Part of the World Bank Report
Green Horizon: East Asia's Sustainable Future

INDUSTRIAL DECARBONIZATION IN EAST ASIA

TRANSFORMING ENERGY, FINANCE, TECHNOLOGY, AND JOBS

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Cover design: Kevin Kunyu Sun

Cover image: The images featured on the four designed banners are adapted from artwork generated using ChatGPT-5 in August 2025. Each banner image was developed based on a specific prompt: the green banner ("solar panels, wind turbines, smart grids, and battery storage in a single composition"); the blue banner ("dynamic sustainable finance and financial markets in action"); the silver banner ("representative image for green hydrogen, green ammonia, carbon capture utilization and storage, and green steel"); and the gold banner ("jobs and workforce for green industries requiring digital and interdisciplinary skills"). All other cover elements were originally created by the cover designer.

Foreword

East Asia is pivotal to the world's decarbonization efforts. In 2023, on a per-capita basis, greenhouse gas emissions in the East Asia and Pacific region (excluding high-income economies) were 7.11 tCO_{2e} per capita—lower than in OECD countries (8.01 tCO_{2e} per capita) and high-income countries (9.89 tCO_{2e} per capita). Yet, the region's contribution to global emissions is large and expected to rise alongside economic growth and industrialization. In 2023, the region produced more than a third of global greenhouse gas emissions and was the largest consumer of coal worldwide. China, Indonesia, and Viet Nam account for 80 percent of the region's emissions and 88 percent of its coal consumption, with the power and industrial sectors responsible for 75–87 percent of energy-related emissions. The choices made in East Asia will shape the global energy and industrial landscape for decades to come. This report - *Green Horizon: East Asia's Sustainable Energy Future* is an important contribution to understand the pathways to intertwine energy and development imperatives in East Asia.

The power and industrial sectors must decarbonize in tandem. Their emissions are closely linked, with industries relying heavily on electricity and power generation shaped by industrial demand. As electricity use accelerates, decarbonizing the power sector is the linchpin of the region's clean energy and industrial transformation—not only to reduce its own emissions but also to enable industry to shift to clean energy. Advancing both transitions together, through energy and material efficiency, electrification, green hydrogen, carbon capture, and clean feedstocks, is essential to achieving deep and lasting reductions.

Massive and coordinated investments will be needed. Industrial decarbonization alone will require USD 1.7 trillion in cumulative capital through 2050—around USD 70 billion per year across China, Vietnam, and Indonesia. Decarbonizing the power sector in these economies will require USD 9 trillion in cumulative investments from 2020 to 2040. These investments must be planned in a synchronized manner to ensure that industrial system of tomorrow run on the clean electricity generated by power systems of tomorrow.

These transitions present a transformative opportunity. A shift to clean power and low-carbon industry can strengthen competitiveness, modernize production systems, enhance energy security, and create significant new employment opportunities across East Asia's economies.

The World Bank Group is committed to realizing this opportunity. We will work with governments, industry leaders, financiers, and development partners to mobilize capital, share knowledge, and enable policies that will deliver an ambitious, integrated clean energy and industrial transformation across East Asia.

MANUELA V. FERRO
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Executive Summary

This report is the first to systematically address the complex challenge of industrial decarbonization in East Asia, one of the world's most dynamic economic areas. Drawing on original data and in-depth assessments of three key economies—China, Indonesia, and Viet Nam—the report identifies viable technical pathways, unveils implementation challenges, and offers a comprehensive policy package to accelerate the transition to net-zero industry.

Importance | Transforming 40 percent of global industrial output for sustainable growth and the energy transition

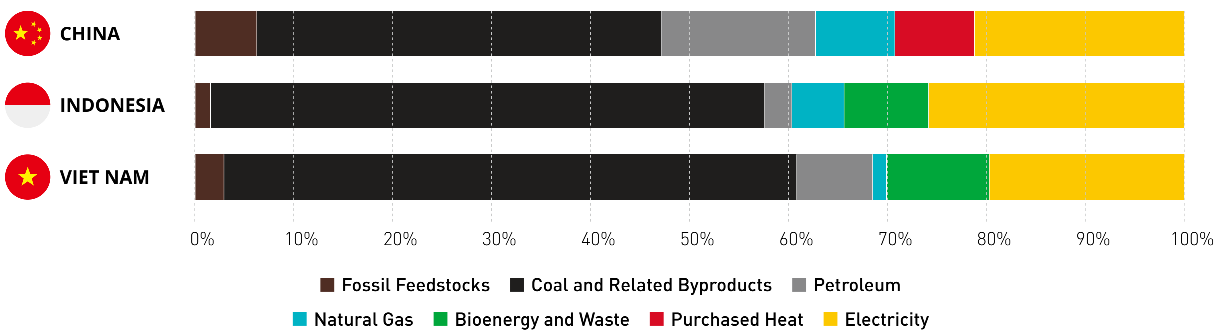
The powerhouse of global economic growth, East Asia is anchored by a dynamic industrial sector that contributes 38 percent of regional GDP and employs nearly a third of its workforce (World Bank 2025b).

The region's industries are diverse and strategically significant: China leads in heavy industries, accounting for more than 50 percent of global steel, cement, aluminum, copper, and nickel production; Indonesia anchors resource-based sectors and petrochemicals; and Viet Nam is rapidly expanding its light manufacturing and electronics exports. Beyond the nearly 300 million direct jobs it provides, industry generates widespread indirect employment by fueling demand along the value chain—from energy production and construction to finance, engineering, and digital services.

The region consumes 40 percent of global primary energy, emits 40 percent of global greenhouse gases, and remains heavily dependent on fossil fuels for industrial energy use (Ritchie et al. 2024).

In 2022, the industrial sector accounted for the largest share of final energy use in China (47 percent), Indonesia (44 percent), and Viet Nam (51 percent). Coal, related byproducts and fossil feedstocks dominate industrial energy use—47 percent in China, 57 percent in Indonesia, and 61 percent in Viet Nam. Fossil fuel shares rise to 71, 66, and 70 percent, respectively, when petroleum and natural gas are included **(FIGURE ES.1)** (NBS 2024, MEMR 2024, VNEEP 2024, and VSA 2024). As a result, these countries' industrial emissions, as a share of their total energy-related emissions, far exceed the global average: industry contributes 26 percent of energy-related carbon dioxide (CO_2) emissions in China, 24 percent in Indonesia, and 31 percent in Viet Nam, versus 18 percent globally. Adding emissions from electricity consumed by industries, the share rises to 65, 48, and 57 percent in China, Indonesia, and Viet Nam respectively, versus a world average of 30 percent (IEA 2023c).

FIGURE ES.1 Industrial sector energy use by fuel for China, Indonesia, and Viet Nam shows fossil fuel dependence



Industrial decarbonization presents a strategic opportunity to accelerate the energy transition, boost economic competitiveness, and create quality jobs across the East Asian region.

For developing economies, industrial decarbonization delivers a triple dividend: greater productivity through energy and material efficiency, increased investment and green job creation, and improved public health and social welfare from reduced air pollution and an enhanced work environment. By shifting to clean energy and modern industrial processes, countries in the region can meet their net-zero targets (i.e., 2060 for China and Indonesia, 2050 for Viet Nam), avoid locking in carbon-intensive infrastructure, and gain competitiveness in an increasingly carbon-conscious global market.

Decarbonizing industry remains a critical yet overlooked component in the energy transition.

The carbon- and energy-intensive industrial sector has made limited progress and receives just 1.4 percent of global climate finance (Naran et al. 2024). While power and transport dominate decarbonization policy priorities, the industrial sector, especially in developing countries, remains largely neglected. One key reason for this policy gap is the sector's inherent complexity, its deep interlinkages with other areas of the economy, and its contribution to economic competitiveness. Practical challenges compound this gap, including the high cost of clean energy, grid constraints on renewable deployment, low readiness of emerging technologies, and shortages of skilled labor. Without targeted attention, this sector could become the weak link in achieving national and global decarbonization goals.

Methodology | Unpacking industrial decarbonization strategies and global best practices

This report employs a mixed-methods approach combining technical modeling, case studies, and stakeholder consultation.

It integrates bottom-up quantitative modeling with five international case studies to identify technical pathways and policy recommendations for industrial decarbonization in China, Indonesia, and Viet Nam. In addition, stakeholder consultations in studied countries were conducted for contextualization. Together, the three countries account for 85 percent of energy-related CO_2 emissions from the Asia-Pacific industrial sector. Their distinct industrial profiles and energy system characteristics offer a compelling case for advancing industrial decarbonization—both within the region and globally.

Given the complexity of industrial decarbonization, six tiers of technical strategies were defined to clarify how limited resources can deliver the greatest impact.

These technical strategies are ranked based on cost-effectiveness and technological readiness. As shown in TABLE ES.1, lower-numbered tiers include the most mature and affordable interventions, while higher-numbered tiers feature more-expensive and less-developed solutions. Each tier represents a distinct, nonoverlapping set of measures that can cumulatively cut 95–97 percent of each country's industrial emissions. These include direct CO_2 emissions from fossil fuel combustion at industrial facilities, process CO_2 emissions from cement production, and fugitive methane (CH_4) emissions associated with the extraction of fossil fuels purchased by industry. The modeling scope is limited to the industrial sector, with the assumption that the power sector will achieve full decarbonization in line with the countries' net-zero targets.

TABLE ES.1 The Six-Tier Approach: Strategies for industrial decarbonization based on cost-effectiveness and technological readiness

Tiers	Strategies	Interventions	Targeted industrial subsectors
Tier 1	**Energy efficiency, material efficiency, and product longevity**	• Improving thermal and electrical energy efficiency (e.g., waste heat recovery, energy management systems, energy-efficient equipment) • Material-saving product design and manufacturing technologies (e.g., net shape manufacturing, fewer process steps) • Designing products and buildings for longevity and maintenance	Key processes and cross-cutting systems (process heating, steam, motors, pumps, fans, etc.) across all industrial subsectors
Tier 2a	**Easy electrification:** electrification of nonthermal processes, low-temperature heating, and scrap-based steelmaking	• Replacing diesel engines with electric motors • Replacing fossil-fueled boilers with industrial heat pumps for low-temperature (<150°C) industrial heating • Switching a portion of primary steelmaking based on blast furnace-basic oxygen furnace (BF-BOF) to secondary scrap-based steelmaking in electric arc furnaces (scrap-EAF)	Food and beverage, textiles, pulp and paper, and iron and steel Also targets motor and steam systems used across most industrial subsectors
Tier 2b	**Other electrification:** electrification of medium-to-high-temperature process heating	• Replacing fossil-fueled boilers with electric boilers and thermal batteries • Replacing fossil-fueled furnaces, kilns, and other heating equipment with electrified replacements (such as electric resistance heating, induction heating, electric arcs/plasma torches, dielectric heating, and infrared heating)	Chemicals, refining, nonferrous metals, nonmetallic minerals, and manufacturing of machinery and equipment
Tier 3	**Carbon capture, utilization and storage (CCUS)**	• Amine-based CO_2 capture • Oxy-fuel combustion CO_2 capture • Direct capture of process CO_2 emissions from cement-making • Retrofitting a portion of blast furnaces (BF-BOF) with CCUS • CO_2 transport and use or sequestration	Nonmetallic minerals (cement, lime, etc.), iron and steel
Tier 4a	**Green hydrogen (H_2)**	• Transitioning a portion of primary steel production from the BF-BOF route to the green hydrogen–based direct reduced iron-electric arc furnace (H_2-DRI-EAF) method • Replacing fossil fuel combustion with green hydrogen in high-temperature processes where electrified options are technologically immature • Replacing fossil fuel combustion with green hydrogen in subsectors that already use hydrogen for other purposes	Iron and steel, chemicals, refining, and nonmetallic minerals (glass, cement)
Tier 4b	**Clean feedstocks**	• Replacing fossil fuels used as chemical feedstocks (e.g., coal, natural gas, and petroleum) with clean feedstocks (green H_2, blue H_2, bioenergy)	Ammonia, methanol, olefins, aromatics (used in fertilizers, plastics)

The modeling incorporates anticipated technological and financial developments that can be applied under the policy recommendations provided in this report.

The modeling assumptions include a substantial reduction in the cost of clean hydrogen,[1] with green hydrogen reaching $1.80/kilogram (kg) in China, $3.50/kg in Indonesia, and $2.17/kg in Viet Nam by 2050, respectively.[2] It also incorporates a carbon price that increases from present-day values to $50/tonne CO_2 by 2050,[3] which represents the combined effects of direct carbon pricing such as carbon markets and carbon taxes, as well as indirect carbon pricing, such as withdrawing existing fossil fuel subsidies and accounting for the social cost of carbon.[4] These modeling assumptions affect the cost-effectiveness of the technological interventions. The full list of technical model assumptions is presented in Appendix D.

Five global case studies were analyzed to assess the enabling policies and support frameworks behind successful industrial decarbonization initiatives across major energy-intensive sectors.

The cases cover steel, cement, chemicals, and industrial parks—in both developed and developing countries. The cases illustrate key technical pathways in these sectors: steelmaking powered by renewable energy (RE) in India, green hydrogen in Sweden and Saudi Arabia, carbon capture and storage (CCS) in Norway, and renewable integration in China's industrial parks. A common framework was used to examine policy, financing, institutional coordination, and infrastructure readiness in various contexts.

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[1] "Clean hydrogen" includes hydrogen produced from fossil fuels coupled with carbon dioxide capture and storage (combustion based) or carbon storage (pyrolysis based). These are also known as "low-carbon hydrogen" or "blue hydrogen." Hydrogen produced from water electrolysis using renewable electricity or from biomass is known as "renewable hydrogen" or "green hydrogen." "Conventional hydrogen" or "gray hydrogen" refers to fossil fuel-based production without carbon dioxide capture and storage.

[2] The estimated 2050 green hydrogen cost for China is from Erofeev (2025) citing the latest estimate from BloombergNEF. The estimated 2050 green hydrogen cost of 2050 for Vietnam is from UNDP (2023), Tuyen (2024), and ERIA (2024); and the 2050 green hydrogen cost of Indonesia are from ERIA (2024) and Bloomberg NEF (2023).

[3] In this report, "$" signifies U.S. dollars unless otherwise specified and that "tonne" signifies "metric ton".

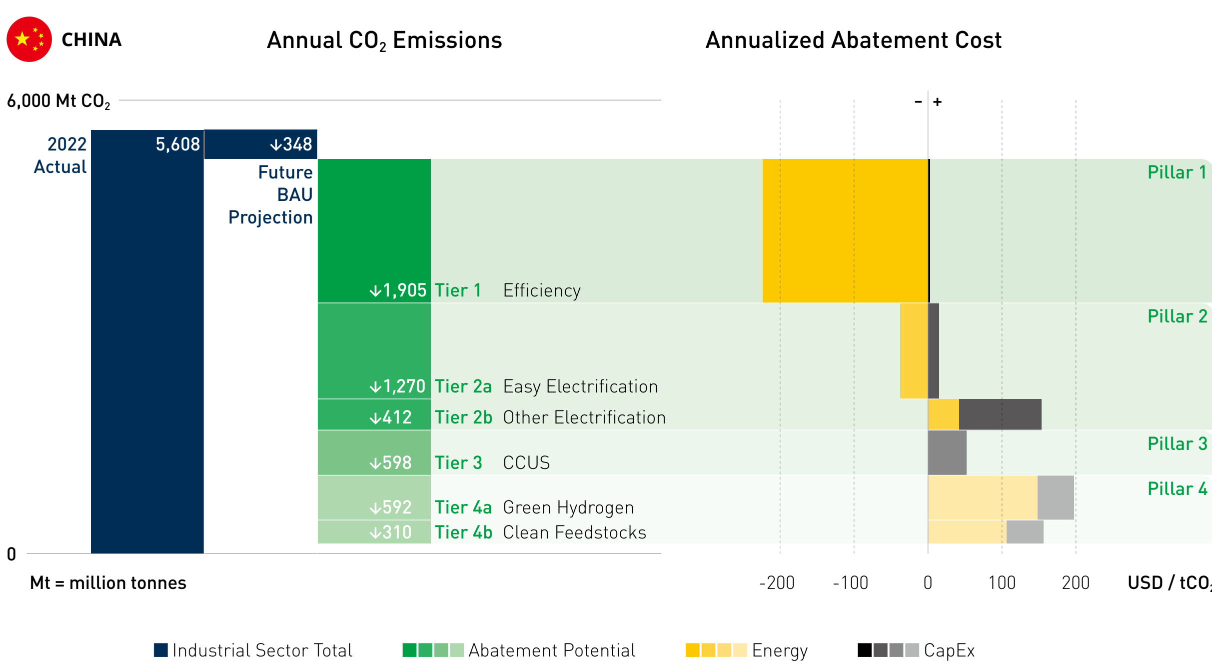
[4] We define "present day" carbon prices based on prevailing carbon market levels in 2023–2024, particularly in East Asia, which remain well below global policy-guided shadow price levels: in 2024-2025, carbon pricing in China is around $13/tonne CO_2, and about $2/tonne CO_2 in Indonesia, and around $5/tonne CO_2 in Vietnam (voluntary markets). The $50/tonne cap was selected to reflect this market reality and provide a conservative benchmark for assessing near-term investment competitiveness. We note that the World Bank's Shadow Price of Carbon (SPC), recommended for project economic appraisal, is distinct from prevailing or market carbon prices and also from the Social Cost of Carbon (SCC), which estimates the external damages from emissions. As noted in the World Bank's 2024 SPC Guidance note, the SPC in the range of $40–80 per tonne of CO_{2e} in 2020, rising to $50–100 per tonne of CO_{2e} by 2030, is based on a review carried out by the High-Level Commission on Carbon Prices and assumes a supportive global policy environment. Since many East Asian countries do not yet have strong carbon pricing frameworks or enabling conditions, our use of a $50/tonne cap reflects a realistic upper bound for short- to medium-term decision-making in the regional context.

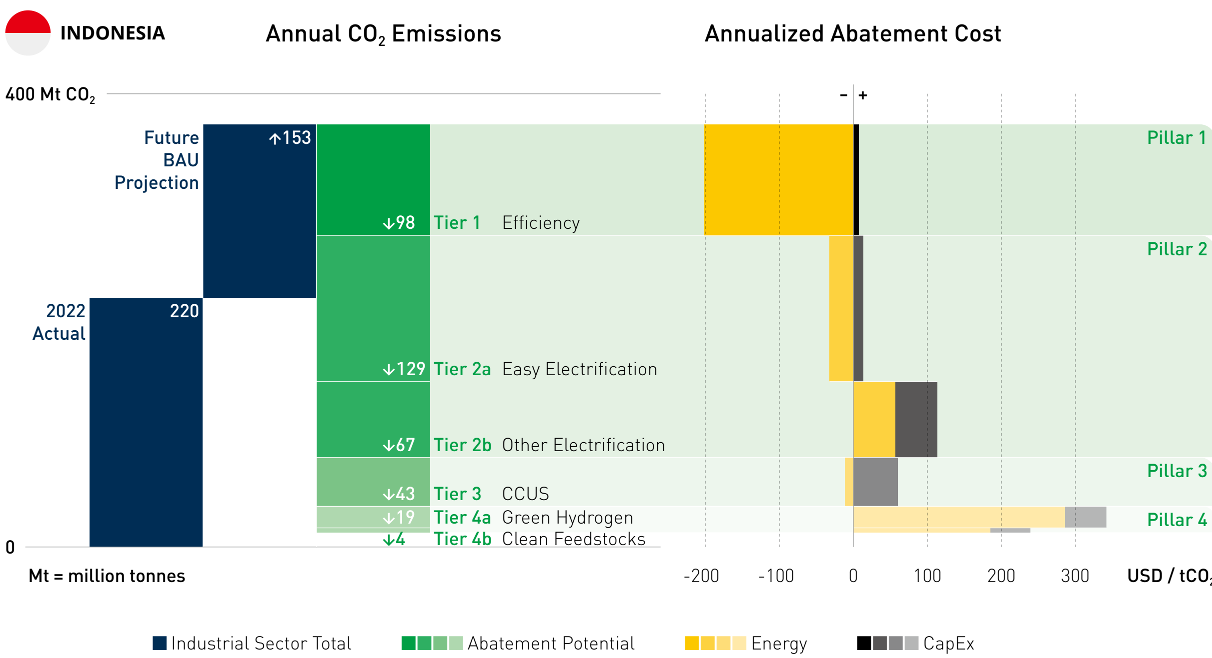
Technical Pathways | Decarbonization potential, cost-effectiveness and trade-offs

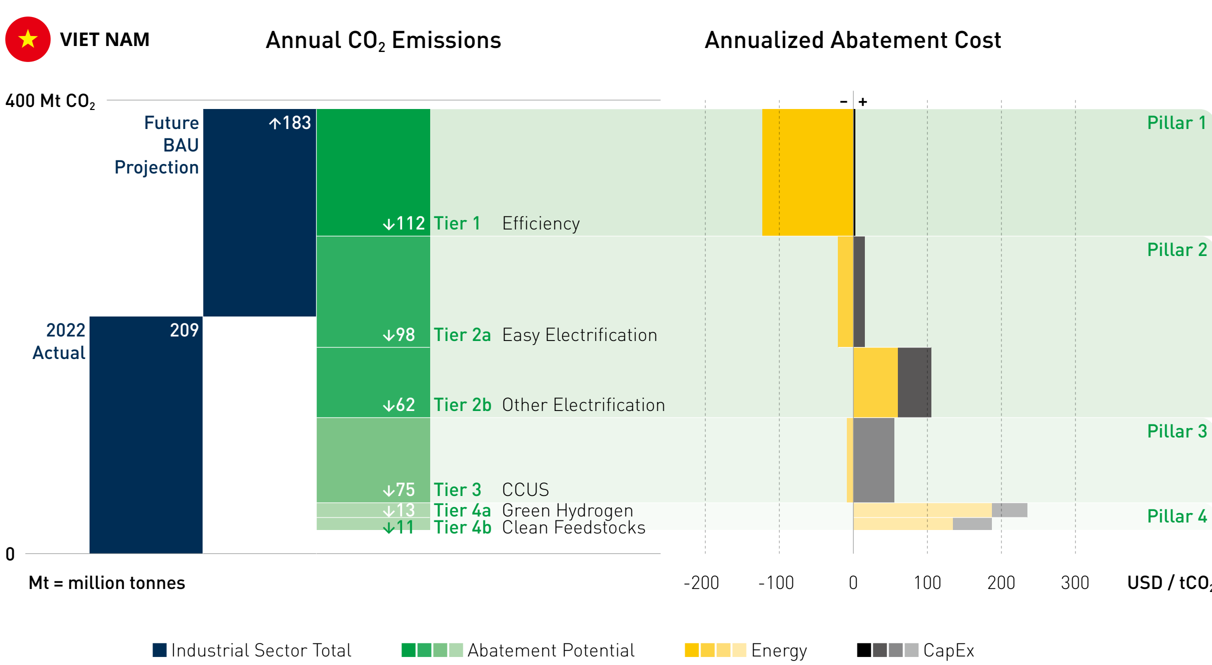
The modeling revealed common technical pathways to reach net-zero industrial emissions in all three countries, even after considering country-specific industrial structures, economic scales, and development stages.

