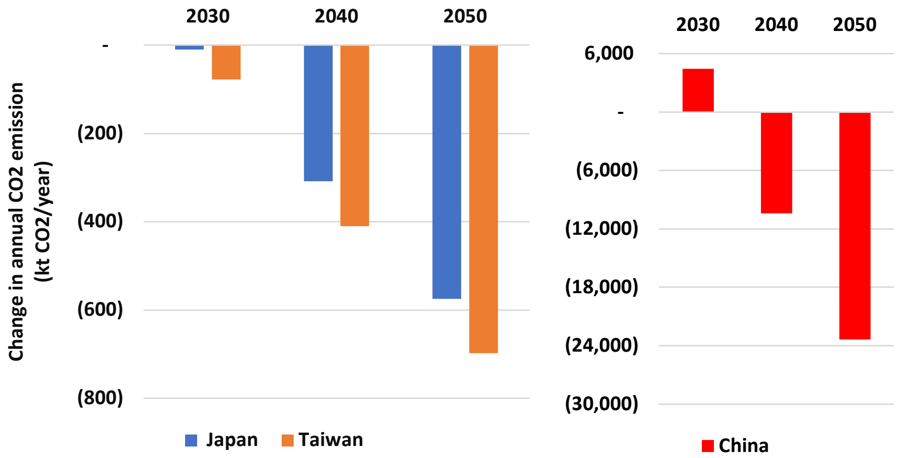


Figure 74. Total combined change in annual CO_2 emission after electrification of all seven studied wet-processing processes (This is technical potential assuming a 100% adoption rate.)

Our analysis for electrification through textile end-use processes shows that around three quarter of the CO_2 emissions reduction potential in 2050 comes from electrification of three processes: drying, dyeing, and heat-setting (stenter) (Figure 75). Around half of the emissions reduction potential comes from electrification of drying and heat-setting processes. The electrified machines for these two processes are already commercially available and these two processes can be good candidates to start with for process electrification in textile plants.

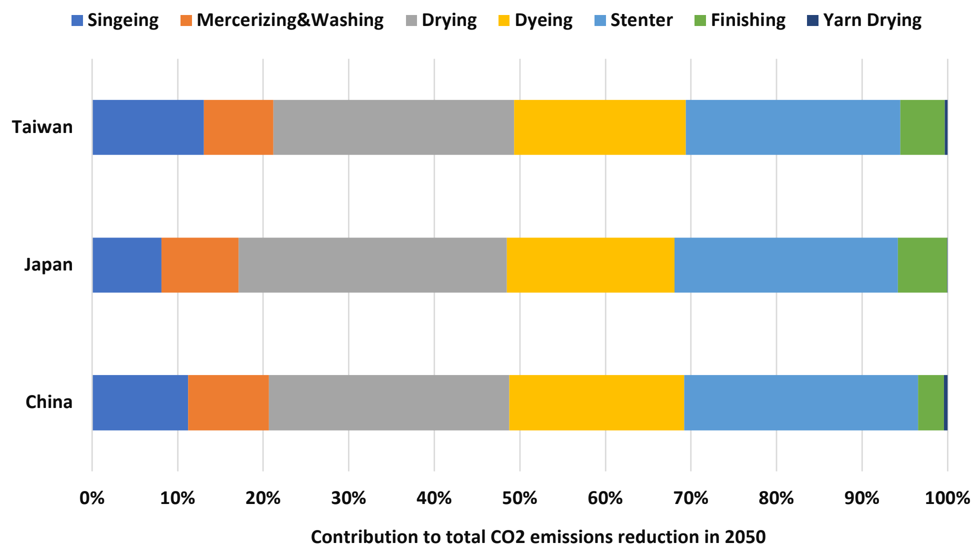


Figure 75. Contribution of each textile wet processes electrification (in end-use electrification scenario) to total CO_2 emissions reduction in 2050 .