Within this pathway, the six tiers are grouped into four pillars of industrial abatement for China, Indonesia, and Viet Nam **(FIGURE ES.2)**: (1) energy and material efficiency; (2) electrification with renewable energy; (3) carbon capture, use, and storage (CCUS); and (4) green hydrogen and clean feedstocks. This section explains the abatement potential, abatement cost, and focus subsectors of each technical pillar based on modeling results.

FIGURE ES.2 Industry decarbonization technical pathways: Abatement potential and abatement cost per tonne of CO_2




INDONESIA
Annual CO_2 Emissions
Annualized Abatement Cost
400 Mt CO_2
Future BAU Projection
↑153
2022 Actual
220
0
↓98 Tier 1 Efficiency
↓129 Tier 2a Easy Electrification
↓67 Tier 2b Other Electrification
↓43 Tier 3 CCUS
↓19 Tier 4a Green Hydrogen
↓4 Tier 4b Clean Feedstocks
Pillar 1
Pillar 2
Pillar 3
Pillar 4
- +
-200 -100 0 100 200 300 USD / tCO_2
Mt = million tonnes
Industrial Sector Total
Abatement Potential
Energy
CapEx


VIET NAM
Annual CO_2 Emissions
Annualized Abatement Cost
400 Mt CO_2
Future BAU Projection
↑183
2022 Actual
209
0
↓112 Tier 1 Efficiency
↓98 Tier 2a Easy Electrification
↓62 Tier 2b Other Electrification
↓75 Tier 3 CCUS
↓13 Tier 4a Green Hydrogen
↓11 Tier 4b Clean Feedstocks
Pillar 1
Pillar 2
Pillar 3
Pillar 4
- +
-200 -100 0 100 200 300 USD / tCO_2
Mt = million tonnes
Industrial Sector Total
Abatement Potential
Energy
CapEx

Pillar 1 Supercharging energy and material efficiency (Tier 1)

The largest emissions reduction potential comes from improving energy efficiency, material efficiency, and product longevity—strategies applicable across all subindustries. They represent the most practical, cost-effective, and scalable approach and are therefore a no-regrets solution for all countries. Even if the power sector fails to decarbonize, the CO_2 reduction potential from these efficiency measures remains largely unchanged because such measures can reduce energy demand, material demand, or both.

Abatement potential: Pillar 1 abates 36 percent of industrial CO_2 emissions in China, 26 percent in Indonesia, and 29 percent in Viet Nam through efficiency measures alone **(FIGURE ES.2)**. Energy efficiency is the most important strategy, with the potential to reduce energy consumption by 13–19 percent for most industrial subsectors. Material efficiency can reduce material intensity of products by 5–24 percent depending on product type, with the highest achievable reductions for plastics and the lowest for pulp and paper. Product lifetime extension can cut demand by as much as 25 percent, depending on the subindustry.

Cost-effectiveness: Efficiency measures have the lowest capital costs because efficient technologies are relatively mature and often not capital-intensive relative to less efficient equipment. More importantly, efficiency measures cut energy use substantially, thus lowering energy costs. Overall, this pillar saves $223 per tonne of CO_2 in China, $196 per tonne in Indonesia, and $119 per tonne in Viet Nam. Savings are greatest in China and Indonesia because their 2050 projected energy prices for industrial firms are higher than those in Viet Nam.

Pillar 2 Scaling up electrification with renewable energy (Tiers 2a and 2b)

Direct electrification, powered by RE, is the best solution for most industrial process heat, given its favorable emissions impact compared to CCUS and its impressive efficiency compared to green hydrogen combustion. Implementing Tier 2a (using industrial heat pumps for low-temperature heat, electrifying nonthermal processes, and scaling up electric arc furnaces for scrap-based steelmaking) significantly reduces CO_2 emissions—especially when paired with grid decarbonization and distributed renewable energy solutions. Specific choices between grid-purchased electricity and captive installations depend on a range of factors, such as cost of acquired electricity and energy storage, electricity load demand profiles, type of industries, locations, and emission reduction needs. However, without a clean grid, Tier 2a has little effect on emissions, as 85–90 percent of the avoided emissions from the industrial sector are replaced by increased emissions from the electricity sector. Tier 2b (electrifying medium- and high-temperature heat) could even lead to an increase in CO_2 emissions in Indonesia and China, whose electric grids have higher carbon intensities than Viet Nam's. Therefore, renewable energy adoption must be scaled up alongside electrification measures to fully realize the decarbonization potential of electrification.

Abatement potential: Overall, Pillar 2 abates 32 percent of industrial CO_2 emissions in China, 53 percent in Indonesia, and 41 percent in Viet Nam **(FIGURE ES.2)**. These differences arise from differences in subindustry structure. Electrification plays a bigger role in Indonesia, which has a large food and beverage industry that is relatively easy to electrify. Electrification makes a smaller dent in Viet Nam's industrial emissions, much of which are cement process emissions, or China's, which primarily arise from heavy industries that require high temperatures. The highly efficient Tier 2a technologies deliver 24 to 35 percent of total abatement, while Tier 2b technologies achieve 8 to 18 percent of total abatement—provided that all electrification is backed by RE.

Cost-effectiveness: In this modeling, Tier 2a is modestly cost-saving, reducing expenses by $23 per tonne of CO_2 abated in China, $19 per tonne in Indonesia, and $5 per tonne in Viet Nam in 2050, meaning the annual energy cost savings more than offset the annualized capital investment required. In Tier 2b, the annualized capital and energy costs are $88 per tonne of CO_2 abated in China, $115 per tonne in Indonesia, and $104 per tonne in Viet Nam. In these cases, energy costs account for 49 to 58 percent of the total, while capital expenditures make up the remainder.

Pillar 3 Unlocking CCUS for hard-to-abate emissions in specific subsectors (Tier 3)

CCUS is a crucial technology for decarbonizing cement-making and for decarbonizing primary steelmaking through blast furnace retrofits, until alternative solutions (e.g., hydrogen direct reduced iron or electrolysis of iron ore) are commercially available. The cement industry is the largest energy-consuming sector in Viet Nam and currently depends on coal for over 80 percent of its energy. Cement is also among the top four energy-consuming sectors in Indonesia and China. CCUS plays a dual role in the cement industry, capturing both process emissions and those energy-related emissions that are not directly electrified. Meanwhile, CCUS also has significant downsides, including upstream emissions from fossil fuel extraction and processing, residual on-site emissions (since CCUS captures less than 100 percent of the formed CO_2), the risk of locking in fossil fuel–using equipment and infrastructure, the need for the industrial facility to be located near a suitable CO_2 storage site, and long-term risks of CO_2 leakage from underground storage (or the use of captured CO_2 in products that ultimately release that CO_2 when they are burned or decay).

Abatement potential: CCUS is responsible for 11–12 percent of total industrial abatement in China and Indonesia, and 19 percent in Viet Nam, where cement constitutes a larger fraction of the industrial sector **(FIGURE ES.2)**.

Cost-effectiveness: The annualized capital and energy costs for CCUS are $53 per tonne of CO_2 abated in China, $48 per tonne in Indonesia, and $46 per tonne in Viet Nam. Capital expenditures account for essentially all of the added costs, as spending on the additional fuels needed to power the CCUS process is offset by savings from avoided CO_2 emissions under the $50/tonne carbon price. CCUS's capital costs per tonne of CO_2 abated are the highest of all modeled technology tiers (inclusive of equipment to capture carbon, transport it by pipeline, and inject it underground), but its energy costs are low because carbon capture relies on fossil fuels, mostly coal, which is several times cheaper than electricity in China, Indonesia, and Viet Nam. While overall CCUS abatement costs are relatively low (lower than medium-to-high temperature electrification in Tier 2b or green hydrogen combustion in Tier 4a), they are unlikely to decline much further, whereas the abatement costs of electrification and hydrogen could decline significantly with renewable energy deployment and technological advancement.

Pillar 4 Closing the gap with green hydrogen and clean feedstocks (Tiers 4a and 4b)

Green hydrogen plays a crucial role in decarbonizing industrial processes requiring high-temperature heat that cannot be electrified. It also offers a vital pathway to shift from fossil-based to clean chemical feedstocks. In refining chemicals, nonmetallic minerals (cement and glass), and iron and steel, green hydrogen combustion provides emission-free heat (Tier 4a). In the chemicals industry, green hydrogen (alongside blue hydrogen and bioenergy) replaces hard-to-abate fossil-based feedstocks (Tier 4b). Green hydrogen is essential for decarbonizing ammonia and methanol where conventional hydrogen is already used. However, since green hydrogen is produced using renewables, the availability and affordability of clean power is essential to its decarbonization results. Green hydrogen is energy-intensive, costly, and technically complex, so it should be deployed strategically—where other decarbonization options are not feasible—to close the emissions gap.

Abatement potential: The contribution of green hydrogen combustion (Tier 4a) to total industrial decarbonization in the model is 11 percent in China, 5 percent in Indonesia, and 3 percent in Viet Nam (FIGURE ES.2). China's percentage is the largest owing to the country's major refining and chemicals subsectors. Meanwhile, transitioning to clean chemical feedstocks (Tier 4b) is responsible for around 6 percent of total abatement in China, 1 percent in Indonesia, and 3 percent in Viet Nam.

Cost-effectiveness: The annualized capital and energy costs for green hydrogen combustion (Tier 4a) are $198 per tonne of CO_2 abated in China, $341 per tonne in Indonesia, and $234 per tonne in Viet Nam, making it the most expensive abatement strategy. The differences in cost are largely due to differences in projected 2050 prices for clean hydrogen. In each country, over 80 percent of the cost is attributed to requirements for renewable energy and electrolyzers. Clean feedstocks

(Tier 4b) have costs of $157 per tonne abated in China, $239 per tonne in Indonesia, and $187 per tonne in Viet Nam. Clean feedstock economics are favorable compared to hydrogen combustion economics. First, clean feedstocks displace refined petroleum and natural gas feedstocks, defraying some of the cost. In contrast, much clean hydrogen combustion occurs at refineries, where it displaces low-value refinery fuel gas and petcoke. Second, in some cases, hydrogen feedstock use replaces costly grey hydrogen production (for instance, to make ammonia for fertilizers). That said, some clean feedstock technologies are not yet fully commercialized, so their economics are still uncertain.

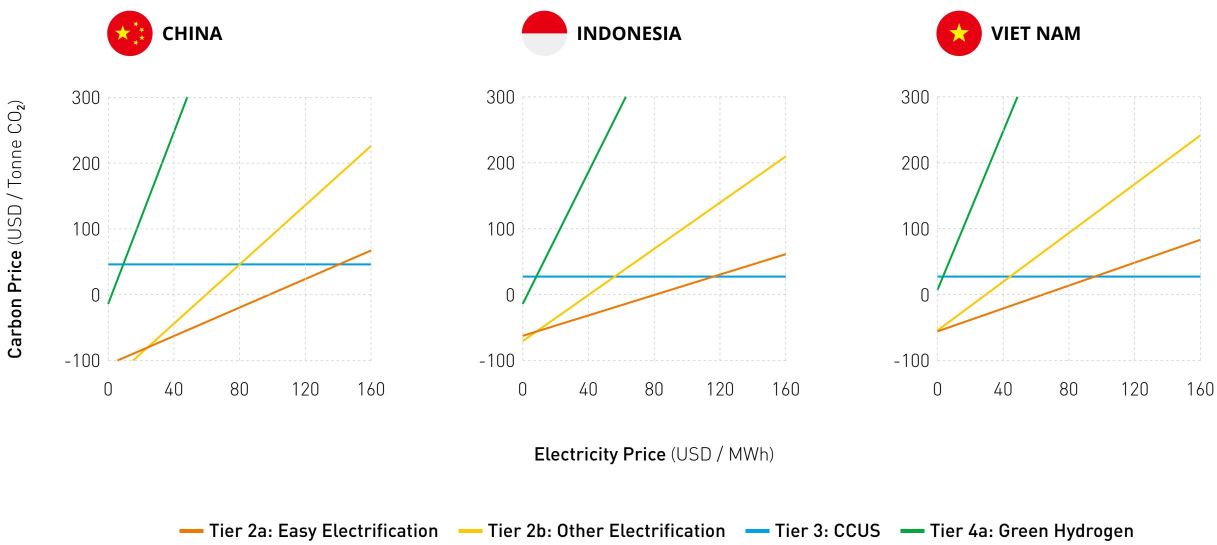
Electricity price and carbon pricing trade-offs

Achieving financial viability for clean industrial technologies is essential for scaling their deployment. Clean industrial investments must demonstrate a credible pathway to returns that meet or exceed those of conventional, high-emission production methods. Beyond addressing the higher upfront capital costs of clean technologies, it is equally important to narrow the operating cost gap between clean energy and fossil fuels. This report models targeted interventions—such as optimized electricity pricing and the introduction of carbon pricing mechanisms—to illustrate the trade-offs involved and the policy levers available to improve the competitiveness of low-carbon industrial solutions.

FIGURE ES.3 presents a theoretical modeling of the electricity and carbon price combinations required to achieve breakeven annual energy costs for selected clean industrial technologies in each modeled country. Taking Viet Nam as a representative case, the analysis shows that easy electrification (Tier 2a) measures are already cost-competitive at current electricity prices of $72/megawatt-hour (MWh) for industrial buyers, even with minimal carbon pricing. Other electrification measures (Tier 2b) would need carbon prices of approximately $100 per tonne of CO_2 to be cost-competitive at these electricity price levels or require significantly lower electricity prices. Electricity prices do not affect CCUS (Tier 3), as the process does not depend on additional electricity. Consequently, it can achieve breakeven annual energy costs at a carbon price of around $25 per tonne of CO_2. By contrast, green hydrogen combustion (Tier 4a) remains cost-prohibitive under current market conditions, requiring electricity prices of around $40/MWh and carbon prices of $250 per tonne of CO_2 to break even—levels not anticipated in the near term.[5]

[5] Electricity used to produce green hydrogen can be obtained at lower cost than typical purchased electricity because: 1. Dedicated renewable resources can be built for hydrogen production, and 2. hydrogen electrolyzers can be operated flexibly, producing more hydrogen in the hours of the day when electricity is cheapest and most abundant, and the hydrogen can be stored until needed. Therefore, $40/MWh electricity may be achieved for green hydrogen production even when the price of purchased electricity is higher.

FIGURE ES.3 Breakeven carbon pricing and electricity cost combinations in China, Indonesia, and Viet Nam



Note: *Technologies that deliver efficiency gains (Tier 1) are excluded, as they generate operating cost savings under virtually all pricing conditions. Tier 4b is also excluded, as feedstock-related emissions are typically realized downstream and are not subject to carbon pricing under current frameworks.*

While electricity market reforms and carbon pricing are critical to closing cost gaps, they may not be sufficient on their own, calling for targeted policy and market intervention. In cases where operating cost parity remains unattainable, governments may consider complementary instruments such as technology-neutral performance standards or product-based carbon-intensity benchmarks. Such measures would allow industrial producers to pass through incremental costs, enabling capital recovery while positioning domestic industry to remain competitive in international markets that are increasingly subject to carbon border adjustments.

Implementation Challenges | Energy, finance, technology, and jobs

Successful implementation of industrial decarbonization strategies relies on four distinct but interconnected foundations:

- Sufficient and cost-competitive clean power;
- Adequate and fit-for-purpose financing;
- Commercially viable and locally available technologies;
- A skilled workforce.

However, the readiness level of each of these foundations faces significant challenges in Asia-Pacific countries.

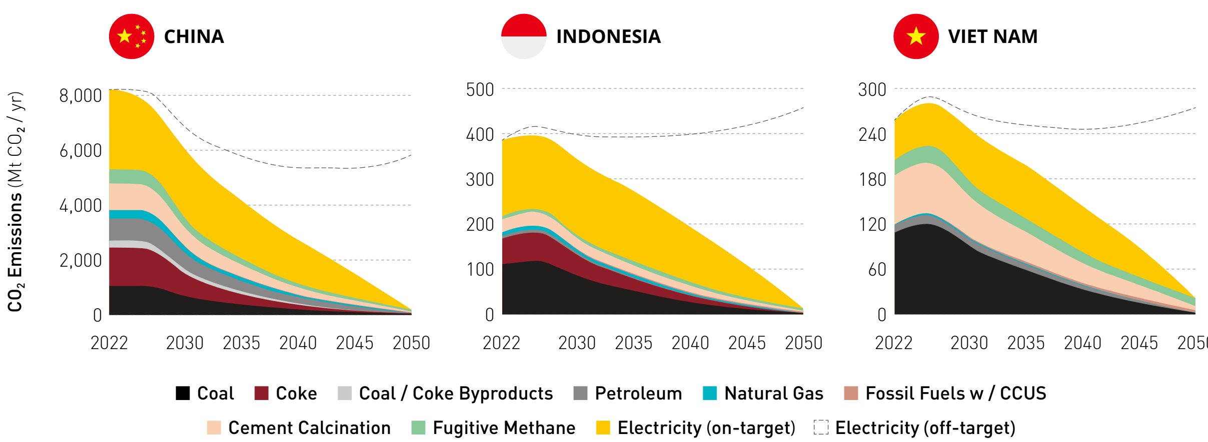
Energy: Sufficient and cost-competitive clean power

Countries in East Asia must scale up clean power to meet rapidly rising industrial demand for electricity over the next three decades, driven by economic growth and decarbonization. Modeling results indicate that for industrial emissions to approach net zero, even with strong improvements in energy and material efficiency (Pillar 1), Chinese industry will require 1.9 times as much electricity as it would in a future business-as-usual (BAU) scenario.[6] The corresponding figures are 1.5 times for Indonesia and 1.6 times for Viet Nam. However, many countries in the region lack the transmission infrastructure needed to reliably deliver low-carbon power to industrial users. In Viet Nam, renewable energy's growth has outpaced grid upgrades, leading to power shortages and clean energy curtailment. In Indonesia, industrial facilities like nickel processors are often far from major grids and rely on captive coal-fired plants. Cumbersome interconnection requirements further discourage industrial electrification at scale.

[6] The BAU scenario reflects a continuation of existing policies, such as today's carbon pricing or energy efficiency standards. Targets (such as each country's economywide net-zero targets) are not considered policies in this context. The net-zero targets are not achieved in the BAU scenario, as additional policies are required to reach these targets. The BAU scenario includes projected changes in industrial output and growth of electricity demand. In 2050, in the BAU scenario, the industrial sector demands 1.04, 1.8, and 3.1 times as much electricity as in 2022 in China, Indonesia, and Vietnam respectively.

All electricity must come from zero-emission sources if industrial decarbonization goals are to be realized. **(FIGURE ES.4)** shows that if power sector decarbonization targets are missed (e.g., not on track to decarbonize by 2050), direct emissions from industrial facilities would be offset by rising emissions from industrial electricity use (dotted line in figure). In fact, the East Asian region has some of the most coal-dependent power systems in the world: In 2022, coal accounted for around 61 percent of electricity generation in China, 62 percent in Indonesia, and 40 percent in Viet Nam. China is the world's largest coal consumer, responsible for more than half of global coal-fired power generation and continued to install 94.5 gigawatt (GW) of thermal power in 2024. Indonesia is the world's largest exporter of coal for power generation. Despite the growing share of renewable energy in the power mix, a substantial gap remains if industrial clean power needs are to be met in the region. To reach net-zero in China, Indonesia, and Viet Nam, rising industrial electricity demand must be powered by clean energy.

FIGURE ES.4 CO_2 emissions from industry and from electricity purchased by industry



The price of clean energy, and of electricity in general, combined with insufficient and unreliable power supply, is among the top barriers for the industrial clean energy transition. The cost of energy represents most of the abatement cost in identified strategies (apart from CCUS), and in most countries of the East Asian region, fossil fuels are far cheaper than electricity for industries. In China, at 2022 retail rates for industrial buyers, electricity cost eight times more than coal per unit of energy and more than twice as much as natural gas (although rates varied province by province). Part of the energy price differential in China comes from cross-subsidy policies, where industrial users pay around 40 percent more to subsidize the residential and agricultural sectors. In the United States and Europe, by contrast, industries benefit from lower tariffs owing to their stable and predictable load profiles and grid operators' need to maintain less electricity distribution infrastructure versus that required to serve widely distributed residences.

Fossil fuel subsidies distort market prices, making clean energy more expensive and less competitive. In 2022, explicit fossil fuel subsidies were $104 billion in China (1 percent of GDP), $34 billion in Indonesia (3 percent of GDP), and $33 billion in Viet Nam (5 percent of GDP) (IEA 2023a). When implicit subsidies, such as overlooking environmental and health costs, forgoing tax revenues, or direct funding support for fossil fuel projects are included, subsidies in China amounted to $2.2 trillion (12.5 percent of GDP), while Indonesia and Viet Nam each allocated over 14 percent of their GDP for the same purpose (Black et al. 2023). These price distortions risk delaying industry's shift to cleaner power, posing a major obstacle to decarbonization.

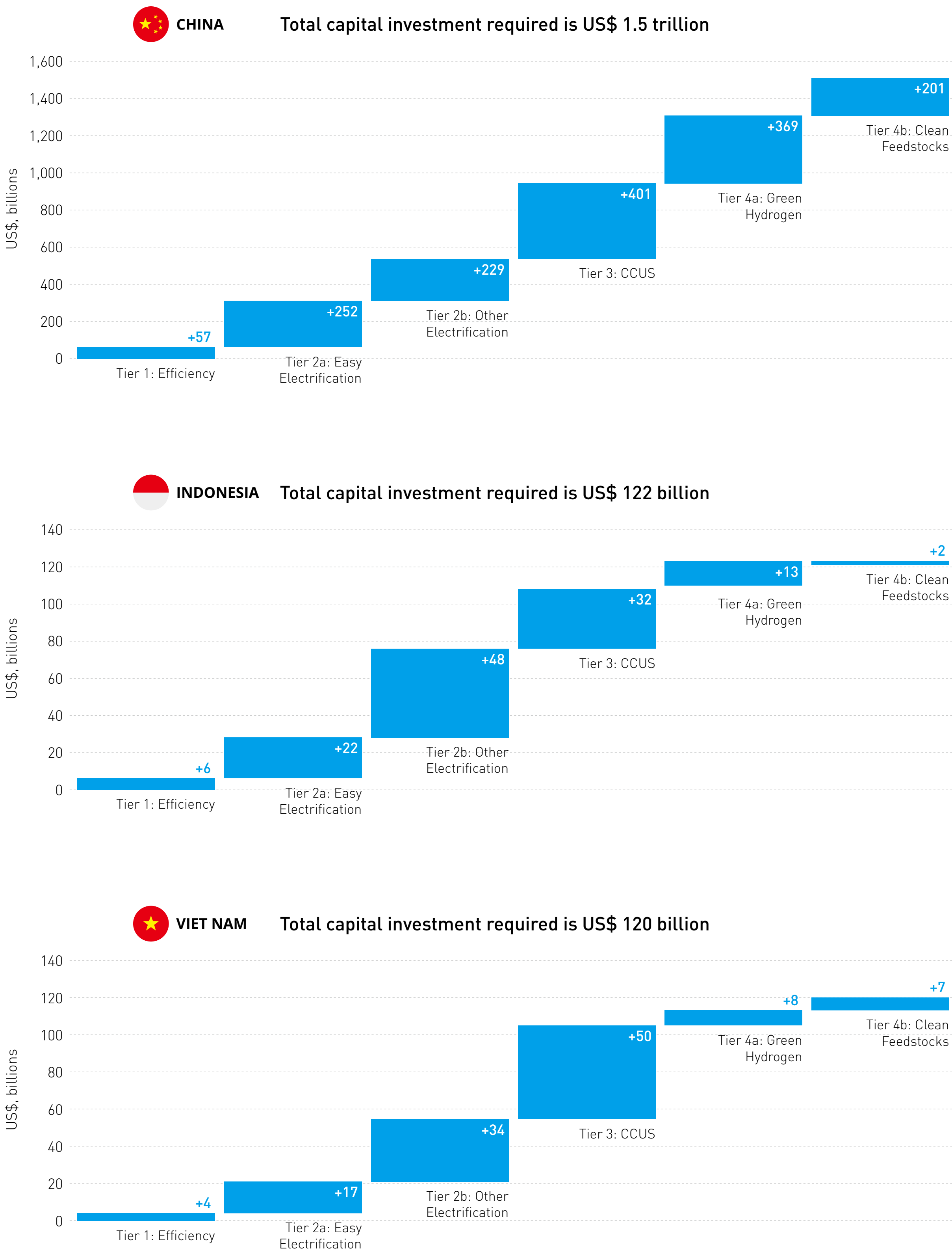
Finance: Adequate and fit-for-purpose

While the capital investments needed to decarbonize industry are significant, they yield substantial emissions reductions and long-term benefits. This study finds that China requires $1.5 trillion in capital investment, with Indonesia and Viet Nam needing $122 billion and $120 billion, respectively, to reach net-zero emissions in the industrial sector **(FIGURE ES.5)**. Over 25 years, this translates into an annual, inflation-adjusted need of $60 billion per year in China and $5 billion per year in Indonesia and Viet Nam. These figures refer to capital investments in equipment in the industrial sector and hydrogen electrolyzers, excluding additional capital investment in the electricity sector—such as renewable and clean power generation capacity, grid expansion and enhancement, utility scale energy storage and other renewable integration investments. These investments could deliver substantial emissions reductions—5.1 billion tonnes of CO_2 per year in China, 360 million tonnes CO_2 per year in Indonesia, and 371 million tonnes CO_2 per year in Viet Nam in 2050—at relatively low average capital costs per tonne of CO_2 abated.

Current financial flows in the East Asian region—both public and private—are insufficient to meet the scale of investment needed for industrial decarbonization. In 2022, only $52 billion (1.4 percent) of the finance was directed toward industrial decarbonization (Naran et al. 2024). Across the region, public investment is constrained by a sluggish post-COVID recovery and global economic uncertainty, especially concerning international trade, while private sector participation remains limited due to high perceived risks and delayed returns. The absence of a scalable public-private partnership framework and an enabling environment further hinders long-term private investment for both industrial decarbonization and supporting infrastructure. These factors collectively pose major barriers to mobilizing capital for a low-carbon industrial transition.

The complexity and diversity of industrial decarbonization strategies require highly tailored investment instruments that many financiers are ill-equipped to provide. Investments must align with the unique financing needs of the sector, including longer payback periods and higher risks associated with newly commercialized technologies. Industrial equipment, processes, and supply chains are complex, heterogenous, and unstandardized, requiring novel investment strategies and deep sector expertise (U.S. DOE 2023b). Successful investments within a facility often depend on their coordination with other investments in enabling infrastructure, including

FIGURE ES.5 Capital investment needed per tier in China, Indonesia, and Viet Nam to reach net-zero



renewable energy generation and grid expansion, hydrogen electrolyzers and pipelines, and CO_2 storage sites. These substantial investments require a comprehensive enabling environment.

Technology: Commercially viable and locally available

While many industrial decarbonization strategies are technically feasible, their adoption in the region remains limited owing to high upfront costs, constrained availability, and low market awareness. The limited uptake of clean technologies has resulted in a shortage of dependable, context-specific performance data for industrial firms. This information gap further reduces confidence in low-carbon industrial technologies and impedes their broader uptake. In addition, the weakness or absence of industrial standards for energy efficiency, emissions reduction, and robust monitoring, reporting, and verification (MRV) systems discourage investment in advanced technologies. More innovative technologies like thermal batteries, CCUS, green hydrogen, and clean feedstocks are still in the early stages for some applications, making research and development (R&D), demonstration projects, and early deployments critical for their commercialization.

Jobs: A skilled and robust workforce

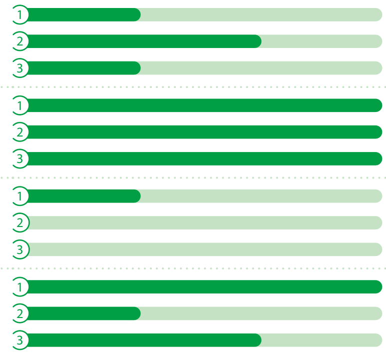
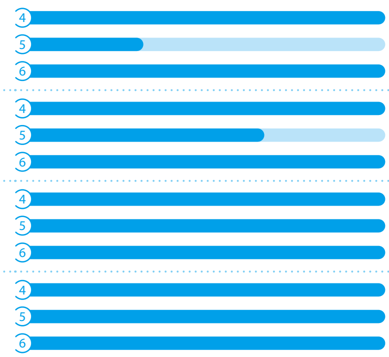
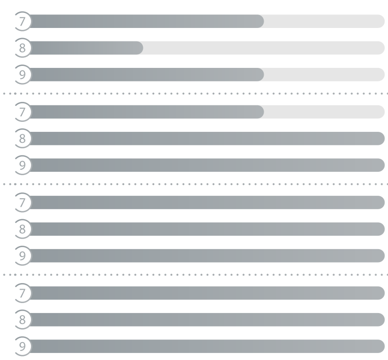
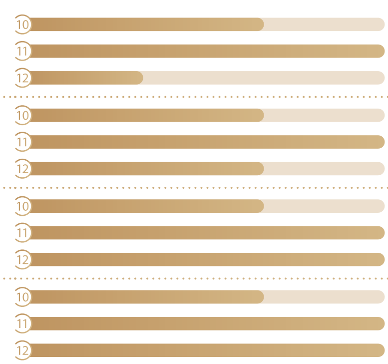
A growing mismatch exists between the skills demanded by emerging industrial decarbonization jobs and those provided by current education systems. China's rapid energy and industrial transition, for example, is driving increased demand for professionals who can integrate technical expertise with decarbonization literacy, digital capabilities, and a strong understanding of regulatory frameworks at the local, national, and international levels. However, graduates of technical and vocational education and training (TVET) institutions—and even universities—are often not adequately prepared for real-world roles involving industrial energy management, carbon accounting, stakeholder engagement, or environmental compliance. This gap is further widened by the rise of hybrid roles such as carbon trading specialists and clean energy market analysts, which are becoming essential to the industrial transition. Bridging this skills gap is critical to developing a workforce capable of supporting large-scale industrial transformation. In addition, job creation opportunities from the industrial transition also depend on addressing supply chain challenges, including the current global concentration of key equipment manufacturing. Countries are increasingly adopting local content policies to build domestic capabilities and retain value-added jobs, though such policies may raise costs or delay deployment if domestic supply chains are underdeveloped.

The Policy Package

To align with East Asian countries' focus on industrial competitiveness, the policy package emphasizes on making key technical strategies viable and scalable. Recommendations are structured around the four enabling foundations—energy, finance, technology, and jobs—and include twelve actionable policies for the near, medium, and long term.

TABLE ES.2 summarizes the comprehensive policy package, with color bars to indicate the importance of the policy for enabling each technical pillar. Longer bars represent higher priority policies, while shorter bars represent lower-priority policies for each technical pillar.

TABLE ES.2 The industrial decarbonization policy package for East Asia

	Recommendation	Technical Pillar	Prioritization
Energy Sufficient and Cost-competitive Clean Power	1 Industry-Power Co-optimization	Energy & Material Efficiency	
	2 Industrial Demand-Side Resources	Electrification with Renewable Energy	
	3 Direct RE Procurement, Open Access	Carbon Capture Utilization & Storage	
		Green Hydrogen & Clean Feedstocks	
Finance Adequate and Fit-for-purpose	4 Cluster-Based Approach via Concessional Finance & PPP	Energy & Material Efficiency	
	5 Carbon Pricing & Carbon Finance	Electrification with Renewable Energy	
	6 Derisking Instruments	Carbon Capture Utilization & Storage	
		Green Hydrogen & Clean Feedstocks	
Technology Commercially Viable and Locally Available	7 Industrial Standards & MRV	Energy & Material Efficiency	
	8 Pilot Emerging Technologies & Business Models	Electrification with Renewable Energy	
	9 Technical Assistance	Carbon Capture Utilization & Storage	
		Green Hydrogen & Clean Feedstocks	
Jobs Skilled and Robust Workforce	10 Vocational Training	Energy & Material Efficiency	
	11 Digital & Interdisciplinary Competence	Electrification with Renewable Energy	
	12 Workforce Transition Program	Carbon Capture Utilization & Storage	
		Green Hydrogen & Clean Feedstocks	

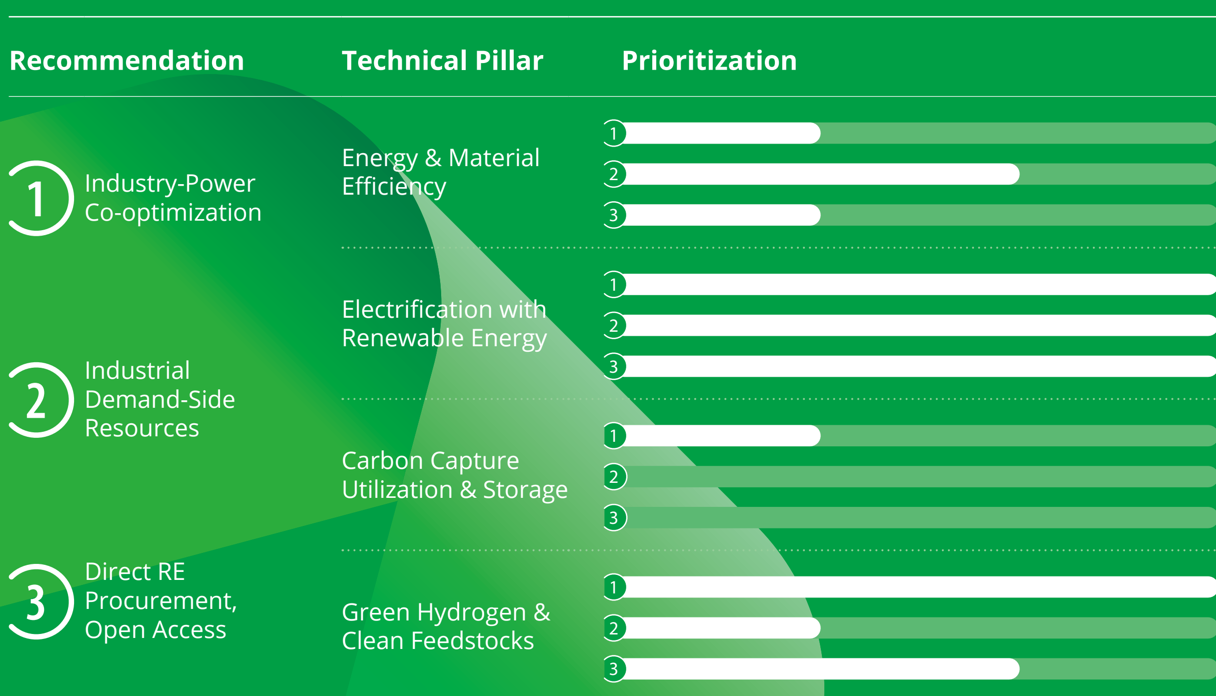
Enabling the energy foundation

Electrification, green hydrogen, and clean feedstock strategies depend on substantial clean electricity tailored to different industrial needs, necessitating co-optimization between the industry and power sectors.

Sector coupling allows industrial firms to access reliable and affordable clean energy. At the same time, industries can contribute to grid expansion by investing in their own renewable generation and flexibility resources. Industries can also support grid stability by offering services such as load optimization and demand response. In return, they can benefit from compensation or preferential electricity rates. Realizing this synergy, however, requires integrated system planning, power market reforms, and coordinated development of industrial ecosystems.

Energy

Sufficient and
Cost-competitive clean power



Recommendation 1 Industry-Power Co-optimization

Balancing power system expansion with rising clean power demand from industrial electrification and green hydrogen is critical. Major low-carbon electrification projects—such as switching from coal-based blast furnaces to electric arc furnaces (EAFs)—can increase electricity demand dramatically. For example, producing one tonne of steel with an EAF using scrap requires around 530 kilowatt hours (kWh) of electricity, whereas a blast furnace that makes steel from iron ore gets almost all its energy from coal and coke, not electricity. If the EAF uses green hydrogen–based direct reduced iron (DRI) instead of scrap, total electricity demand can be up to 3.5 MWh per tonne of steel, with roughly two thirds powering the hydrogen electrolyzer and the remainder consumed by the EAF and ancillary equipment (Rissman 2024). These sharp, location-specific load increases require coordinated system planning and targeted expansion of renewable energy.

Early integration of clean hydrogen development into power grid planning is essential to prevent infrastructure bottlenecks in later stages. The cases of northern Sweden's green industrial hub and Saudi Arabia's green ammonia projects highlight the critical role of infrastructure planning in enabling industrial transformation projects. Large-scale electrolyzers introduce significant and often localized electricity demand. One million tonnes per year of green hydrogen production requires about 10 GW of electrolyzers and 20 GW of RE (World Bank 2025a). The localized surge in demand from hydrogen production requires aligning the siting of production with proactive grid upgrades, efficient connection processes, and integration of renewable energy. Such coordination is essential to avoid congestion in transmission lines, ensure timely access to power, and maintain system reliability.

Optimizing existing grid infrastructure through grid-enhancing technologies should be prioritized to support early industrial decarbonization. Enhancing current infrastructure before pursuing major grid expansion investments—which often take longer to materialize—offers a more cost-effective and strategic approach. Amid the increased integration of renewable energy, technologies such as dynamic line ratings, advanced power flow control, and topology optimization become vital. These tools improve real-time power flow management, boost grid flexibility, and unlock additional capacity, helping to meet short-term demand and maintain system stability. In the long term, combining targeted deployment of grid-enhancing technologies with strategic grid expansion is optimal for supporting renewable growth and ensuring a resilient energy transition.

Recommendation 2 Industrial Demand-side Resources

Industries offer significant demand-side resources that can mitigate rising electricity needs from decarbonization while providing valuable grid services. These include demand response, distributed energy resources, energy storage, and load optimization. When well-supported, these resources can reduce peak demand, defer infrastructure investments, and improve system efficiency. Their impact is further enhanced when aggregated through virtual power plants (VPP), which enable coordinated participation in energy markets that benefit large-, medium-, and small-sized industries.

Unlocking industry-grid synergy via demand-side resources requires a shift in mindset and strengthened digital infrastructure. Flexibility must be seen not as a disruption but as a strategic asset. Effective coordination between the industrial and power sectors depends on advanced digital management tools that enable real-time integration and optimization—using sensors, control systems, and automation to enable real-time energy management, as well as energy storage systems such as thermal batteries to allow industrial facilities to continue steady operations while being flexible in their electricity consumption. While these technologies increase responsiveness, their high cost remains a barrier. Accelerating adoption will require targeted investments, supportive policies, and access to affordable financing.

Power market design plays a critical role in making industrial demand-side participation viable. Dynamic pricing mechanisms—like time-of-use rates or real-time pricing—are essential to incentivize flexible energy use. Experience in the United States and Europe shows strong industry engagement when reductions are monetized through wholesale or flexibility markets. Meanwhile, China is rapidly shifting toward market-based pricing mechanism to liberalize renewable electricity generation and enhance the flexibility market. This report's analysis of Viet Nam's power market for industrial demand side resources shows that its current policy framework for demand response has key gaps in both incentive design and regulatory adaptability (Appendix B). Strengthening financial incentives for industrial consumers via market-based mechanisms would significantly enhance program effectiveness and align consumption behavior with evolving grid needs.

Recommendation 3 Direct Renewable Energy Procurement and Open Access

Corporate procurement of renewable energy is a powerful lever for industries to secure its supply at market prices. This report's in-depth look at industrial electrification in China (Chapter 6) shows that green electricity certificates (GECs) have become a key mechanism to certify renewable energy use and support environmental, social, and governance reporting. Recent policies have strengthened the GEC framework by expanding eligibility to all renewable sources and introducing mandatory green power quotas for high-emitting industries. In Viet Nam, a direct power purchase agreement pilot program launched in 2024 enables large electricity consumers to directly procure renewable energy from independent power producers, marking a significant step toward liberalizing the power market and accelerating corporate clean energy adoption.

Open-access policies are critical enablers of industrial decarbonization, allowing companies not only to procure renewable energy via power purchase agreements, but also to develop their own renewable generation capacity and contribute to grid expansion. The report's case study on India demonstrates how such policies empower both large- and medium-sized industries to invest in substantial renewable energy generation projects to reduce emissions and enhance energy security. By enabling long-term power purchase agreements, open access helps de-risk renewable investments, improve cost predictability, and accelerate clean energy deployment. These policies not only advance industrial sustainability but also foster greater competition and innovation within the power sector. The Swedish case further highlights the critical role of open access policy in enabling zero-carbon industrial transformation by securing vast renewable energy supply at competitive prices.