7.9. Impact of electrification of the textile industry on the electricity grid

This analysis results clearly show that electrification results in a reduction in the total annual final energy use in the textile industry in China, Japan, and Taiwan. While electrification decreases net final energy demand, electricity demand increases. Figure 76 shows that electrifying seven textile wet-processes results in an increase in annual electricity consumption of 64000, 1500, and 1600 GWh/year in China, Japan, and Taiwan, respectively in 2050. This translates into an increase in renewable electricity load after electrification of 30, 0.7, and 0.8 GW in China, Japan, and Taiwan, respectively in 2050 (Figure 77). It should be noted that we assumed the additional electricity will have to come from renewable sources to provide the CO_2 emissions reduction befits of electrification. Therefore, we used the capacity factor of renewable power generation to estimate the additional electricity power generation load needed. The additional electricity demand for electrification of the textile industry with electric boilers or industrial heat pump scenarios are also presented in these figures.

For comparison, in 2021, China had around 2,380 GW, Japan had around 313 GW, and Taiwan had around 59 GW of power generation capacity (EIA 2022, JEPIC 2022). To estimate these additional loads, we assumed all the additional load is coming from clean renewable energy sources. We further assumed that two-thirds of this additional load is coming from solar power and one-third from wind power and assumed the capacity factor accordingly.

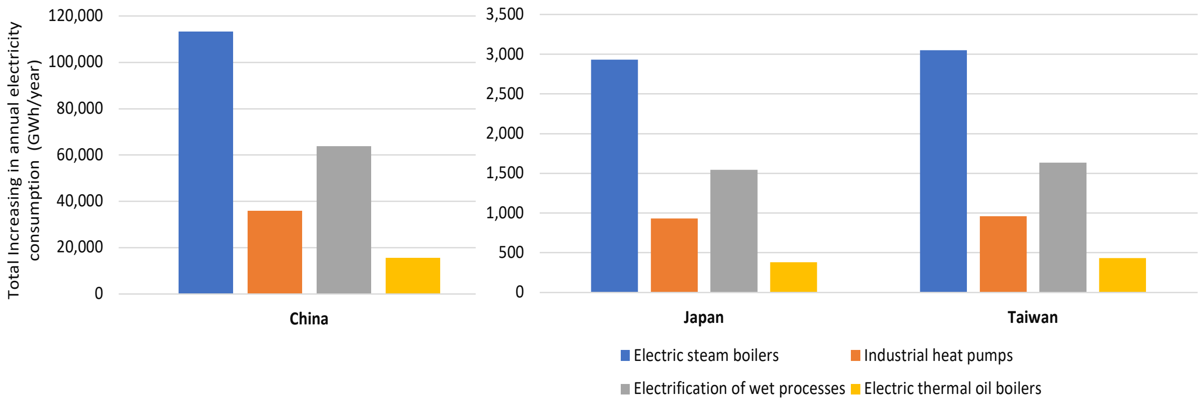


Figure 76. The total increase in annual electricity consumption (GWh/year) after electrification under each technology pathways (This is technical potential assuming a 100% adoption rate.)

Industrial electrification has the potential to reduce CO_2 emissions from the textile industry when the electricity grid is decarbonized enough, but the infrastructure and competing demands for renewable electricity resources pose challenges to realizing these reductions in China, Japan, and Taiwan. Investing in the electricity grid and increasing the share of renewable energy in the power sector energy mix will help to accelerate industrial electrification and contribute to a reduction in CO_2 emissions.

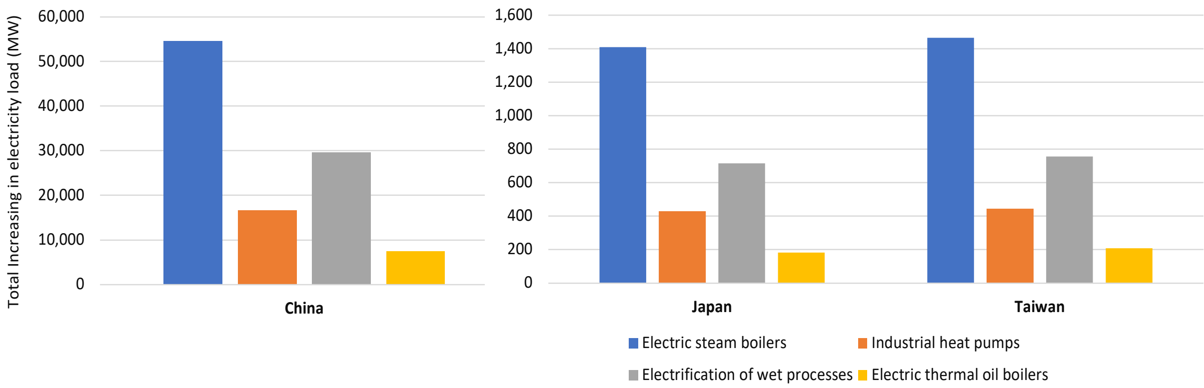


Figure 77. The total increase in renewable electrical load (MW) after electrification under each technology pathways (This is the technical potential assuming a 100% adoption rate.)

The electricity grid is a complex, interconnected system linking generation resources to customers with varying and variable electricity needs. Electricity generation from renewable resources has increased over time in these three economies, but the electricity grid still has a very high carbon intensity in these countries.

Managing the grid's resources, infrastructure, and energy flows is a considerable undertaking that will continue to be complicated by trends towards more distributed generation resources, renewable resources, and electrification. Additional pressure will be placed on an already strained grid system as multiple sectors, including transportation and buildings in addition to industry, move to electrify to access renewable resources and reduce their emissions. To deliver electrification at scale, investment will be needed to build or upgrade key infrastructure, including renewable electricity production, energy transmission, and distribution networks, and end-user infrastructure (Hasanbeigi et al. 2022).

Developing a coherent power sector strategy is essential to accelerate the pace of power sector decarbonization which is a prerequisite to beneficial electrification of industry. Utilities, policymakers, industry, and other stakeholders should pay attention to this potential increase in demand for renewable electricity, and the associated need for more renewable electricity generation, additional energy storage, demand response programs, transmission and distribution system expansion, and grid modernization. Ensuring that sufficient renewable resources are brought online and connected to demand centers will be critical to a smooth energy transition and rapid multisector electrification (Hasanbeigi et al. 2022).

8 Recommendations to Accelerate Electrification in the Textile Industry

While there are numerous benefits to electrifying industrial processes, including reduced energy demand and emissions, barriers still inhibit the development and deployment of electrified technologies, as described in our previous report (Hasanbeigi et al. 2021). This chapter recommends the six most impactful changes that would support increased electrification in the textile industry. These changes will require numerous actors to work together to solve significant challenges in renewable electricity generation and transmission, technology development and deployment, and workforce development.

1. **Increase renewable electricity generation**

   Top priority should be given to increasing renewable electricity generation capacity and the decarbonization of the electric grid in the three economies studied in this report and the rest of the world, so that CO_2 emissions reductions go hand in hand with electrification initiatives undertaken by textile manufacturers and apparel brands. To achieve that aim, governments should consider financial incentives that reduce renewable energy costs and carbon taxes that increase the costs of fossil fuels. To be successful, it is also essential that governments develop a coherent power sector strategy that pays attention to the potential rapid increase in demand and competition for renewable electricity across many sectors and end uses, and the subsequent need for additional renewable electricity generation, additional energy storage, and demand response programs. The strategy to increase renewable electricity should incentivize the development of distributed renewable energy generation at industrial sites as well as the central grid. Apparel brands can work with their textile suppliers in China, Japan, and Taiwan to increase investment in on- and offsite renewable electricity generation projects and/or work with governments and power utilities through industry groups to communicate private sector demand for increased access to renewable electricity supply.

2. **Enhance and modernize the electric grid**

   As more renewable electricity is generated, it is important to ensure that these additional renewable resources can connect to the transmission and distribution system. This will require grid upgrades that can manage the overall increased clean electricity volume as well as distributed renewable generation. Enhancements should also include resiliency measures to protect against severe weather threats to the grid.