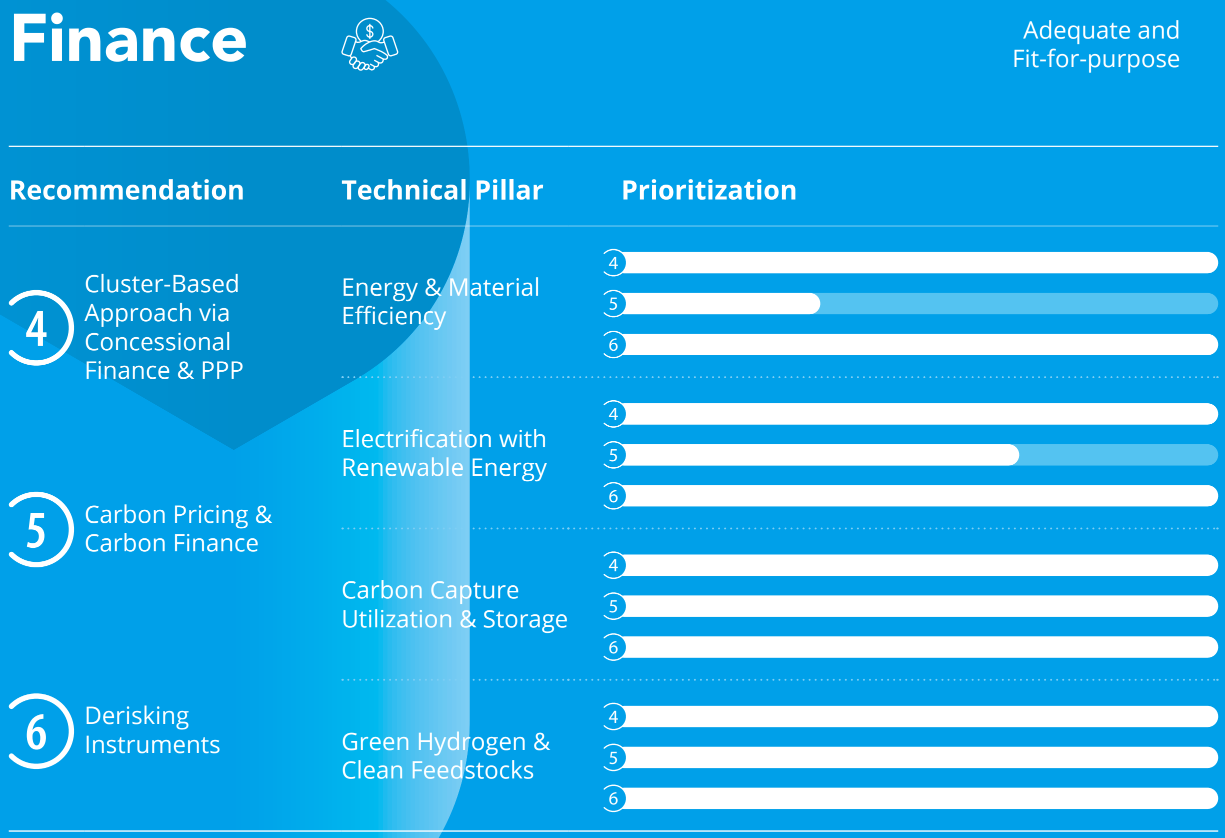
To strengthen corporate renewable energy procurement and open access as a tool for industrial decarbonization, certain improvements in market design and policy are essential. In China, the green electricity certificate market faces several challenges, including oversupply, low prices, limited international recognition, and the risk of double counting of green electricity certificates and carbon credits. Key policy enhancements could include implementing differentiated pricing mechanisms by region and technology to reflect the true value of green power, addressing rebound effects through parallel energy efficiency initiatives, and improving the transparency and credibility of green electricity certificates to meet international standards. Establishing a clear separation between carbon and green electricity certificate markets, along with streamlined rules to prevent double counting, will help build trust and support global recognition. With the right policy framework, both GECs and direct power purchase agreements can drive stronger corporate investment in renewable energy and accelerate industrial decarbonization.

Enabling the finance foundation

By rethinking how clean technologies are deployed and financed, innovative business and financial models can improve the commercial viability of low-carbon solutions and accelerate adoption across the value chain.

Meanwhile, financial strategies must be tailored to the diverse and complex needs of each technical pathway, rather than relying on undifferentiated increases in funding volumes. Models such as cluster-based decarbonization support scalable and viable industrial decarbonization projects. Long-term concessional finance, combined with deep sector expertise, enables systemwide investments across industrial clusters and shared infrastructure like clean power, hydrogen, and CCUS (IEA 2021b). For small and medium enterprises (SMEs), derisking mechanisms incentivize private capital. Additionally, hybrid carbon price and carbon finance tools help to create strong market signals and ensure fair competition while also delivering upfront capital and revenue certainty for industrial decarbonization investments.

Finance



Recommendation 4 Clustered-Based Approach via Concessional Finance and Public Private Partnership

The cluster-based approach offers a powerful pathway to accelerate industrial decarbonization by leveraging geographic proximity to enable shared infrastructure, coordinated planning, and aggregated demand across co-located industries. The approach not only reduces costs and mitigates risk but also fosters innovation and systemwide efficiency (IEA 2021b). Compelling examples are offered in this report, including Norway's zero-carbon cement production (enabled by a CCUS hub), and China's emerging zero-carbon industrial parks, which supply 80–100 percent green electricity through dedicated renewable energy, energy storage, and demand optimization across firms.[7] In addition, these clusters can offer traceable green electricity and carbon abatement certificates through shared energy and carbon management digital platforms, enhancing firms' global competitiveness (World Economic Forum 2025). These cases demonstrate how clustering can enable collective transitions that would be difficult for individual firms to achieve independently. However, realizing the full potential of cluster-based decarbonization requires moving beyond isolated pilots to scalable and replicable models.

Public-private partnerships are essential for the acceleration of cluster-based decarbonization that can be activated through supportive regulation, anchor projects, and collective financing. First, enabling regulatory frameworks that facilitate joint investment in shared low-carbon infrastructure, such as carbon transport and storage networks, hydrogen hubs, and centralized renewable energy systems, should be established. Second, anchor projects with long-term offtake agreements that reduce market uncertainty for first movers and create a strong demand signal for follow-on investments across the cluster should be identified and supported by public and private consortia. Third, blended finance mechanisms must be deployed in a coordinated manner—including contracts for difference, innovation grants, and concessional loans—to de-risk early-stage technologies and bridge the commercial viability gap. International financial institutions (IFIs) can also play an important role in financing and investing in common-use infrastructure in these industrial clusters. By aligning regulation, finance, and industrial planning, policy makers can unlock the full benefits of cluster-based decarbonization and position industrial parks as engines of low-carbon growth.

Recommendation 5 Carbon Pricing and Carbon Finance

A hybrid carbon-pricing approach—combining explicit and implicit instruments—offers a pragmatic and effective pathway to narrow the decarbonization cost gap. Explicit tools such as carbon taxes and emissions trading systems directly assign a cost to greenhouse gas emissions, creating strong financial incentives to reduce them. While effective, these instruments can face

[7] For details, see Chapter 4: Case Studies of International Industrial Decarbonization in the full report.

political resistance and implementation challenges. Implicit measures—including fuel excise taxes, as well as removing fossil fuel subsidies and tax differentials—though not always labeled as climate policies, still influence carbon-intensive behaviors by shifting relative energy costs. Integrating both explicit and implicit mechanisms enables governments to uncover hidden incentives, close policy gaps, and develop more balanced and context-sensitive carbon pricing frameworks.

Aligning with international carbon pricing mechanisms—such as the Europe's Carbon Border Adjustment Mechanism—can accelerate export-oriented industrial decarbonization in developing countries by reshaping market incentives and safeguarding the competitiveness of low-carbon industries. Predictable and gradually rising carbon prices help firms plan compliance strategies and invest in cleaner technologies. To effectively align with Europe's Carbon Border Adjustment Mechanism and similar international measures, developing countries must establish credible MRV systems. Robust MRV frameworks are essential for accurately tracking emissions, demonstrating compliance and ensuring transparency. In addition, complementary financial instruments such as green bonds and carbon contracts for difference can mobilize upfront capital and provide long-term revenue certainty to support industrial decarbonization efforts.

Recommendation 6 Derisking Instruments

Small and medium-sized enterprises (SMEs) account for nearly half of the regional economy yet often struggle to access finance for decarbonization and competitiveness upgrades. Risk-sharing facilities are effective instruments to unlock finance for SMEs pursuing low-carbon technologies, particularly in the East Asian region, where access to credit remains constrained. By reducing lender risk through publicly funded guarantees, risk-sharing facilities enhance the bankability of clean technology investments. India's Partial Risk Sharing Facility, supported by the World Bank, has successfully mobilized sizable commercial financing for SME energy efficiency projects. However, the impact of such mechanisms depends not only on sound design but also on effective execution. Strong capacity building for financial institutions and SMEs—alongside technical assistance—is essential to ensure proper risk assessment, infrastructure development, and long-term sustainability.

Enabling the technology foundation

Effective energy efficiency and emissions standards—underpinned by reliable data and robust enforcement—create the regulatory certainty needed to accelerate the deployment of both mature and emerging technologies.

Targeted pilot projects and technical assistance further support the localization and commercialization of innovative solutions, helping bridge the gap between technical viability and market adoption.

Technology

Commercially viable
and Locally available

Recommendation	Technical Pillar	Prioritization
7 Industrial Standards & MRV	Energy & Material Efficiency	
8 Pilot Emerging Technologies & Business Models	Electrification with Renewable Energy	
9 Technical Assistance	Carbon Capture Utilization & Storage	
	Green Hydrogen & Clean Feedstocks	

Recommendation 7 Industrial Standards and MRV system

Industrial standards play a critical role in supporting decarbonization by providing clear technical benchmarks and regulatory certainty. Energy efficiency and emissions standards drive the adoption of cleaner technologies and operational improvements, while emerging areas like CCUS require standardized protocols to ensure safety, reliability, and environmental integrity. Similarly, green hydrogen development depends on robust safety and handling standards to build investor and public confidence. Establishing and enforcing such standards reduces technical and financial risks, fosters market trust, and accelerates the scale-up of low-carbon solutions across industrial sectors.

Without reliable data, the enforcement of standards becomes weak, affecting the impact of decarbonization policy. A robust MRV system is therefore critical for the effective implementation of energy efficiency and emission standards. It ensures compliance, enables performance tracking, and builds confidence among investors and regulators. China's experience demonstrates this clearly—its Top-1,000 and Top-10,000 energy efficiency programs were anchored by a standardized MRV framework that required enterprises to submit verified annual energy data. This enabled data-driven policy adjustments, facilitated benchmarking across industries, and directed financial support to high-performing firms, leading to notable improvements in industrial energy intensity.

Recommendation 8 Pilot Emerging Technologies and Business Models

Targeted piloting of innovative technologies and business models accelerates the commercialization of emerging technologies in hard-to-abate sectors. Strategic pilots—such as thermal battery storage, CCUS in cement, and clean feedstocks in the chemicals industry—can validate technical performance, reduce costs, and de-risk future investments. Pilot projects also support building local capacity and facilitating international collaborations. A few high-impact pilot projects can guide action, as described below.

- **Thermal battery technology:** Commercializing thermal batteries offers a potentially cost-effective, scalable way to decarbonize heat-intensive industries. These systems store heat from low-cost electricity—up to 1,700°C—for later use (Rissman and Gimon 2023). In China, for example, heat makes up 90 percent of industrial fossil fuel use, indicating a large potential market. Thermal batteries not only reduce electricity costs for industrial firms but also support grid stability and clean energy deployment by absorbing excess renewable energy and giving utilities a financial return on this electricity that otherwise might have been curtailed.

- **CCUS hub:** By clustering emissions-intensive industries—such as refineries, cement plants, and power stations—CCUS hubs unlock economies of scale, significantly reducing the unit cost of CO_2 transport and storage. Co-location creates synergies by optimizing shared infrastructure and supply chains, while existing industrial hubs can seamlessly transition to incorporate CCUS.
- **Clean feedstocks:** Piloting green hydrogen for ammonia and fertilizer production may replace fossil-based hydrogen. Fertilizer markets offer stable demand, making them ideal early adopters of green hydrogen. Pilots also facilitate testing RE integration of the fertilizer industry, build operational expertise, and inform supportive policies like subsidies and offtake agreements. In the longer term, pilots using green hydrogen and captured carbon or bioenergy to produce petrochemicals such as methanol, olefins, and aromatics will be key to decarbonizing the rest of the chemicals value chain.

Piloting innovative models like clean-energy-as-a-service is key to accelerating industrial decarbonization and complements traditional approaches for deploying technologies such as industrial heat pumps. In the heat-as-a-service (HaaS) model,[8] the technology provider or an energy service company (ESCO) owns, installs, operates, and maintains the system, while the industrial customer pays a fixed or performance-based rate for the heat delivered. This structure reduces the upfront capital burden for end users, lowers financial risk, and incentivizes efficient system performance. When combined with renewable energy procurement and infrastructure services, such as dedicated substations or independent power feeds, HaaS models can further stabilize energy costs, enable flexible siting, and unlock new innovative business models for ESCOs.

Recommendation 9 Technical Assistance

Targeted technical assistance is key to building local capacity, fostering research, development and demonstration (RD&D) ecosystems, and enabling international knowledge exchange. As low-carbon technologies and business models remain nascent in most East Asian countries, technical assistance is essential to accelerate their commercialization. Support should focus on strengthening local capacity through research training and certification programs for industrial standards development, MRV system implementation, and the deployment of innovative technologies and business models. In parallel, technical assistance should help shape an enabling policy environment that incentivizes investment in cost-effective, low-carbon solutions. Finally, fostering international collaboration—through knowledge exchange, joint RD&D, and technology transfer—can facilitate the adoption of global best practices, promote adaptation to local conditions, and scale up the deployment of advanced technologies across the region.

[8] For an in-depth discussion, please see Appendix B: "Policy Recommendations for Electrification of Industrial Heating: Focus on Heat Pumps and Financing Mechanisms."

Enabling the jobs foundation

Enhanced vocational training, upskilling for digital and interdisciplinary competence, and targeted workforce transition programs are key enablers of industrial decarbonization.

Workforce development is not only essential for ensuring a socially equitable transition—particularly in regions with concentrated fossil-dependent employment—but also a strategic investment in industrial productivity and competitiveness, especially in emissions-intensive sectors undergoing digital and technological transformation. To ensure real-world uptake, these efforts must be embedded in concrete institutional delivery mechanisms, integrated financing strategies, and demand-side labor absorption tools.

Jobs

Skilled and Robust workforce

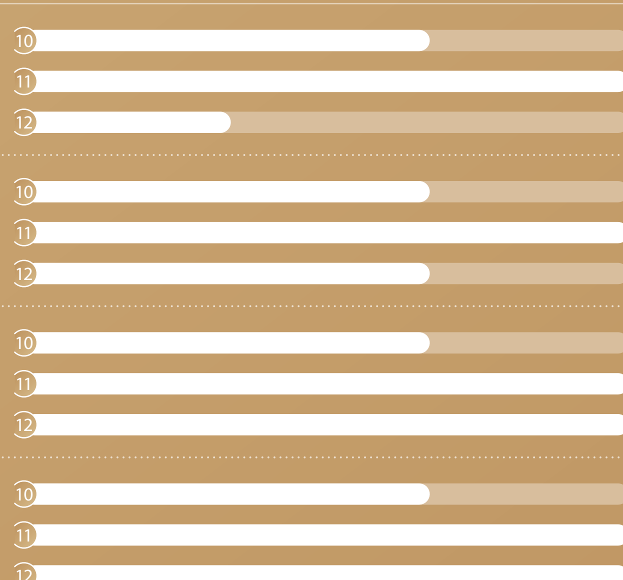
Recommendation

- 10 Vocational Training
- 11 Digital & Interdisciplinary Competence
- 12 Workforce Transition Program

Technical Pillar

- Energy & Material Efficiency
- Electrification with Renewable Energy
- Carbon Capture Utilization & Storage
- Green Hydrogen & Clean Feedstocks

Prioritization



Recommendation 10 Vocational Training

Vocational training must evolve beyond mechanical or electrical basics to incorporate green competencies such as energy management, carbon accounting, energy and carbon market literacy, and safety protocols for clean technologies. To align vocational training with decarbonization goals, policy makers should define high-potential job families—such as retrofit technicians, energy auditors, carbon accounting analysts, and hydrogen safety specialists—and establish national green skills certification authorities and sectoral skills councils with formal mandates to revise curricula accordingly. Institutionalizing partnerships between policy makers, industry, and training providers is essential to ensure that training remains relevant to evolving market demands, with regular updates to curricula and structured apprenticeships embedded in green infrastructure and industrial transformation projects. In Indonesia, efforts are already underway to better align training with industry needs in green manufacturing and energy. These efforts are exemplified by Stranas Vokasi—the National Strategy for Technical and Vocational Education and Training (TVET) Reform—and the establishment of the National Team for TVET Coordination. In addition, linking vocational reform efforts to climate finance through industrial transition funds, or results-based grant instruments, will support training at scale, especially in emerging industrial clusters.

Recommendation 11 Digital and Interdisciplinary Competence

The workforce must be both digitally fluent and interdisciplinary to meet the demands of a decarbonizing industrial sector. Industrial decarbonization requires professionals capable of navigating complex, data-driven systems that span engineering, environmental science, and policy. This calls for embedding digital fluency, systems thinking, and sustainability across vocational, tertiary, and continuing education systems. Applied research universities and TVET institutes, especially in second-tier cities with industrial clusters, have a central role in delivering continuing education and lifelong learning, cultivating mid-level professionals, who can integrate production, compliance, and innovation functions. Policy makers should incentivize the co-development of curricula between industry and academic institutions and support flexible delivery mechanisms, including modular, stackable credentials that bridge sustainability, data systems, and regulatory compliance.

Recommendation 12 Workforce Transition Programs

A targeted workforce transition strategy is essential to prioritize the reskilling of the labor force and to prevent the deepening of social and regional inequalities during the industrial transition. In China, for instance, the decline of fossil-intensive sectors has disproportionately affected provinces like Shanxi and Inner Mongolia, where automation further reduces the availability of low-skilled jobs. Similar dynamics are emerging in Indonesia, where coal-dependent provinces such as East Kalimantan are facing employment vulnerabilities due to shifting energy priorities. In Viet Nam, workforce skilling gaps are particularly acute among SMEs and in rural industrial zones, where access to reskilling opportunities remains limited. Targeted reskilling programs—including through mobile learning platforms to reach workers in underserved regions—are needed to support displaced workers in transitioning to cleaner roles. Performance-based reskilling grants, co-financed through blended finance instruments and tied to verifiable employment outcomes, and demand-side hiring incentives, such as wage subsidies or tax credits for firms that absorb retrained workers, can help scale these efforts. Embedding labor strategies into industrial and infrastructure investment planning is therefore critical across the region to ensure that workforce transition advances in parallel with decarbonization goals.

The World Bank Playbook | Operationalizing country and regional actions

The comprehensive policy package in this report provides a playbook for tackling the core challenge of industrial decarbonization in the East Asian region.

Informed by technical modeling, grounded in global best practices, and validated through in-depth stakeholder consultations, the report offers practical solutions for governments, industry leaders, power sector actors, and other stakeholders. Each country can tailor its implementation strategy by selecting a combination of approaches that align with its national industrial priorities and socioeconomic conditions.

Distinct opportunities exist across the region, shaped by each country's economic and industrial structure.

For instance, China can accelerate the development of zero-carbon industrial parks by reforming power markets to incentivize investments in industrial demand response, battery and thermal storage, distributed RE, electrification, and virtual power plants. China is also well placed to lead global efforts in clean feedstock production and utilization. Indonesia can accelerate investment to tap into its significant energy efficiency and industrial electrification potential, while expanding renewable energy for both grid-connected and dedicated industrial use. Viet Nam, in addition to continuing efforts on industrial energy efficiency, can adopt high proportion clean power for new electric arc furnaces in steelmaking and for electrifying other industrial processes. Viet Nam can also pilot strategic clean ammonia projects to reduce reliance on imports.

With a well-coordinated combination of public policy and targeted financing, East Asia is well positioned to lead the global shift toward clean and competitive industrial systems.

The World Bank, with development partners, is committed to accelerating industrial decarbonization in the region through strategic policy and financing support. This includes investing in critical infrastructure—such as low-carbon power systems, green hydrogen, and CCUS—while de-risking clean technology deployment through blended finance and private capital mobilization. World Bank technical assistance also helps governments strengthen institutions, create enabling policies, and foster market demand for low-carbon industrial products. Through global expertise and concessional financing, the World Bank aims to catalyze transformative projects that drive competitiveness, job creation, and a sustainable, inclusive future.

Lastly, the report's open-source model supports countries' use of data and policy analytics to accelerate industrial transition.

It underscores the commitment of the World Bank and its partners to advancing the global knowledge agenda on industrial decarbonization and mutual learning.

Introduction

More than half of the world's population lives in Asia, and Asia accounts for more than half of global primary energy consumption (Marriott and Aggarwal 2023). In particular, the East Asian region[9] is the largest energy consumer and emitter of greenhouse gas (GHG) emissions worldwide, responsible for about 40 percent of global primary energy use and 40 percent of global emissions in 2023 (Ritchie et al. 2024).