3. **Promote electrification technology development and adoption in the textile sector**

   Governments and utilities should take steps to promote the electrification pathways featured in this report through tax incentives, reduced permitting costs, and grants for switching to electric technologies. Utility rates should be structured to incentivize electrification as appropriate to each economy. Apparel brands can also provide financial incentives to their textile suppliers in China, Japan, and Taiwan to encourage electrification of process heating in their plants.

4. **Promote pilot and demonstration projects**

   Working in partnership with various stakeholders, the textile brands and manufacturers should prioritize the further development, demonstration, and scaling of the four electrification pathways featured in this report, focusing first where reduction potentials are greatest and most immediate – i.e., heat pumps and drying and heat setting equipment. Governments, utilities, brands, and financial institutions should provide grants and other incentives for pilot and demonstration projects to encourage early adoption and demonstrate success of electrification strategies for the textile sector.

5. **Create and distribute education information**

   Many textile engineers, plant managers, apparel brands, financial community, and other important stakeholders are unaware of the potential for the electrification pathways featured in this report to reduce textile and apparel industry's carbon emissions. Educational materials to educate these stakeholders can play an important role in improving policy and investment decisions that deliver real CO_2 emissions reduction.

6. **Workforce development**

   Although fully commercialized, because these technologies are relatively new, there are few in the textile industry with experience to install or operate them or troubleshoot when problems arise. Training on installation, operation and maintenance, and other key technical features are critical to the short- and long-term success of increasing reliance on electrification to reduce textile and apparel industry's carbon footprint.

References

Alabama Power. 2020. Electric Boilers. https://www.alabamapower.com/business/ways-to-save/space-heating/electric-boilers.html

Ansal. 2022.Textile dryers. http://www.textiledryer.com/blog/plufix

Atlas Foundry Company. (n.d). Induction Furnaces. http://www.atlasfdry.com/inductionfurnaces.htm

Benkhaya, S., M'rabet, S., & El Harfi, A. (2020). A review on classifications, recent synthesis, and applications of textile dyes. Inorganic Chemistry Communications, 115, 107891.

Beyond Zero Emissions, 2019. Zero Carbon Industry Plan: Electrifying Industry. Melbourne, Australia.

Brueckner. 2022.Power frame stenter for textile. https://www.brueckner textile.com/en/imprint.html

Elitex finishing. 2022. Electric heating for the Elitex stenter. http://en.elitexfinishing.cz/products/modernization/electric-heating-for-the-elitex-stenter

Fabern. 2022. Radiofrequency dryer yarn dyeing package yarn radio frequency dryerhttps://fabern.en.made-in-china.com/product/KZlExBhGOtkm/China-Radio-Frequency-Dryer-Yarn-Dyeing-Package-Yarn-Radio-Frequency-Dryer.html

Gagneja, A., Pundhir, S., 2016. Heat pumps and its applications. International Journal of Advances in Chemical Engineering and Biological Sciences 3, 117–120. http://dx.doi.org/10.15242/IJACEBS.U0516203

Galoppi, G. et al. 2017. Experimental investigation on industrial drying process of cotton yarn bobbins: energy consumption and drying time. Energy Procedia 126 (201709) 361–368.

GH Induction Atmospheres. (2020). What is Induction Heating?.

Hasanbeigi, A. 2010. Energy Efficiency Improvement Opportunities for the Textile Industry. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-3970E

Hasanbeigi, A. 2013. Emerging Technologies for an Energy-Efficient, Water-Efficient, and Low-Pollution Textile Industry. Berkeley, CA: Lawrence Berkeley National Laboratory. LBNL-6510E

Hasanbeigi, A., Collison, B., Kirshbaum, L., Gardiner, D. (2021). Electrifying U.S. Industry: Technology and Process-Based Approach to Decarbonization. Global Efficiency Intelligence, LLC & David Gardiner and Associates.

Hasanbeigi, A., Kirshbaum, Lynn., Collison, Blaine (2022). Industrial Electrification: An industrial subsector- and state-level analysis. Global Efficiency Intelligence, LLC & David Gardiner and Associates (forthcoming report).

Heraeus Group. (2020). UV Curing Process. Available at: https://www.heraeus.com/en/hng/light_is_more/how_does_it_work/uv_curing/uv_curing.html#tabs-48256-1

Herschel Infrared Ltd. (2020). How Do Infrared Heaters Work?. Available at: https://www.herschel-infrared.com/how-infrared-heaters-work/

https://www.sugimat.com/en/products/thermal-oil-boilers/#:~:text=What%20is%20a%20thermal%20oil,or%20fuel%20derived%20from%20waste.

IEA. 2021. World Energy Statistics 2020. https://www.iea.org/data-and-statistics/data-product/world-energy-statistics

Istook, C. L. (2022). Strategies for Heat Setting in Textile Industry. Journal of Textile Science & Engineering, 12(2), 467. https://doi.org/10.37421/jtese.2022

Jadun, P., McMillan, C., Steinberg, D., Muratori, M., Vimmerstedt, L., & Mai, T. (2017). Electrification futures study: End-use electric technology cost and performance projections through 2050 (No. NREL/TP-6A20-70485). National Renewable Energy Lab. (NREL), Golden, CO (United States).

Japan Electric Power Information Center (JEPIC). 2022. The Electric Power Industry in JAPAN 2022.

Kerone. 2022. Infrared heating and drying for the textile. http://kerone.com/blog/infrared-heating-and-drying-for-textiles/

LightTech LightSources. (2020). UV Curing Applications. https://www.light-sources.com/solutions/uv-curing/uv-curing-applications/

Ma Lei, Zhao Wen Lan. (2004). Electric heat multi-core type contact type singeing frame. Chinese patent: CN1260420C

MKS Instruments. (2014). Application Note – Microwave Heating Applications Part 1: Fundamentals.

Monforts. 2022.Excellent in dyeing and finishing. https://www.ategroup.com/wp-content/uploads/brochures/Thermex-V1.PDF

Nassif, N. A. A. (2019). Effect of different wet processing stages on physical properties of cotton woven fabrics. Fibres and Textiles (4) 2019

Natural Resources Canada (NRCan). (2020). Heating and Cooling with a Heat Pump. Office of Energy Efficiency.

Rightor, E., Whitlock, A., Elliott, N. 2019. Beneficial electrification in industry. American Council for an Energy-Efficient Economy.

RF systems. 2022. radio frequency equipment: Textile Division. https://www.leclairmeert.be/files/7414/5260/4475/Textile_Catalogues.pdf

Sadowski, M., Perkins, L., McGarvey, E., 2021. Roadmap to Net Zero: Delivering Science-Based Targets in the Apparel Sector. https://www.wri.org/research/roadmap-net-zero-delivering-science-based-targets-apparel-sector

Samaterials. 2022. Silicon carbide heating rod. https://www.samaterials.com/silicon-carbon-rods/1763-equal-diameter-silicon-carbon-sic-heating-rods.html

Sonotronic. 2022. Ultrasonic washing environmentally friendly process with great effects. https://sonotronic.de/en/technologies/ultrasonic/ultrasonic-washing/

Stalam. 2022. Radio frequency equipment. https://www.ategroup.com/wp-content/uploads/brochures/Stalam-RF-drier-Leaflet.pdf

Sugimat. 2022. Thermal oil boilers.

Tusief, M. Q., Amin, N., Mahmood, N., & Iqbal, W. (2014). Tensile properties of cotton yarn as affected by different yarn singeing machine variables. Pakistan Journal of Scientific & Industrial Research Series A: Physical Sciences, 57(3), 172–175.

U.S. DOE, 2003. Industrial Heat Pumps for Steam and Fuel Savings.