The industrial sector is a major source of these emissions. Globally, industry is responsible for around a quarter of the world's direct GHG emissions (or a third, if emissions from purchased electricity are included) (U.S. EPA 2023). Its share of economywide emissions is higher in the East Asian region, where manufacturing dominates many countries' economic activities (UN Economic and Social Commission for Asia and the Pacific 2024). In Indonesia and Viet Nam, for example, direct and indirect emissions from industry account for around 50 percent and 60 percent of total CO_2 emissions, respectively (and these shares would be higher if non-CO_2 GHG emissions were included) (IEA 2023c). That share is nearly two-thirds in China, which accounts for 45 percent of global industrial emissions on its own (Rissman 2024), given the size of China's economy and its leading role in global markets.

The emissions impact of the region's industrial sector stems from its heavy reliance on fossil fuels like coal. Whereas the global share of fossil fuels in total energy use was about 80 percent in 2023, that share was 86 percent in the region. Given the energy intensity of the region's economy, its CO_2 emissions per unit of gross domestic product (GDP) are almost double the world average **(TABLE 1.1)**.

TABLE 1.1 Industrial statistics for the East Asian region versus the world average in 2023

	Industry contribution to GDP (%)	Share of employment in industry (%)	CO_2 intensity of GDP (kg CO_{2e} per 2015 US$)	Fossil share of energy consumption (%)	Industry share of CO_2 emissions[10] (%)
World average	26	24	0.4	80	30
East Asian region	38	29	0.7	86	50
China	38	32	0.8	71	65
Indonesia	40	22	0.6	80	48
Viet Nam	37	31	1.0	70	57

Sources: *World Bank 2025b, UN Economic and Social Commission for Asia and the Pacific 2024.*

Note: *The East Asian region here excludes high-income countries, such as Australia, Japan, Singapore, and the Republic of Korea. When high-income countries are included, the contribution from the industrial sector to regional GDP in 2023 was 35 percent.*

9 In the introduction, countries of the East Asian region include Australia, Brunei, Cambodia, China, Indonesia, Japan, Lao People's Democratic Republic, Malaysia, Mongolia, Myanmar, New Zealand, Philippines, Singapore, the Republic of Korea, Thailand, and Vietnam. The later chapters of the study focus on three key countries in the region: China, Indonesia, and Vietnam.

10 Includes both direct and indirect CO_2 emissions. Industry's contributions to economywide GHG emissions (including non-CO_2 emissions) are even higher.

At the same time, industry is a major driver of economic growth, accounting for 26 percent of the world's economic output in 2023. It is an even larger growth engine in East Asia, contributing 38 percent of the region's GDP that same year (World Bank 2025b). That share is similar in China (38 percent), Indonesia (40 percent), and Viet Nam (37 percent). To avoid disrupting growth, the region's industries must evolve to meet the expectations of a changing global market. This includes aligning with the growing prevalence of carbon border adjustment mechanisms and green supply chain standards, which increasingly condition market access on low-carbon production. Moreover, by making their energy use cleaner and more efficient, industries can also strengthen their energy security against volatile fossil fuel markets and reduce conventional air pollution that is placing undue health and economic burdens on many countries in the East Asian region.

Finally, a transition to cleaner industries can create numerous high-quality jobs. Industrial production is already a major source of jobs across the region, employing 29 percent of the region's working population in 2023, compared to the global average of 24 percent. The sector employed even more of the workforce in China (32 percent) and Viet Nam (31 percent), and slightly less than the world average in Indonesia (22 percent) (World Bank 2025b). Beyond directly employing people, industry indirectly creates jobs across the economy by generating demand for goods and services in other sectors, such as energy production, construction, business and financial services, and engineering and software services.

The role of industry in the region's economic development and the energy transition

Given its capacity to drive economic growth, the industrial sector plays a central role in the economic development strategies of the region's emerging economies, providing opportunities for both structural transformation and socioeconomic progress. Emerging economies like China, Indonesia, and Viet Nam, have set ambitious goals to increase industrial output as a means of driving economic growth and improving living standards.

For example, China has set a GDP growth target of “around 5 percent” for 2025 (equivalent to its 2024 target), reflecting its commitment to restoring economic expansion amid slow domestic consumption and geopolitical challenges (Reuters 2025). China relies particularly heavily on industry for its economic growth, given its export-oriented economy and the dominant presence of state-owned enterprises in industry (World Bank 2022a). Moreover, as a key strategy for achieving its GDP goals as outlined in China’s 14th Five-Year Plan and its 2025 Report on the Work of the Government, China plans to manufacture high-margin products (e.g., high-end computer chips) using advanced technologies like artificial intelligence and quantum computing (McCarthy and Gan 2025).

Indonesia launched its “Making Indonesia 4.0” roadmap in 2018, targeting integration of advanced technologies to transform its manufacturing sector (Antara News 2021). The plan focuses on industries like food and beverages, textiles, automotive, electronics, and chemicals, aiming to position Indonesia among the world’s top ten economies by 2030. Last year, Indonesia announced its National Long-Term Development Plan 2025–2045, a plan to become one of the world’s top five economies by 2045 by growing the country’s GDP 8 percent per year (Thawley et al. 2024).

Finally, Viet Nam also set ambitious goals under its national industrial policy, Resolution No. 23-NQ/TW, aiming to be among the top three Southeast Asian industrial economies by 2030 and a modern industrialized country by 2045. Under this policy, Viet Nam’s industrial sector is expected to contribute more than 40 percent of GDP by 2030, with industrial value-added projected to grow by more than 8.5 percent per year between 2019 and 2030 (Vu 2025).

To meet other national policy goals, countries in the East Asian region must ensure that their industrial growth is not only swift, but also sustainable. Many have set ambitious climate goals within their Nationally Determined Contributions (NDCs) under the Paris Agreement. In particular:

China has pledged to peak CO_2 emissions before 2030 and achieve carbon neutrality before 2060. The country aims to lower CO_2 emissions per unit of GDP by more than 65 percent from 2005 levels and intends that non-fossil-fuel energy will make up 25 percent of its primary energy consumption by 2030. China also pledged to install 1,200 gigawatts (GW) of solar and wind capacity by 2030. (For more information on China’s progress toward these targets, see the section on government plans and goals for further renewable energy deployment in Chapter 6.)

Indonesia has committed in its enhanced NDC to reducing GHG emissions by 31.89 percent below business-as-usual (BAU) levels by 2030 through unilateral efforts and up to 43.2 percent with international assistance. The country plans to install 75 GW of renewable power over the next 15 years, including solar, hydropower, geothermal, and nuclear energy as part of its commitment to reach carbon neutrality by 2060 or sooner.

Viet Nam has updated its NDC, increasing its unconditional target to a 15.8 percent reduction in GHG emissions below BAU levels by 2030, with the potential to reach a 43.5 percent reduction with international support. The country also pledged to achieve net-zero emissions by 2050.

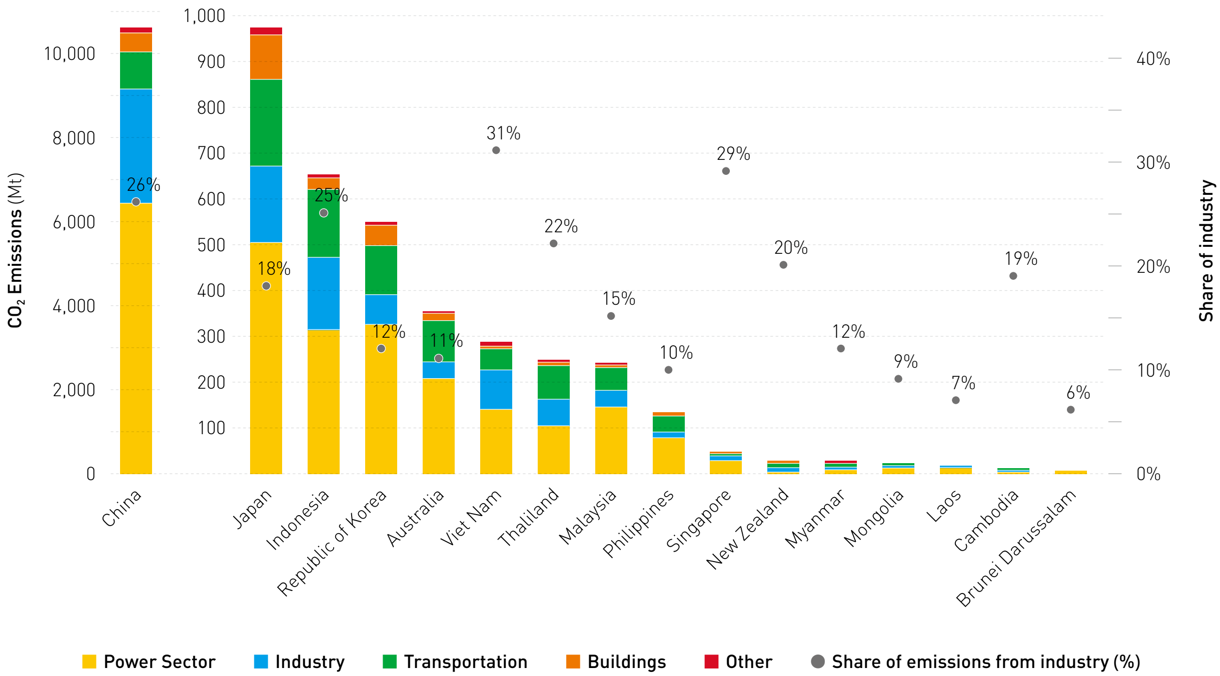
Beyond helping emerging economies meet their policy goals, economic development strategies that prioritize sustainability can set countries up for long-term economic success. East Asian countries that reduce their industrial emissions can preserve their global economic competitiveness as regions around the world implement carbon-based border tariffs, and they can capture additional market share as green supply chains emerge. Efforts to reduce industrial emissions can also create new jobs, improve emerging economies' energy security, increase innovation and productivity, and reduce local air pollution. At the same time, emerging economies that integrate low-carbon industrial equipment early in their development can avoid dependence on fossil fuel technologies, which can unnecessarily inflate the costs of and frustrate future decarbonization efforts.

The first step in developing a robust industrial transition strategy for the East Asian region is to understand the emissions and energy use profile of its industrial sector today.

The emissions impact of the region's industrial sector

As mentioned earlier, industry plays an outsized role in the region's CO_2 emissions, especially in emerging economies like China, Indonesia, and Viet Nam. Total energy-related CO_2 emissions from the region were around 15,000 million tonnes (Mt) in 2022. China is by far the biggest contributor, accounting for 73 percent of those emissions, while Indonesia and Viet Nam contributed 5 percent and 2 percent respectively. When focusing solely on the share of those emissions from industry, China's is still the region's biggest contributor by far **(FIGURE 1.1)**, though emissions from Indonesia and Viet Nam could soar in the future if the two countries continue to industrialize without rapidly decarbonizing. Owing to heavy reliance on fossil fuels, industry contributes 26 percent of national CO_2 emissions in China, 25 percent in Indonesia, and 31 percent in Viet Nam. When emissions from purchased electricity are attributed to end-use sectors, the industrial share rises to 65 percent, 48 percent, and 57 percent, respectively (IEA 2023c).

FIGURE 1.1 Energy-related CO_2 emissions in the East Asian region by country, 2022



Note: Bars represent absolute emissions (left axis). Grey dots represent the share of emissions for which the industrial sector is responsible (right axis).
Source: World Resources Institute 2025.

Industrial energy use in key emerging economies in the region

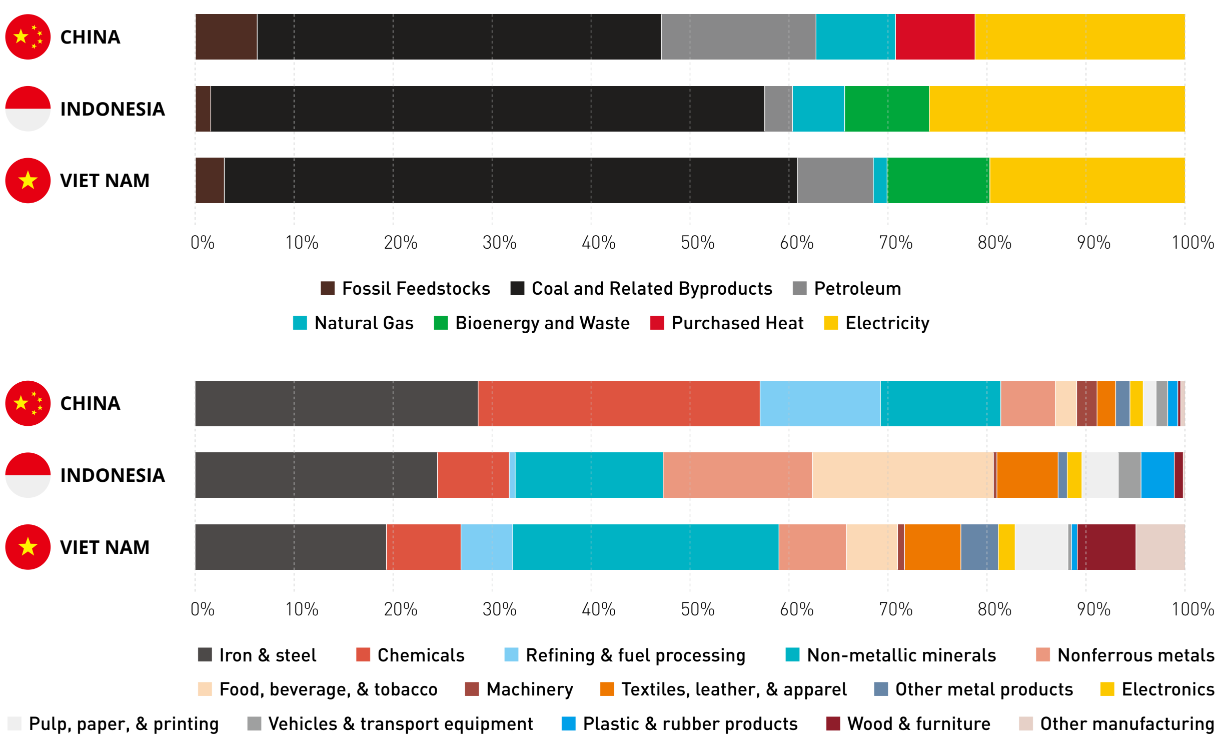
Energy-related emissions in the region's industrial sector come from a variety of energy sources. This section focuses on industrial energy use in China, Indonesia, and Viet Nam, which represented 85 percent of industrial energy-related CO_2 emissions in the region in 2022.

Final energy use in each country's industrial sector varies significantly by fuel and subindustry; however, all three countries' industrial sectors rely heavily on coal, coke, and coal- and coke-related byproducts. Feedstocks, coal, and coke consumption contributed around half of the three countries' total industrial final energy use in 2022, accounting for 47 percent, 57 percent, and 61 percent in China, Indonesia, and Viet Nam, respectively **(FIGURE 1.2, top)**. The share of fossil fuels in industrial energy use, including fossil feedstocks, petroleum products, and natural gas, is 71 percent in China, 66 percent in Indonesia, and 70 percent in Viet Nam.

The share of direct electricity use has been increasing in the region's industrial sectors, but this share varies by country, accounting for only 9 percent in Indonesia's industrial sector, compared to 21 percent in China and 27 percent in Viet Nam. Indonesia and Viet Nam also have a fair share of bioenergy use, contributing another 11 percent and 12 percent, respectively.

The share of fossil fuels in industry is closely related to the structure of each country's industrial sector. Energy-intensive industries, such as iron and steel, chemicals, refining, and nonmetallic minerals, rely heavily on the combustion of fossil fuels to create high-temperature heat for industrial processes. This is especially true in China, where these four subindustries represented 81 percent of total final energy use in industry in 2022. In Indonesia and Viet Nam, the contributions of these heavy industries to industrial energy use are 49 percent and 58 percent, respectively **(FIGURE 1.2, bottom)**.

FIGURE 1.2 Industrial energy use by fuel (top) and by subsector (bottom) in key emerging economies of the region, 2022



Sources: NBS 2024, BPS Statistics Indonesia 2024, MEMR 2024, VNEEP 2024, and VSA 2024.

Compared to China, Indonesia and Viet Nam have a higher share of light manufacturing in their industrial sectors, including food, beverage, and tobacco production and textiles manufacturing. Light industry represents 24 percent and 19 percent of total industrial energy use in each country, respectively. These subindustries depend neither on high-temperature heat nor on fossil fuel-based chemical feedstocks. In fact, light industries derive much of their energy from electricity, which accounted for between 40 percent and 100 percent of final energy use. Graphs depicting energy use by energy type for each subindustry in each country appear in Appendix A.

Given their reliance on low- and medium-temperature process heat, light industries can be electrified much more easily than heavy industries. (For more information on technologies to electrify industry, see the section on technology tiers in Chapter 2.) Still, historical data show that heavy industry plays a significant role in final industrial energy use in all three emerging economies under study. These industries will require newer and more expensive technologies to decarbonize.

Barriers to mitigating industrial emissions in emerging economies of the region

To achieve their climate goals, emerging economies in the East Asian region must rapidly mitigate their industrial emissions using a range of technologies, including energy efficiency, material efficiency, direct electrification, green hydrogen, and carbon capture and use or storage (CCUS). However, there are significant hurdles to deploying these technologies, including:

- Limited energy readiness (i.e., the high costs of clean energy against fossil fuels and challenges related to grid readiness);
- Limited or lack of access to financing opportunities;
- Low technological readiness of some clean industrial technologies;
- Shortages of skilled workers.

Energy prices and grid readiness

Across the region, fossil fuels are currently much cheaper than electricity, which is critical for electrifying industrial heat and producing green hydrogen. Not only is it inherently cheaper to directly combust fossil fuels than to use electricity generated from fossil fuels in most cases, but subsidies and price controls also help to suppress the price of fossil fuels. In China, for example, the price of electricity per unit of energy is about eight times higher than the price of coal and more than double the natural gas price (Sawe et al. 2024). A similar cost disparity exists between electricity and coal or natural gas in Indonesia and Viet Nam.

One key reason for the high electricity price that Chinese industrial buyers face is China's "cross-subsidy" policy, where industrial firms are charged around 40 percent more than residential and agricultural electricity buyers in order to subsidize the latter's electricity consumption. Viet Nam has a similar policy in place but recently passed a law to end cross-subsidies. By contrast, industrial users in the United States and Europe pay lower electricity rates than residential users, in part because industrial firms are bulk buyers with stable electricity demand. While electricity is more expensive than fossil fuels in both hemispheres, East Asian industrial firms face a particularly high price of electricity that strongly disincentivizes electrification and green hydrogen deployment (Sawe et al. 2024).

Direct and implicit subsidies for fossil fuels also inflate the price disparity between electricity and fossil fuels. An International Monetary Fund study found that China offered $2.2 trillion in fossil fuel subsidies in 2022, representing 12.5 percent of its GDP. These included explicit subsidies, like pricing fossil fuels below their supply costs, as well as implicit subsidies, like overlooking environmental costs, forgoing tax revenues, and supporting fossil fuel projects through direct funding, preferential loans, and power purchase agreements (Black et al. 2023). The study also found that Indonesia and Viet Nam each spent 15.4 percent and 14.3 percent of their GDP, respectively, on explicit and implicit subsidies for fossil fuels in 2022. These subsidies cost Indonesia $707 per capita and Viet Nam $574 per capita in 2022, keeping fossil fuel prices artificially low and reducing the competitiveness of clean energy.

Green hydrogen, produced using renewable energy to electrochemically split water into hydrogen and oxygen, is even more expensive than electricity. In China, at the lowest prices it can reach today ($3 per kilogram), it is still seven times more expensive than coal per unit of industrial heat created. Moreover, high electricity and capital costs can make it much more expensive—over three times more expensive than its lowest prices today (ESMAP et al. 2023). Electricity prices vary across geographies and times of day, limiting cost-effective hydrogen production to regions with abundant renewables and time-varying electricity prices. The capital costs of hydrogen infrastructure can also vary significantly, with electrolyzers ranging $500 per kilowatt (kW) in China to up to $2,000 per kW elsewhere, depending on the size of the unit, its constituent materials, and local electrolyzer manufacturing capacity.

In addition to more favorable electricity prices, clean industrial production will depend on the rapid buildout of abundant, reliable low-carbon power, yet grid limitations are a major bottleneck across the region.

China's grid faces growing strain as industrial demand and renewable generation rise unevenly across regions. Most clean energy is produced in the country's north and west, far from eastern and southern industrial hubs, creating transmission bottlenecks and curtailment. Despite major investment in ultra-high-voltage lines, many industrial zones lack the grid flexibility, storage, or load management needed to absorb variable renewables. Without further grid expansions, upgrades, and co-location of clean energy with industry, grid constraints could slow China's industrial decarbonization.

Viet Nam's power grid is also struggling to keep up with demand and renewables' integration. In 2023, extreme heat and drought led to electricity shortages in northern Viet Nam, forcing rolling power cuts for factories and households (Takahashi 2024). Viet Nam looked to wind and solar as a solution, but rapid renewable energy development quickly outpaced grid upgrades, leading to congestion and curtailment of clean power in Viet Nam (Ketelsen et al. 2023). Insufficient transmission infrastructure, load-management systems, and battery storage capacity will impede the integration of new renewable energy capacity, undermining power purchase agreements between renewable energy producers and industry and slowing the adoption of clean electricity within the industrial sector.