US Energy Information Administration (US EIA). 2022. Energy consumption in China. https://www.eia.gov/international/analysis/country/CHN

US. DOE. 2021. Manufacturing Energy and Carbon Footprints (2018 MECS)- Textile Industry. https://www.energy.gov/eere/amo/manufacturing-energy-and-carbon-footprints-2018-mecs

Virock. 2022. Stenter heat setting. http://www.virock.com/en/Product/STENTER_HEAT_SETTING_MACHINE/For_woven/201508/45.html

Wadje, P. R. (2009). Textile–Fibre to fabric processing. Journal of the Institution of Engineers (India), Part TX: Textile Engineering Division, 90, 28–36.

World Trade Organization (WTO). 2021. World Trade Statistical Review 2021.

Yamuna. 2022. Stenter: the fine art of finishing. http://www.yamunamachine.com/stenter.php

Zhejiang. 2022. Hot air stenter. https://www.hotairstenter.com/product/hot-air-stenter.html

Zuberi, J; Hasanbeigi, A.; Morrow, W. (2021). Electrification of Boilers in U.S. Manufacturing. Lawrence Berkeley National Lab & Global Efficiency Intelligence, LLC.

Zuberi, J; Hasanbeigi, A.; Morrow, W. (2022). Electrification through Industrial Heat Pump Applications in U.S. Manufacturing. Lawrence Berkeley National Lab & Global Efficiency Intelligence, LLC.

Appendices

Appendix 1. Assumptions

Table A.1. Energy use in the textile industry in 2019 (PJ/year) (IEA 2021)

	Natural gas	Coal	Fuel oil	Gas/diesel oil	Purchased heat and other fuels	Electricity
China	207	101	1.8	5.7	426	773
Japan	10	-	1.4	3.6	4	14
Taiwan	6	11	4.6	0.0	3	21

Table A.2. Weighted average fuel CO_2 emission factors for the textile industry (kg CO_2/GJ) (calculated based on IEA 2021)

	2021	2030	2040	2050
China	69	67	65	62
Japan	63	63	63	63
Taiwan	80	78	75	72

Table A.3. Electricity grid's CO_2 emission factor (kg CO_2/MWh)

	2021	2030	2040	2050
China	614	409	205	0
Japan	487	325	162	0
Taiwan	548	365	183	0

*2021 values are from IEA (2021). For the projections, we assumed the 2050 grid emissions factor as zero and assumed a linear reduction between 2021 and 2050.

Table A.4. Energy prices for industry (2021$/kWh)

	China				Japan				Taiwan			
	2021	2030	2040	2050	2021	2030	2040	2050	2021	2030	2040	2050
Weighted average fuel price	0.034	0.02	0.04	0.05	0.087	0.06	0.09	0.10	0.037	0.035	0.049	0.060
Electricity price	0.10	0.10	0.10	0.10	0.17	0.17	0.18	0.18	0.09	0.09	0.09	0.09

*2021 energy prices are obtained from various sources and supplemented by the data provided by several textile plants in China, Japan, and Taiwan.

Table A.3. Assumed carbon price in this study (2021US$/t CO_2)

	2021	2030	2040	2050
China	9	30	45	55
Japan	4	37	75	113
Taiwan	0	30	45	55

Appendix 2. Electrification technologies for industry

This section provides a brief description of some of the main electrification technologies applicable to the industrial sector. More detailed information about these electrification technologies can be found in the references cited within the text. Many of these electrification technologies apply to the textile industry as discussed in the main body of this report.

Electric Boiler
Electric boilers typically utilize electric-powered resistive heating elements that help convert electricity into heat. The flow of electric current and the in-turn heating are controlled by a thermostat. The generated heat can be utilized for purposes such as providing hot water for heating systems or generating steam for industrial processes. Larger electric boilers are typically electrode boilers (jet type) that use electricity flowing through streams of water to create steam. A key benefit associated with electric boilers is that they can convert electricity into heat with an efficiency of almost 100%, with minimal radiation losses observed from exposed boiler surfaces (Alabama Power, 2020). On average, the capital cost of an electric boiler is nearly 40% less than that of an equivalent natural gas-fired boiler (Jadun et al., 2017).