Indonesia's archipelagic layout poses unique challenges to electrifying industry. Many Indonesian industrial facilities are located too far away from large power plants to support through typical transmission infrastructure. As a result, industries like metals processing often rely on on-site fossil-fueled power plants. As of 2022, more than 67 percent of Indonesia's total captive coal power capacity is used to power nickel processing facilities, with a total capacity of 7.3 GW. Another 7.7 GW of captive coal power plants are under construction for that industry, while 1.5 GW are in the pipeline. In total, 16.5 GW of captive coal capacity is either in operation or under development to support Indonesia's nickel processing industry (Parapat and Hasan 2023).

Additionally, grid interconnection costs can fall on developers or large consumers, posing an additional barrier to renewable energy deployment and industrial decarbonization. In Viet Nam, policies have required renewable project developers (including those supplying industry) to build their own transmission lines to the nearest grid point, significantly adding expense and delay. These requirements, along with high local capital costs, have been shown to double the cost of solar and wind electricity in Viet Nam (Dapice 2018).

Finance

International financing institutions (IFIs) can play an important role in helping industry to decarbonize, but they have not yet seized this opportunity. Among all economic sectors, industry receives the smallest share of international climate finance (Naran et al. 2024). In 2022, international climate finance totaled $1.3 trillion, nearly half from public sources. Of that $1.3 trillion, only $52 billion (1.4 percent) went to the industrial sector. Moreover, in the last two decades, less than 1 percent of all public climate finance targeted the industrial sector.

The limited international investment in cleaning up industry falls far short of the sector's climate and economic impacts. As mentioned earlier, industry is responsible for a quarter of the world's direct GHG emissions—or a third when indirect emissions from purchased electricity are included (Rissman 2024). China accounts for 45 percent of global industrial emissions. Of all other emerging economies in the region, industrial GHG emissions are highest in Indonesia and Viet Nam. Industry has also enabled the emergence of all major East Asian economies and created vast numbers of high-quality jobs, employing a third of China's working population today (Seric and Tong 2019, World Bank 2025b).

Commercial financing cannot make up the gap, as industrial firms face many barriers to accessing financing for facility improvements, especially state-owned enterprises and small- and medium-sized enterprises. Of 700 Indonesian manufacturing firms surveyed by the World Bank, 32 percent cited a lack of financing as a barrier to energy efficiency investments (World Bank 2023a). Many industrial state-owned enterprises in the East Asian region suffer from weak balance sheets and limited creditworthiness, reducing their ability to access commercial financing. Small- and medium-sized enterprises, which make up a substantial share of industrial output in some sectors, often lack the collateral or financial track record needed to secure loans, even for cost-effective energy efficiency improvements. These challenges collectively slow the pace of technology adoption and highlight the need for targeted policy interventions.

Increasing IFIs' prioritization of industry is not simply a matter of shifting finance from one sector to another. The clean industrial transition demands different types of financing than power sector decarbonization, where most international public climate finance goes today (Naran et al. 2024). The Climate Investment Fund's Industrial Decarbonization Program is part of an emerging momentum to provide financial support to industrial sectors. Linking industrial decarbonization to green supply chains, export competitiveness, and public health goals may also increase the level of interest from IFIs. Industrial decarbonization finance must accommodate higher risks, longer payback periods, and complex and heterogenous industrial processes. It must also be deployed alongside investments in enabling infrastructure and align with adjacent policy priorities, like industrial competitiveness and job creation.

Technological readiness

The transition to low-carbon industrial processes is made more challenging by the low technological readiness of certain solutions, especially those that create high-temperature process heat. This challenge contributes to low equipment availability, firms' limited awareness of available technologies, and high upfront costs for equipment. Low technological readiness thus limits market demand for clean industrial technologies, further inhibiting their development and commercialization.

While there are many commercial energy- and material-efficiency technologies that can reduce industrial energy use—and while commercial technologies like industrial heat pumps and electric boilers can provide low-and medium-temperature process heat—higher temperature heating technologies like thermal batteries and hydrogen-based steelmaking are still being piloted and demonstrated. Other technologies, like electrified cement kilns and clean chemical feedstocks, are still at the laboratory phase.

Given the limited adoption of these technologies worldwide, industrial firms in the East Asian region have limited access to reliable and credible information about the performance and costs of clean industrial technologies or about energy use at the facility level. Information on commercially available heat pumps, for example, is scarce, and their performance characteristics—such as heat production capacity, energy consumption, operational stability, and space requirements—must be validated and more broadly communicated. Without high-quality data, many firms are not only hesitant to deploy proven clean technologies but may also fail to develop technical know-how at the practitioner level. In the aforementioned survey of Indonesian manufacturing firms, 43 percent of respondents cited lack of information as a key barrier to investing in energy efficiency (World Bank 2023a).

Workforce readiness

A successful clean industrial transition requires skilled workers trained in science, technology, engineering, and mathematics (STEM) disciplines, including digital skills. As the deployment of clean industrial technologies accelerates, demand will grow apace for engineers, researchers, technicians, computer scientists, and other specialists capable of designing, installing, and maintaining the systems.

In China, while a large number of STEM students graduate annually, many are trained in conventional energy and industrial systems rather than in advanced electrification and low-carbon process technologies. This leaves the industrial workforce unprepared for a transition from fossil-fuel-based processes to clean alternatives. In Indonesia and Viet Nam, the rapid growth of the manufacturing sector is far outpacing the availability of technical workers trained in operating and maintaining clean industrial technologies. This shortage affects not only large industrial firms but also smaller manufacturers looking to transition to more sustainable energy sources. Skilled employment in research and development is also important for continuing commercialization of clean industrial technologies. China exceeds the global average, with 1,687 researchers per one million people, but Indonesia and Viet Nam have only about 400 and 779 researchers per million people, respectively (World Bank 2025b).

Expanding the pool of skilled STEM workers, especially those trained in clean industrial technologies, will require long-term investments in education, vocational training, and capacity building programs (Lu et al. 2024). Industry-academic partnerships can ensure that graduates are prepared for the real-world challenges that industry will face in its pathway to zero emissions.

Methodology

Decarbonizing a sector as heterogenous as industry requires a mix of solutions, including efficiency measures that reduce energy use, low-carbon substitutes for fossil fuels, and technologies that capture emissions from fossil fuel use. However, none of these solutions are likely to reach meaningful scale in the East Asian region in the absence of policies and investments to increase their cost-effectiveness and practicality. Therefore, our analysis begins by estimating future industrial GHG emissions in the region in a business-as-usual (BAU) scenario, without any additional policies, based on projected demand growth for industrial products. Then, we model the most practical, cost-effective technological interventions for eliminating emissions between now and 2050. Finally, our analysis identifies key policies and investment strategies that can drive the deployment of those interventions based on their modeled costs.

This study uses an open-source computer model built in Microsoft Excel that cites more than 85 public data sources, facilitating transparency and clarity in the calculations and assumptions. The model uses government publications to identify industrial energy use in the most recent year for which data are available (2022), uses projected future energy demand changes to construct a future BAU case, and then applies technological interventions divided into six tiers (of increasing cost and technological difficulty) to mitigate those emissions.

Scope of analysis

Countries: The quantitative analysis focuses on the industrial sectors of three countries, namely China, Indonesia, and Viet Nam. When combined, these three countries accounted for 85 percent of total energy-related CO_2 emissions from the industrial sector in the East Asian region in 2022. China is the world's largest industrial producer, energy consumer, and emitter of CO_2, meaning that its efforts to decarbonize industry will have an immense emissions impact while also setting a precedent for emerging, export-oriented economies in the region. Meanwhile, Indonesia and Viet Nam represent the challenges faced by smaller but fast-growing economies with important manufacturing sectors. Prominent among those challenges are infrastructure gaps and limited space in government budgets. While reported energy consumption and cost figures are specific to these three nations, the study's broader findings (e.g., on viable technological pathways and policies to deploy them) can be generalized to other nations with ambitions for industrial development.

Subindustries: The analysis covers manufacturing activities, which include fabricating raw materials (such as steel, cement, and chemicals), refining or processing fuels, cooking and packaging food, and producing finished products such as vehicles and machinery. Non-manufacturing activities such as mining and quarrying, oil and gas drilling, agriculture, and construction are excluded. Additionally, the analysis focuses specifically on pathways to decarbonize industry, rather than pathways to scale up manufacturing of clean fuels or clean energy technologies. A list of included subindustries appears in the bottom panel of **(FIGURE 1.2)** in the previous chapter.

Energy sources: The study considers all energy sources purchased by these subindustries, including fossil fuels, bioenergy, electricity, and heat/steam (e.g., district heating). Intermediate energy carriers (such as refinery fuel gas produced and consumed within a refinery, or electricity produced by a captive power plant) are not explicitly tracked, but the inputs used to create those intermediate energy carriers are included. The analysis focuses on pathways by which industry can transition away from fossil fuel use. To achieve emissions benefits, it is necessary for the electricity sector to similarly transition to non emitting sources. Though the electricity sector is not modeled in detail in this study, key electricity-related outputs are covered in Chapters 3 and 5. It is also important to ensure that bioenergy and district heat are produced sustainably, but bioenergy and district heat supply are not covered in the present study. Feedstocks (fuels transformed to become part of the output products, such as petroleum that goes into making plastics) are included in the study and are shown separately from non-feedstock fuels in graphs.

Pollutants: This study assesses CO_2 emissions from industrial fossil fuel use and from the calcination of minerals to form cement (Scope 1 emissions). It also considers upstream CO_2 emissions from purchased electricity under multiple assumptions about progress toward electricity sector decarbonization (Scope 2 emissions), as well as methane (CH_4) emissions attributable to the fossil fuels purchased by manufacturers (i.e., leakage from oil and gas extraction operations and coal mine methane). However, the study does not include all greenhouse gas emissions caused by industrial activity; it excludes industrial emissions of nitrous oxide (N_2O), a byproduct of nitric and adipic acid manufacturing, and emissions of fluorinated gases (F-gases), chemical products often used as refrigerants and propellants.

Timeframe: Viet Nam has pledged to achieve net zero greenhouse gas emissions by 2050, while Indonesia and China have set 2060 targets. For consistency and comparability of results across countries, this study uses the same time frame for its analysis of all three countries. It reports outputs in 2022 (the most recent year for which data are available) and in five-year increments from 2025 through 2050 (the latest date that complies with all three countries' targets). However, the end date is not a very important factor in the analysis, affecting only projections of future changes in product demand. The technological pathways remain valid and would require broadly similar levels of inflation-adjusted investment whether accomplished by 2050, 2060, or even later. Therefore, the study can be seen as assessing the technology and investment needed to achieve clean industry over any reasonable timeframe this century.

Costs: This study estimates two types of costs: energy costs and capital equipment costs. Energy-using industrial equipment such as boilers and furnaces often lasts for decades, so energy costs are typically the largest contributor to the total lifetime costs of owning and operating the equipment. Capital cost—the cost of purchasing the equipment, amortized over its lifespan—is the second-largest contributor. The costs of installation, buildings, and land are not included. Other costs (such as operations and maintenance, insurance premiums, etc.) are typically smaller and tend to be similar between clean and emitting variants of a technology. For instance, electric boilers and natural gas boilers may require a similar number of workers to operate and maintain them. Therefore, these costs are excluded. Purchased nonenergy inputs such as metal purchased by an automobile manufacturer or flour purchased by a food manufacturer represent the largest cost that manufacturers face (Rissman 2024), but this study does not estimate these costs, as this study is focused on energy and energy-using equipment, and—except in the case of material efficiency technologies—the costs for nonenergy inputs are similar between low- and high-emitting production processes.

Carbon pricing: In addition to the costs noted above, the modeled scenario incorporates a carbon price that increases from present-day values to \$50/tonne CO_2 by 2050, which represents the combined effects of direct carbon pricing, such as a carbon credit market or carbon tax, and indirect carbon pricing, such as the withdrawal of existing fossil fuel subsidies. This carbon price affects the cost-effectiveness of the technological interventions detailed in the section on costs in Chapter 3.

Green hydrogen costs: The model incorporates three price scenarios for green hydrogen costs, which vary by country. The default ("High Improvement") settings used in our modeled scenario are based on favorable projections for drops in hydrogen's cost by 2050. These are $1.80/kg in China, $3.50/kg in Indonesia, and $2.17/kg in Viet Nam (Erofeev 2025, Suryadi et al. 2021, Agora Industry 2024, UNDP 2023, BloombergNEF 2023, Tuyen 2024, and ERIA 2024). Achieving these prices would require significant progress toward reducing the costs of renewable electricity generation and transmission. The model also supports "Low Improvement" and "Present Day" pricing assumptions as alternate cases. In all three cases, these prices are used as the cost of the electricity consumed to produce the green hydrogen, not the unit cost of energy in the produced hydrogen. Unit costs of the produced hydrogen would be moderately higher since electrolyzers operate at 76 percent efficiency in our model. Even so, the costs of electricity for green hydrogen are far below the costs of electricity used for direct electrification in our modeled scenario. This is because hydrogen production using certain electrolyzers (e.g., polymer electrolyte membrane and pressurized alkaline electrolyzers) can be concentrated in the hours of the day with the lowest electricity prices owing to the inherent ability of hydrogen to store energy until it is needed, while firms employing direct electrification must purchase electricity at the time it is needed (absent other storage technologies such as batteries, which are not included in the modeled scenario).

Data sources

The model uses more than 85 data sources, all of which are cited within the Excel-based model, which will be released on an open-source basis with this report. This section summarizes some of the major sources. Additionally, a selection of key numerical inputs to the model are shown in Appendix D.

For data on industrial energy use, the model relies on published government data sources such as the China Energy Statistical Yearbook (from China's National Bureau of Statistics), the Statistics of Indonesia Manufacturing Industry 2022 (from BPS Statistics Indonesia), and the Handbook of Energy and Economic Statistics of Indonesia 2023 (from Indonesia's Ministry of Energy and Mineral Resources). For Viet Nam, we utilize Energy Statistics Viet Nam published by the Viet Nam National Energy Efficiency Program, supplemented by data from the Viet Nam Steel Association.

The future BAU case is built using projected changes in demand for industrial products from published studies. Examples include a net-zero roadmap for China's steel industry published by Hasanbeigi et al. (2023), global projections of plastics use by Dokl et al. (2024), and industrial decarbonization roadmaps for Indonesia by Lu et al. (2024). In the case of Viet Nam, data are from the Viet Nam Energy Outlook Report: Pathways to Net-Zero by the Electricity and Renewable Energy Authority in Viet Nam (EREA). Data on petroleum refining demand are from a global projection (the median of seven scenarios from a range of sources) since refined petroleum products are globally traded commodities and country-specific projections of refining activity were not available (IEA 2024).

Energy costs vary by fuel type and are based on in-country data where available. Data on technological performance, such as the energy efficiency of industrial technologies, and the capital costs of industrial equipment are based on a mixture of in-country and international sources, prioritizing country-specific data where available, especially in the largest industries (iron and steel, and cement), where we develop bottom-up capital cost accounting models.

Sensitivity analysis

The model supports sensitivity analysis, allowing for increases or decreases in BAU 2050 energy use, energy costs, capital costs, and discount rate. The model can also simulate a range of future electricity costs and carbon pricing levels (without affecting other energy costs) and thus can represent the effects of policies that scale up renewable energy to lower the cost of generating electricity and so improve the bankability of industrial decarbonization projects (discussed in Chapter 5). The model also supports various scenarios for future clean hydrogen costs, which vary by country. Indifference curves built using the model's sensitivity analysis features are presented in Chapter 3.

Technology tiers

This study divides technologies and other changes to industrial processes into four broad technological pillars—efficiency, electrification, carbon capture, and clean hydrogen—and six tiers. The first tier represents the highest priority interventions; the last, the lowest, with the priority level of each determined by the costs, technological maturity, emissions impacts, and practicality of the interventions it includes. Each tier represents a nonoverlapping set of measures, and the six tiers cumulatively mitigate 95 percent to 97 percent of industrial energy-related and cement calcination emissions in each country.

This tiered modeling approach aims to help international financial institutions and policy makers sequence their support for interventions in a way that facilitates their economic and practical success. Similar in some ways to a marginal abatement cost curve, the approach indicates where limited resources can have the greatest emissions impact between now and 2050. However, interventions need not be maximized in one tier before resources are allocated to other tiers. Investments can and should be directed to multiple tiers at once, depending on available resources, policy appetite, and developments in technology and enabling infrastructure.

Below, we explain which interventions are included in each tier, and why.

Tier 1: Material efficiency, product longevity, and energy efficiency

The first tier encompasses the lowest-hanging fruit among industrial decarbonization solutions: those that reduce industrial energy use or material intensity without reducing product quality. These interventions, which span energy efficiency, material efficiency, and product longevity, often save firms money by reducing input costs. Their deployment is limited in a BAU scenario in light of their upfront costs (e.g., product redesigns, additional worker training) and nonfinancial barriers (e.g., firms' habituation and risk aversion), but small nudges from policy makers and investors can overcome these barriers. Tier 1 applies all three strategies to the industrial subsectors where it is most applicable (energy efficiency is applied to most subsectors, whereas material efficiency and product longevity are applied to a select few). Tier 1 reduces energy demand in the relevant subsector based on the maximum potential scale of each strategy in each subsector. Specific potentials for each country are shown in Appendix A.

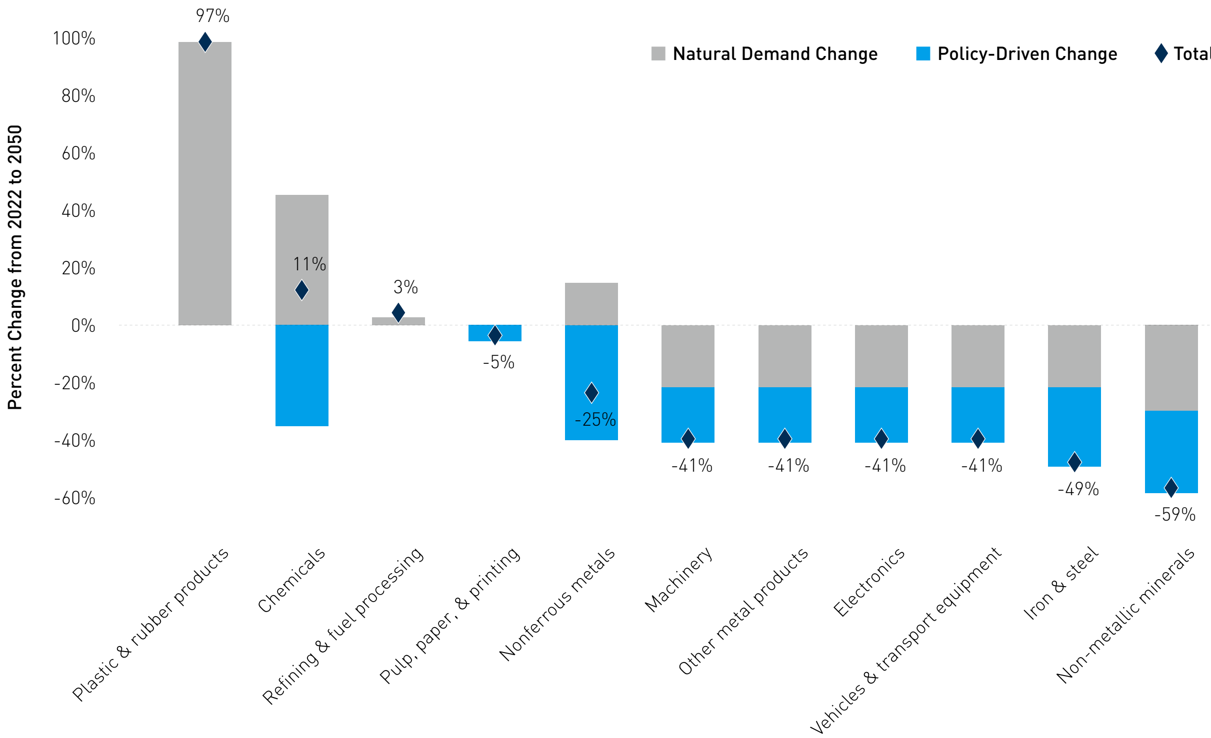
Energy efficiency interventions reduce energy use within equipment categories or across facilities and supply chains, typically by mitigating energy losses from the conversion of fuel to usable energy or the transfer of energy to industrial processes (Rissman 2024). In 2018, the International Energy Agency estimated that readily available energy efficiency technologies could reduce global industrial energy demand by 44 percent between 2018 and 2040 (IEA 2018). Equipment-level interventions (e.g., selecting efficient equipment models and adjusting their speed, pressure, or other operating parameters) are most common today given the standardization of industrial equipment and the relative ease of regulating them (Rissman 2024). Facility-level interventions (e.g., aligning the size of equipment with material flows or designing pipes to move fluid efficiently) and supply-chain-level interventions (e.g., shortening supply chains, altering product designs) are less common today but can be encouraged by policy.

Material efficiency strategies minimize the amount of new material used to create the same product, mainly by altering either product designs (e.g., material substitution, new configurations) or industrial processes (e.g., automation, additive manufacturing). Since they reduce the need to process new materials, they are most effective at reducing emissions from industries that manufacture basic materials (e.g., steel, cement, chemicals) rather than those that assemble materials into products (e.g., automotives, machinery). For example, material efficiency measures could reduce energy demand by the global cement industry by 22 percent (GCCA 2022). Material efficiency is deployed far below its potential scale today, in part because firms find standardized parts and processes more familiar and practical, and because end-users can be skeptical of the performance and safety of material-efficient products.

Product longevity strategies keep materials, products, and physical infrastructure (e.g., buildings) in use for as long as possible, reducing both material waste and demand for newly manufactured materials (Rissman 2024). Examples of such strategies include the use of durable and long-lasting materials in manufacturing and construction, designing products for easy repair and remanufacture, and "adaptive reuse" strategies that find new uses for intact materials, products, and infrastructure. Increasing the lifetime of buildings and steel products, for example, can reduce their material use by a quarter (Hasanbeigi et al. 2023). Product longevity often requires significant coordination between stakeholders across the product value chain, such as manufacturers, construction workers, resellers, and waste management entities. In addition, the emissions impact of product longevity depends not only on the energy avoided from new product manufacturing but also the energy use of the longevity measure itself and the emissions impact of using the resulting product in place of alternatives. In some cases, keeping old materials and products in circulation could increase emissions if cleaner alternatives become available (e.g., remanufactured internal combustion engines could reduce electric vehicle market share). In our modeling, we assume longevity improvements apply to product types that reduce emissions; specific percentage potentials for each country are shown in Appendix A.

This report distinguishes anticipated natural changes in demand for industrial products (for example, due to population growth, changes in the structure of the economy, or reaching peak urbanization) from changes in demand that could be achieved through policies promoting material efficiency and the longevity of entire products or buildings. **FIGURE 2.1** shows the change in demand for products by industrial subsector in China, with natural demand changes and potential policy-driven demand changes broken out. Data on changes in product demand for Indonesia and Viet Nam can be found in Appendix A.

FIGURE 2.1 Anticipated percent changes in product demand in China by industrial subsector



Note: *Anticipated and potential changes achievable through material efficiency and longevity policies in China by 2050 (relative to 2022). Similar graphs for Indonesia and Viet Nam appear in Appendix A.*

Previous reports and industry association roadmaps sometimes offer a combined value for natural and policy-driven demand changes. For example, a 2022 study by Rocky Mountain Institute and the China Cement Association found that demand reduction can cut cement-making emissions by 67 percent in 2050 relative to 2020 levels, including the effects of natural reduction in demand (due to China reaching peak urbanization) and additional mitigation measures to reduce buildings' cement requirements, extend building lifespans, and reuse cement and concrete (RMI and CCA 2022). That finding is closely aligned with the value in this study (a 59 percent reduction from 2022 to 2050; **FIGURE 2.1**) after adjusting for the difference in base year and in industry scope. (This study covers the entire nonmetallic minerals subsector, which includes cement, glass, brick, and lime.)

The steel industry provides another example. Previous work by Lawrence Berkeley National Laboratory and Global Efficiency Intelligence found a 38 percent reduction in steel production (from around 1,070 million tonnes per year (Mt) in 2020 to around 660 Mt/year in 2050) under a net-zero scenario that includes natural and policy-driven demand change (Hasanbeigi et al. 2023). A study by Rocky Mountain Institute found greater reduction potential, with steel production ranging from 621 to 475 Mt/year in 2050, corresponding to reductions of 42–56 percent (Chen et al. 2021). This study's value of 49 percent **(FIGURE 2.1)** is in the same range as these prior studies.

Tier 2a: Electrification of non-thermal, low-temperature, and some steelmaking processes

The next tier represents the most mature, lowest-cost options for switching the remaining industrial energy use to low-carbon energy. These options electrify processes that currently rely on fossil fuel combustion, thereby increasing their efficiency and reducing their emissions impact if powered by clean electricity. In each country, Tier 2a electrifies all nonthermal processes and low-temperature thermal processes (below 150°C). It also shifts the majority of primary steelmaking (60 percent in China and Viet Nam and 70 percent in Indonesia) to secondary steelmaking by 2050.

Nonthermal processes such as material grinding, compression, and conveyance activities powered by diesel engines can easily be electrified using commercial technologies like electric motors. In fact, “machine drive” already accounts for half of industrial electricity use in the United States (Rissman 2024). Replacing diesel engines with electric motors can reduce operating expenses because electric motors are more efficient than combustion engines and because diesel fuel is a comparatively expensive fossil fuel, relative to coal, in the East Asian region.

Electrifying thermal processes is more challenging given the high costs of electricity relative to fossil fuels, which makes most electric heating equipment more expensive to operate than conventional equipment. Industrial heat pumps, which are commercially available and can supply heat up to 150-200°C, are an exception to this rule. Heat pumps move heat from a source to a sink, increasing its temperature by manipulating its pressure. Because they use electricity to move heat rather than convert electricity to heat, they can deliver much more energy than they take in, partially or fully overcoming the higher operating costs of electrification (Rissman 2024).

Secondary steelmaking involves the use of electric arc furnaces (EAFs) to turn scrap steel into recycled steel (Rissman 2024). Although recycled steel can replace primary steel in most end uses, it cannot fully replace primary steelmaking owing to limitations on steel scrap purity and availability, especially if material efficiency measures are maximized, which will tend to reduce steel waste (IEA 2020). However, where scrap is available, it is a cost-effective pathway for reducing industrial GHGs.

EAFs are widely available and account for 29 percent of global steelmaking today (mainly in the United States and Europe), with scrap steel accounting for around a quarter of steelmaking’s material inputs globally (Hasanbeigi et al. 2023, Rissman 2024). Scrap steel is typically loaded into the bottom of the furnace while graphite electrodes are lowered in from the top. When electric currents are run through the electrodes, lightning-bolt-like “arcs” form between the electrodes and scrap metal, melting the metal via both radiative heating and electric resistance within the metal itself. Today’s EAFs are not emissions-free, as carbon in the charge materials and consumption of the carbon electrodes releases CO_2, and peripheral natural gas burners that regulate EAF temperatures emit GHGs. Still, EAFs create only a fraction (7 percent) of the direct GHG emissions of blast furnaces in primary steelmaking, and new furnace designs can help to mitigate them.

Tier 2b: Electrification of medium- and high-temperature processes

After the first two tiers are implemented, the remaining fossil fuel use represents medium- and high-temperature industrial process heat, which is more challenging to decarbonize. At temperatures above 150°C, low-carbon heating options are expensive to operate and often involve nascent technologies. These include direct electrification of heating processes, replacing fossil fuels with low-carbon fuels (e.g., green hydrogen), and capturing CO_2 from fossil fuel combustion.

Tier 2b directly electrifies most of this remaining heat. Existing electric technologies can provide process heat at all temperatures used in industry today, although much of the relevant equipment is not yet commercial and is more expensive to operate than conventional heating equipment. Still, direct electrification has advantages over green hydrogen and CCUS (Rissman and Sawe 2024). Direct electrification is much more energy efficient than green hydrogen combustion, which requires electricity to form the hydrogen, then wastes energy in the form of hot exhaust gases, water vapor, and radiative heat. After accounting for combustion's heat losses, relying on green hydrogen combustion for industrial heat roughly doubles the amount of electricity required per unit of heat produced relative to direct electrification (Rissman 2024). Compared to CCUS, electrification is far less capital intensive and has the potential to drop significantly in cost if powered by renewable energy. (Some approaches to increase industrial access to clean electricity are described in Chapters 5 and 6.) Electrification also avoids both upstream emissions from fossil fuel extraction and point-source emissions that CCUS technologies cannot capture, as well as the risk of locking in fossil fuel infrastructure and delaying the broader clean energy transition. Therefore, green hydrogen and CCUS should be reserved for process heat that is too difficult to electrify.

Today, medium-temperature industrial heat (150 to 500 °C) is often provided by fossil-fuel-fired boilers, for which electric boilers are a one-to-one substitute (McMillan and Narwade 2018). Electric boilers are commercially available today and rely on one of two mature technologies: electrodes and electric resistance (Rehfeldt et al. 2024). Electrode boilers heat water by running an electric current through electrodes in the water, whereas electric resistance boilers run an electric current through a metal or ceramic resistor that generates and transfers heat to the water. Unfortunately, both types of boilers are far more expensive to operate than conventional boilers. According to a recent comparative analysis of industrial heating technologies in China, electric boilers are estimated to cost $97 per megawatt-hour of thermal output (MWhth) in 2030 compared to $39 per MWhth for coal-fired boilers and $52 per MWhth for gas-fired boilers (accounting for China's anticipated 2030 carbon price) (Sawe et al. 2024).

High-temperature heat (above 500°C) is concentrated in a few energy-intensive industries: iron and steel, chemicals, nonmetallic minerals, and nonferrous metals (Rissman 2024). A variety of proven electric technologies reach the highest temperatures used in industry today and are suitable for bulk heating applications, including electric resistance heating, induction heating, and electric arcs. However, equipment that utilizes these technologies to electrify specific industrial processes is still being researched and piloted. For example, electric steam crackers that leverage electric resistance to break chemical feedstocks down into high-value chemicals are still in the demonstration stage (Rehfeldt et al. 2024). Additionally, like electric boilers, high-temperature electric heating technologies are more expensive to operate than conventional technologies (Rissman 2024). Thermal batteries are one exception to that rule. They leverage electric resistance to convert electricity to heat and store that heat for hours or days, releasing heat whenever it is needed. Firms with flexible operations and in regions with variable time-of-use electricity pricing can use thermal batteries to selectively purchase electricity when it is cheapest, potentially overcoming the cost premium for electrified heat (Sawe et al. 2024). Still, commercialized thermal batteries can only reach 300 to 500°C, and those that can reach 1,700°C are still being piloted.

Tier 3: Carbon capture and use or storage

Certain high-temperature industrial processes will likely lack commercial electrification options for several decades. For example, plasma torches that can heat cement kilns and electrolytic technologies that can replace fuel-fired steelmaking are still at the laboratory stage (Rissman 2024). CCUS may be the best option for decarbonizing these processes. Not only is retrofitting fossil fuel combustion with CCUS less expensive in our model than burning green hydrogen, but it also demands no additional electricity from the grid (though it increases the fossil fuel consumption of the process it is applied to). Moreover, CCUS can play a dual role in the cement industry, addressing both energy-related emissions and process CO_2 emissions until alternative cement chemistries or electrified cement kilns and precalciners are commercialized. In our model, Tier 3 applies CCUS to fossil fuel use remaining after Tier 2b in each country's nonmetallic minerals industry, iron and steel industry, and nonferrous metals industry. It is applied to most or all remaining fossil fuel use in targeted industries—that is, nonmetallic mineral production and a portion of iron and steel production. Although CCUS is commercially deployed today on high-purity CO_2 streams (e.g., from ethanol and ammonia production), Tier 3 does not apply CCUS to those activities because our model does not disaggregate the chemicals subsector down to the level of specific products.

Many existing technologies can capture CO_2 from carbon-containing fuels, either by separating CO_2 from a gas or creating a pure stream of CO_2 during fuel combustion (Rissman 2024). They do not capture non-CO_2 pollutants like particulate matter or nitrogen oxides. Separation technologies capture CO_2 from one of three types of gas:

1. Flue gas released after a fuel is combusted (post-combustion capture);
2. A hydrogen-CO_2 mixture derived from syngas, which is thermochemically derived from a fuel (pre-combustion capture);
3. Raw natural gas (natural gas processing).

Commercial separation technologies have been around for decades and achieve capture rates of 90 percent, typically using amine-based solvents or sorbents that selectively bind to CO_2. Newer ones may use CO_2-filtering membranes or cryogenic separation. Technologies that alter fuel combustion to create a pure CO_2 stream can reach higher capture rates but are not yet commercial. They include oxy-fuel combustion, which burns fuel in pure oxygen rather than air, and chemical looping combustion, which uses metal oxides to deliver oxygen to the fuel combustion process.

Today, most commercial carbon capture projects are in natural gas processing, where CO_2 is separated from raw natural gas to create pipeline-quality gas or involve post-combustion capture on high-purity CO_2 streams, such as from ethanol production. Capturing CO_2 from lower purity streams like cement kiln flue gas is comparatively expensive, given the higher energy requirements, but it leverages the same mature underlying technology (U.S. DOE 2023a). Once carbon is captured and compressed, it can be transported via pipeline for long-term sequestration, either in products that do not release CO_2 as they are used or in underground geologic formations. CO_2 compression, transportation, and storage are collectively less energy-intensive and expensive than carbon capture (which increases a process' fuel demand by 15 percent to 25 percent), but they involve significant coordination with regulatory bodies and CO_2 off-takers.

Tier 4a: Green hydrogen combustion

Tier 4a replaces all fossil fuels remaining after Tier 3 with green hydrogen, excluding fossil fuel feedstocks for the chemicals industry. This encompasses the remaining process heat in the chemicals, refining, iron and steel, and nonmetallic minerals. While the creation of green hydrogen can be too energy-intensive to be cost-effective for many applications (Esposito 2024), it may make economic sense in industries with high temperature needs where electrification is not yet technologically mature and hydrogen is already used in process streams (e.g., chemicals, refining), and in other industries that still have remaining emissions to address even after deploying earlier tier strategies are deployed (e.g., primary iron and steel). In the iron and steel industry, green hydrogen can simultaneously serve as a low-carbon feedstock and source of high-temperature heat when used in direct reduced iron furnaces (H_2-DRI). In such specific circumstances, the utilization of green hydrogen for process heat can be a sensible strategy to reach net zero. Bioenergy may be a similarly viable option for high-temperature process heat, but given limits on sustainable bioenergy availability, competing uses (such as for sustainable aviation and shipping fuels), and concerns about risks of deforestation and food insecurity, it is used in this study only for chemical feedstocks in Tier 4b. This is deemed to be a suitable application where there are not scalable alternatives.

Today, nearly all of the world's hydrogen is produced from fossil fuels, around three-quarters from steam methane reforming of natural gas, and around a quarter from the gasification of coal (ESMAP et al. 2023). Both processes involve reacting fuels with steam at high pressures and temperatures to create syngas, a gaseous mixture of hydrogen and carbon monoxide (Rissman

2024). Hydrogen is then chemically extracted from syngas, releasing large volumes of CO_2. CCUS can be retrofitted to this process to create low-carbon “blue hydrogen,” though it neither fully eliminates on-site emissions nor addresses fugitive emissions from natural gas production. The most promising zero-carbon hydrogen production pathway involves the use of renewable energy in electrolyzers to split water into hydrogen and oxygen, creating what is commonly known as “green hydrogen.” All three forms of hydrogen are molecularly identical—only their production pathways vary.

Like fossil fuels, hydrogen can be combusted for industrial process heat. It can replace fossil fuels in most industrial equipment, but the equipment must be upgraded to accommodate hydrogen’s lower volumetric energy density and manage safety risks like leakage and flammability. Hydrogen also has a higher flame temperature than natural gas, leading to higher emissions of nitrogen oxides (NOx) unless safeguards are implemented. Finally, hydrogen requires substantial enabling infrastructure, including electrolyzers to produce hydrogen, renewable energy to power electrolyzers, and dedicated pipelines that are designed to prevent small hydrogen molecules from leaking.

Tier 4b: Clean chemical feedstocks

One of the last and most technically challenging aspects of industrial decarbonization is shifting from fossil-based to clean chemical feedstocks used to make ammonia, methanol, olefins, aromatics, and downstream products like plastics and fertilizers (Rissman 2024). This does not address energy-related emissions from the facility, but it can address upstream (Scope 3) emissions from fossil fuel production and processing, as well as downstream (Scope 3) emissions from the use and end-of-life of products. It can also reduce process CO_2 emissions that arise because only some of the carbon in feedstocks ends up in chemical output products. However, zero-carbon feedstocks are only used at small scale today (and some pathways, like conversion to BTX aromatics, are still being researched and demonstrated), so it may take decades before they reach meaningful scale.

Tier 4b shifts all fossil fuel feedstocks to low-carbon feedstocks by 2050. In all three countries, 30 percent of feedstock demand is met with bioenergy, 40 percent with green hydrogen, and 30 percent with blue hydrogen. These proportions roughly account for the available supplies of sustainable biomass for feedstocks and clean electricity to produce green hydrogen. The production of blue hydrogen is not emissions free, but it may be a good option for decarbonizing steam methane reforming equipment before it is ready for replacement, and where clean electricity for green hydrogen production is unavailable. Another potential fit is for petroleum refineries that today burn byproducts of the crude oil they refine—refinery fuel gas and petcoke. These substances could be converted to blue hydrogen for use in refinery processes like hydrocracking and desulfurization.

Biomass feedstocks and clean hydrogen are promising low-carbon replacements for fossil fuel feedstocks (Rissman 2024). Like fossil fuel feedstocks, biomass feedstocks (e.g., wood waste, biofuels) contain carbon. Since biomass absorbs CO_2 as it grows, these feedstocks are carbon neutral as long as the biomass is sustainably sourced (i.e., does not displace existing carbon land sinks). Clean hydrogen does not contain carbon, but it can be a low-carbon feedstock for ammonia production (which does not require carbon) or when combined with a net-negative source of captured CO_2 (captured from bioenergy combustion or directly from the air).

Some biomass feedstock conversion routes are already commercial, like the conversion of ethanol (a biofuel) to ethylene (a light olefin) (Rissman 2024). Others are nearing commercialization, like the gasification of biomass to produce methanol (Harris et al. 2021). Clean hydrogen can be used to produce ammonia today, as it can serve as a drop-in replacement for fossil-fuel-derived hydrogen. Technologies to convert hydrogen and CO_2 to methanol are in the early commercial stages (Rissman 2024). Finally, methanol derived from either feedstock can be converted into olefins (a commercial process) or aromatics (a demonstration-stage process).

Both types of feedstocks should be prioritized, as there are advantages and drawbacks to each. Biomass feedstocks contain high-energy molecules and may require less energy to process than fossil fuel feedstocks, but the high costs of biomass processing equipment and limited supplies of sustainable biomass constrain their potential scale. The use of clean hydrogen as a feedstock may be constrained by limited supplies of net-zero CO_2, as well as by the energy and infrastructure investments needed to sustain blue and green hydrogen production.

3
Modeling Results

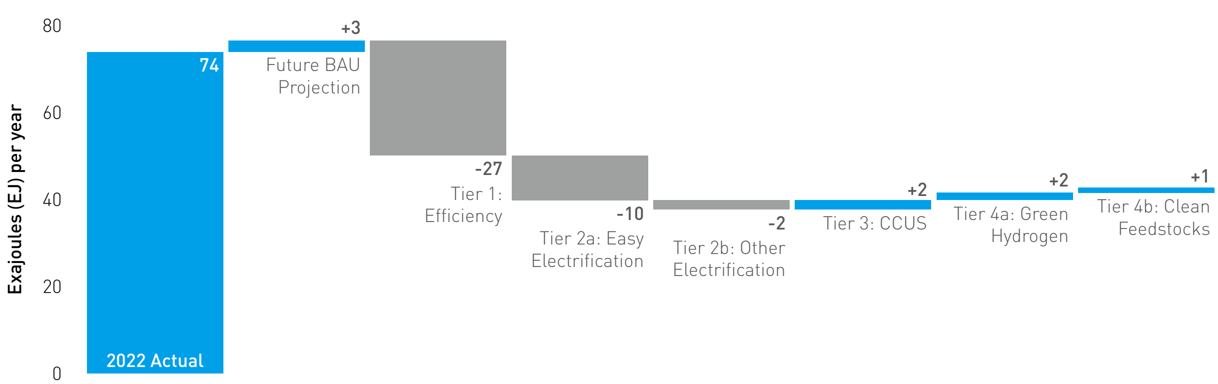
This study reports results on energy use, CO_2 emissions, and costs (including energy and capital equipment costs) for each country. In addition to the results in this section, additional graphs are available in Appendix A.

Energy use

China

China's industrial sector accounted for 47 percent of the country's final energy use in 2022. When including upstream industries (mining and quarrying), associated industries (e.g., construction), and feedstock energy use, the industrial sector accounted for 60 percent of the country's final energy use. The business-as-usual (BAU) scenario exhibits a 4 percent increase in the industrial sector's energy use by 2050 **(FIGURE 3.1)**, heavily reliant on coal and coke and their byproducts as well as petroleum **(FIGURE 3.2)**.

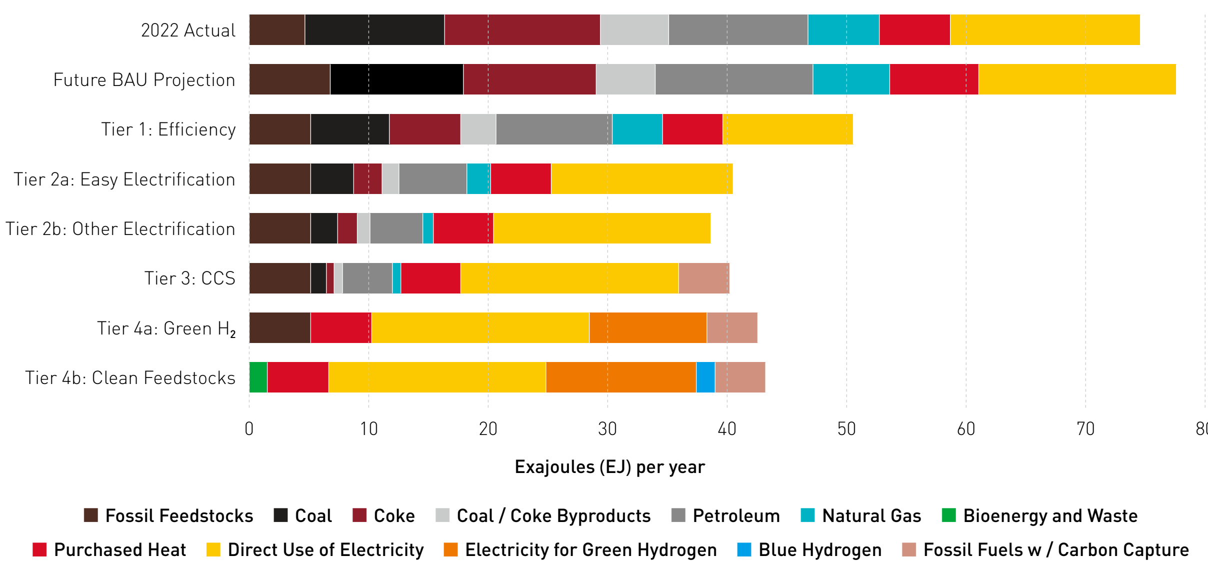
FIGURE 3.1 Annual industrial sector final energy use in China (across intervention tiers)



Note: This waterfall chart displays the considerable reductions in industrial sector energy use compared to the projected 2050 BAU scenario in the first two intervention tiers (efficiency and easy and other electrification approaches), as well as nominal increased energy demands from CCUS, green hydrogen, and clean feedstock interventions necessary to reach net zero. Combining these interventions results in a 44 percent reduction in final energy use compared to the 2050 BAU scenario.