Heat Pump
Heat pumps are devices that extract and transfer heat from one place to another. Common examples of this technology include refrigerators and air conditioners. Inside a heat pump, a refrigerant is cycled across two heat exchanger coils. In the first coil, it undergoes evaporation by gathering heat from its surroundings and in the second coil, the refrigerant is condensed, leading to the release of absorbed heat (NRCan, 2020). The technology offers a high coefficient of performance (COP) and has the potential to save costs through the replacement of gas-fired heating processes (Beyond Zero Emissions, 2018).

Electric Arc Furnace
Electric arc furnaces melt metals via direct and radiant heating, generated using electricity that jumps from the energized to the grounded (neutral) electrode, resulting in high voltage electric arcs (Flournoy, 2018). These furnaces are most commonly utilized for melting steel for recycling, producing almost 30% of the world's steel output. They utilize substantially lower energy compared to primary steel production using blast furnace-basic oxygen furnace (Beyond Zero Emissions, 2018).

Induction Heating
Induction heating occurs by placing the material that needs to be heated inside an electromagnetic field generated by passing electricity through a conductor or coil. The electromagnetic field helps heat the material by inducing circulating electric currents within the material (GH Induction Atmospheres, 2020). The process is utilized for a wide range of applications including metal hardening, soldering, and annealing. Some of the advantages of this technology are enhanced process efficiency, uniform and precise heating, and no on-site emissions (GH Electrotermia, 2011).

Radio-frequency Heating
Radio-frequency heating is a form of dielectric heating with systems operating in the 10-30 MHz frequency and 10-30 meters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material. Since the entire thickness of the material is heated simultaneously, the process offers uniform heating at low temperatures. This technique works well with materials that are poor conductors of heat and electricity due to its greater depth of penetration and is much more efficient than conventional heating processes (Beyond Zero Emissions, 2018).

Electric Infrared Heater
Electric infrared heaters operate through the conversion of electricity into radiant heat. The process involves the direct heating of the object instead of heating the air in between, thus ensuring the efficient transfer of heat (Herschel, 2020). These systems can be designed with temperature requirements and the target material's ability to absorb infrared radiation in mind. The technology offers numerous advantages, including high overall efficiency, faster response time than gas convection systems, low cost, and minimal maintenance effort (Beyond Zero Emissions, 2018).

Ultra-violet (UV) Heating
UV radiation is primarily utilized for the efficient curing of coatings such as paints, inks, and adhesives. The process works by exposing UV formulations (inks, coatings, or adhesives containing a small proportion of photoinitiators) to UV radiation, resulting in their instant curing. Some advantages of the UV curing process include improved resistance to abrasion, faster production speeds, low energy intensity, and a reduction in processing times (Heraeus Group, 2020). The technology is utilized for various applications such as adhesive bonding, general electronics, packaging, semiconductors, and coatings, among others (LightTech, 2020).

Microwave Heating
Microwave heating is a form of dielectric heating with systems operating in the 900-3000 MHz frequency and 10-30 centimeters wavelength ranges. The process works by agitating the molecules of the material, resulting in the generation of heat within the material (Beyond Zero Emissions, 2018). This process is utilized for a wide variety of industrial applications, including simple heating, drying, and defrosting. It is especially useful for heating products or materials with poor thermal conductivity, large volume and small surface area, and high sensitivity to large surface and bulk temperature differentials (MKS, 2014).

Electric Induction Melting
The working principle behind electric induction furnaces is the induction of a low voltage, high current in a metal (secondary coil) with the help of a primary coil at a high voltage (Atlas Foundry Company, n.d.). The induced current leads to the development of a stirring motion, which maintains the molten metal at a constant temperature, ensuring homogenous and good quality output. Induction furnaces are categorized into channel induction furnaces and crucible induction furnaces. Channel induction furnaces are utilized for melting non-ferrous metals with lower melting points, operating at an efficiency of around 80 to 90%. Crucible induction furnaces are utilized for melting metals with higher melting points (such as steel and cast iron) and they operate at an efficiency of 80% (Beyond Zero Emissions, 2018).