Interventions in Tiers 1 and 2a—consisting solely of efficiency measures and easy electrification—can, however, reduce projected 2050 energy use in the industrial sector by 47.7 percent; an additional 2.4 percent reduction can be achieved through the more complex electrification measures from Tier 2b, slashing China's fossil fuel use in the sector. Technological interventions in Tiers 3 through 4b require additional energy inputs **(FIGURE 3.2)** to attain net zero. Owing to the efficiency gains and direct electrification, however, the sector still uses 44 percent less energy as the BAU projection after Tier 4b.

FIGURE 3.2 Cumulative annual industrial energy use in China by energy type

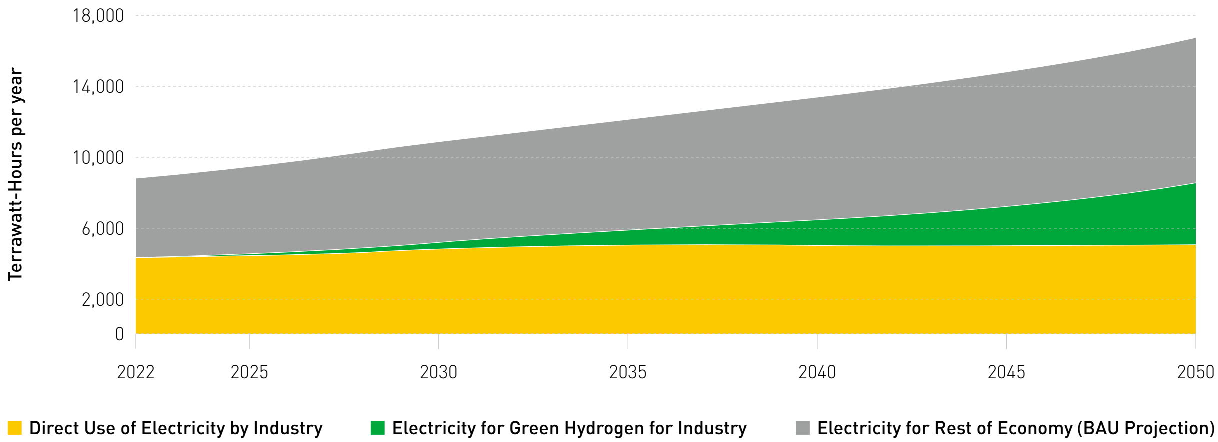


Note: Industrial sector energy use is displayed for historical and BAU scenarios as well as the cumulative addition of each industrial decarbonization intervention tier; each tier's energy use is visualized here while incorporating the effects of the earlier. Colors denote the type of energy resource utilized. Rather than depict green hydrogen use itself, the graph depicts electricity used to make green hydrogen to demonstrate the total electricity demand of industrial decarbonization.

Since the production of green hydrogen is energy intensive, it demands more of China's renewable energy resources as part of the decarbonization portfolio in Tiers 4a and 4b **(FIGURE 3.3)**. By 2050, China's industrial sector's electricity demand is projected to grow over 93 percent, with only 14.3 percent of that growth needed for direct electricity use and the remainder for green hydrogen production. Electricity for green hydrogen generation for China's industrial processes is projected to consume 3,492 terawatt hours (TWh by 2050, equivalent to 40 percent of the country's total economywide electricity demand in 2022.

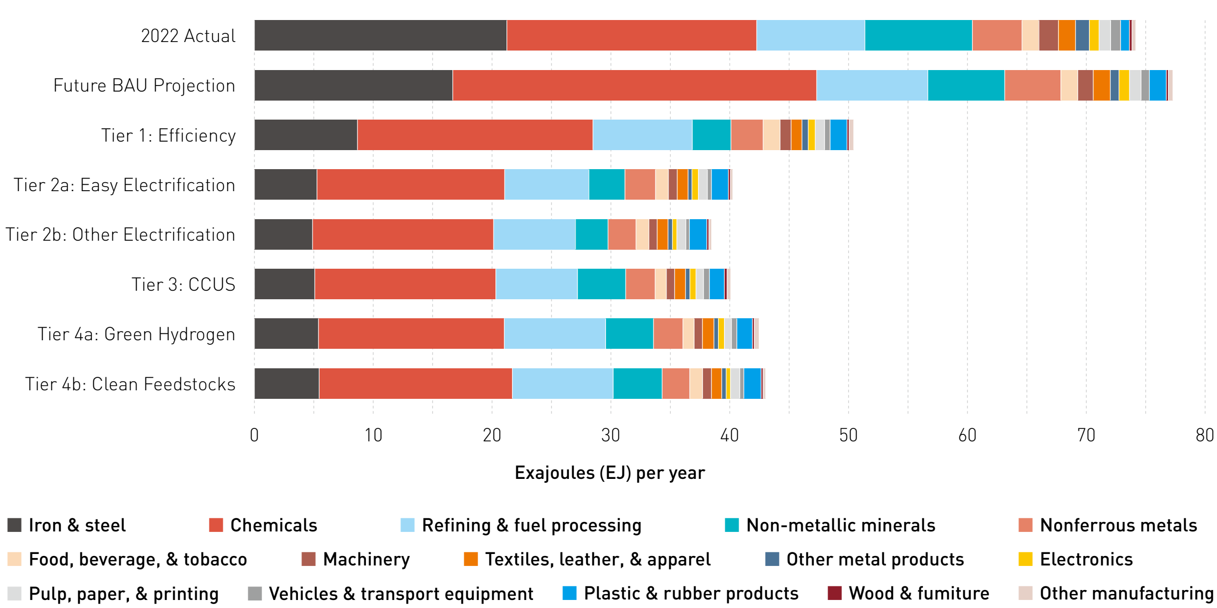
Chinese industrial final energy use is dominated by five subindustries—iron and steel, chemicals, petroleum refining, nonmetallic minerals, and nonferrous metals—which together comprise 87 percent of industrial energy demand **(FIGURE 3.4)**. While natural changes in demand are expected

FIGURE 3.3 Industrial sector electricity demand in China



Note: The sector's electricity demand is expected to increase over 93 percent compared to 2022 historical data, the vast majority of which is driven by green hydrogen production to decarbonize. The industrial sector is forecast to require 8539 TWh to decarbonize by 2050 compared to its historical 4414 TWh demand.

FIGURE 3.4 Annual industrial energy use in China by subindustry

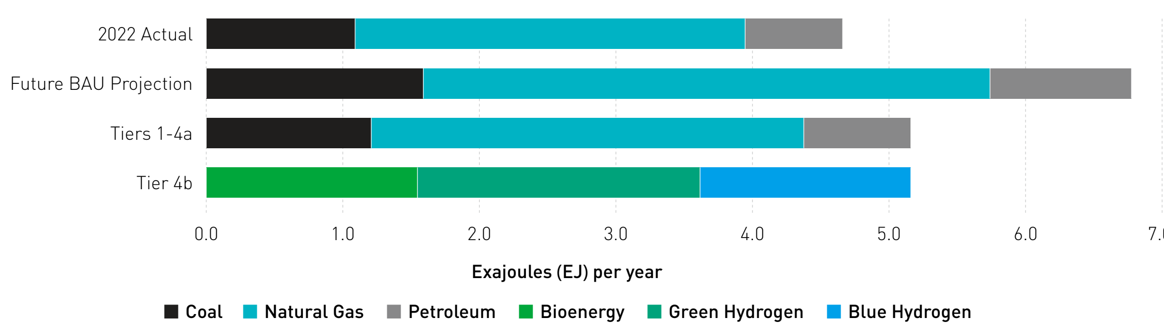


Note: Industrial sector energy use is displayed for historical and BAU scenarios as well as the cumulative addition of each industrial decarbonization intervention tier. Note that each tier's energy use incorporates the effects of the earlier tiers. Colors denote the type of subindustry utilizing the energy.

to reduce energy use in many subindustries, demand for chemicals is expected to grow precipitously, increasing that subindustry's energy use by 45 percent. The efficiency and electrification interventions in Tiers 1, 2a, and 2b, which collectively reduce energy demand by 50 percent, show the largest reductions relative to 2050 BAU in chemicals (15.53 EJ), iron and steel (11.85 EJ), and nonmetallic minerals (3.64 EJ). Tiers 3, 4a, and 4b hike energy demand only by 6 percent, an increase concentrated in refining (1.49 EJ), nonmetallic minerals (1.38 EJ), and chemicals (1.09 EJ).

For the chemicals industry, fossil fuel feedstocks in Tier 4b are replaced entirely with bioenergy and green and blue hydrogen sources. Because production of chemical products is predicted to rise 45 percent by 2050, a commensurate increase will occur in the feedstock energy required annually by 2050 in the BAU projection, from 4.66 EJ to 6.77 EJ **(FIGURE 3.5)**. Material efficiency gains moderate this impact to a projected 5.16 EJ. While the sources of chemical feedstocks are altered in Tier 4b's intervention, the amount of energy they contain is not.

FIGURE 3.5 Annual chemicals industry feedstock uses in China by energy type

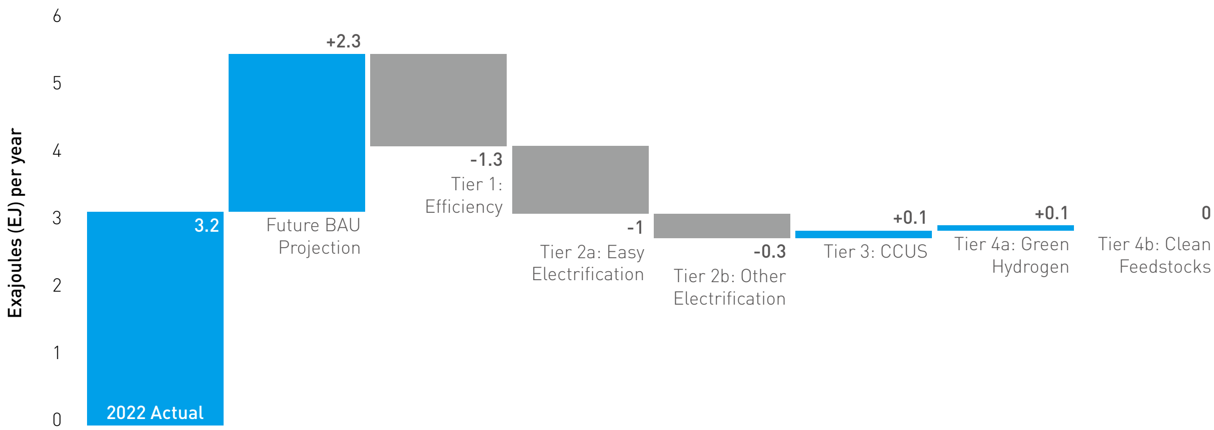


Note: *The "Natural Gas" category includes natural gas liquids like ethane, propane, and butane. Industrial sector feedstock energy use is displayed for historical and BAU scenarios as well as the cumulative addition of industrial decarbonization intervention Tiers 1–4a and Tier 4b. While the prior interventions reduce the required energy for chemical feedstocks by 24 percent, Tier 4b does not change energy requirements but does move chemical feedstocks entirely away from fossil fuels, instead drawing solely from bioenergy and hydrogen sources.*

Indonesia

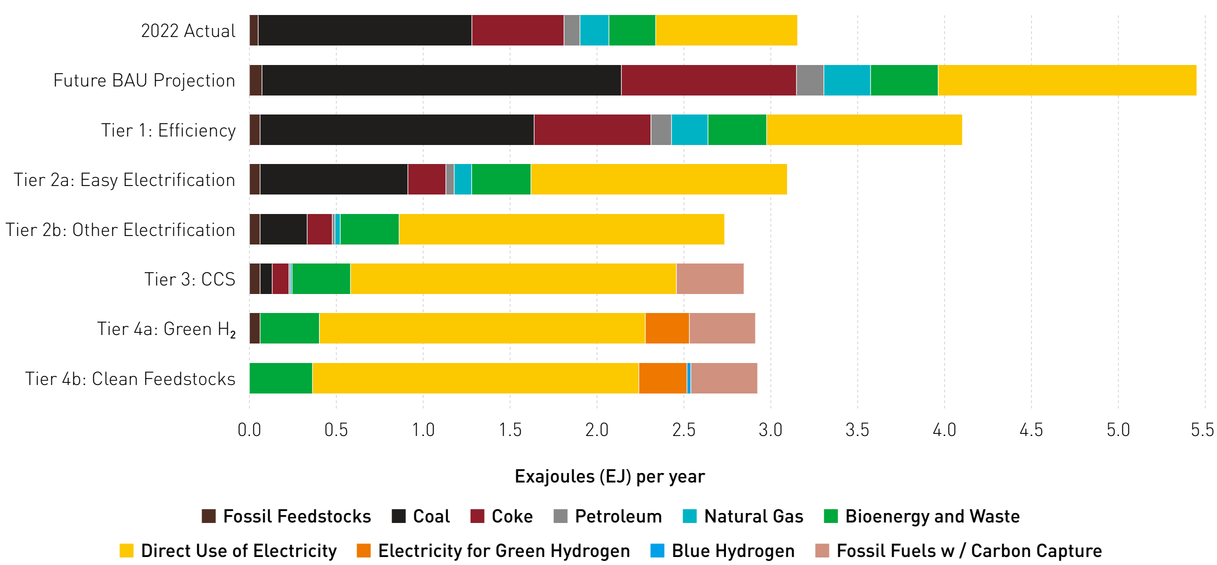
Indonesia's industry sector accounted for 44 percent of the country's final energy use in 2022. The sector's annual energy demands grow 73 percent in the BAU projection by 2050, fueled by high growth in demand for several products. Investment in the first two tiers of industrial decarbonization, however, can reduce demand from the 2050 BAU projection by almost 50 percent, slightly below 2022 levels. This is fueled by Tier 1 efficiency gains (24 percent), Tier 2a easy electrification interventions (19 percent), and Tier 2b additional electrification contributions (6 percent) **(FIGURE 3.6)**. The additional energy inputs required of interventions in Tiers 3 through 4b only nudge the needle, and energy demand to achieve net zero with the full portfolio of industrial decarbonization strategies is still 46 percent less than the 2050 BAU scenario. As an example, Indonesia relies on coal and coke to meet its industrial energy needs (and would need much more to meet its 2050 BAU energy requirements). By investing in the first three intervention tiers (through CCUS), the country could eliminate 83 percent of demand for those fossil fuel types **(FIGURE 3.7)**.

FIGURE 3.6 Annual industrial final energy use in Indonesia



Note: This waterfall chart displays the sizeable reductions in industrial sector energy use compared to the projected 2050 BAU scenario in the first two intervention tiers (efficiency and easy and other electrification approaches), as well as nominal increased energy demands from CCUS, green hydrogen, and clean feedstock interventions necessary to reach net zero. Combining these interventions results in a 46 percent reduction in final energy use compared to the 2050 BAU scenario.

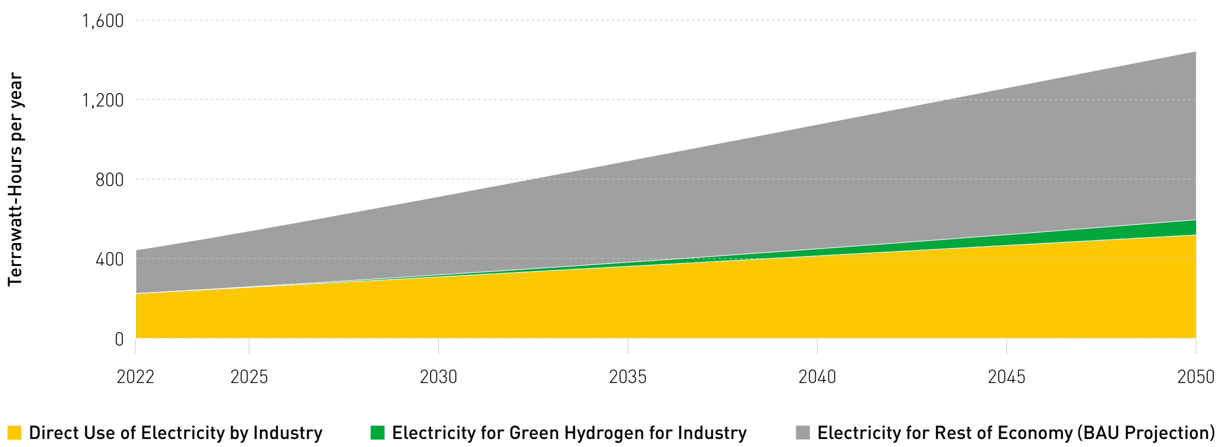
FIGURE 3.7 Annual industrial energy use in Indonesia by energy type



Note: Industrial sector energy use is displayed for historical and BAU scenarios as well for as the cumulative addition of each industrial decarbonization intervention tier. Note that each tier's energy use is visualized here while incorporating the effects of the earlier tiers. Colors denote the type of energy resource utilized. Rather than depict green hydrogen use itself, the graph depicts electricity used to make green hydrogen to demonstrate the total electricity demand of industrial decarbonization.

Indonesia's economywide electricity demand is projected to rise precipitously, growing to 3.25 times its 2022 demand. The industrial sector on its own requires over 2.6 times its current electricity demand to decarbonize by 2050 **(FIGURE 3.8)**; 79 TWh (13 percent) of this industrial electricity demand would go to generating green hydrogen.

FIGURE 3.8 Industrial sector electricity demand in Indonesia

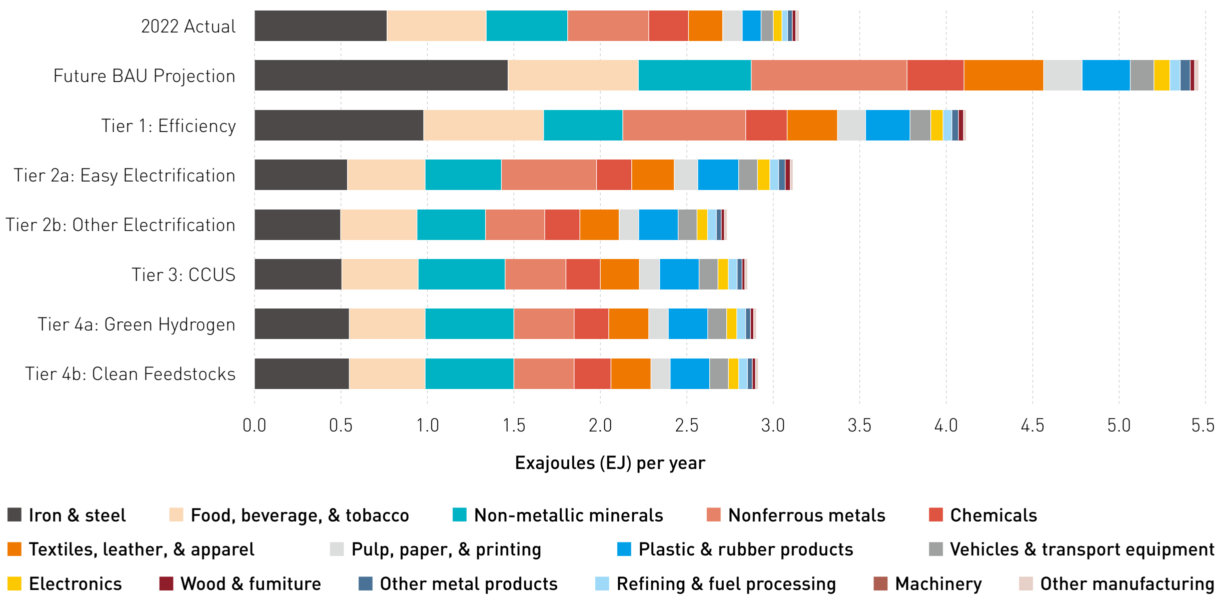


Note: *The sector's electricity demand is expected to increase over 165 percent compared to 2022 historical data in order to decarbonize. The industrial sector is forecast to require 602 TWh to decarbonize by 2050 compared to its historical 227 TWh demand.*

Five industries represent 80 percent of industrial final energy usage in Indonesia: iron and steel; food, beverages, and tobacco; nonferrous metals; nonmetallic minerals; and chemicals **(FIGURE 3.9)**. Iron and steel production operates primarily on coke while the others rely on coal (Appendix A). While natural changes in demand project high energy use for 2050, Tier 1 efficiency gains and Tier 2a's easy electrification across industries are sufficient to account for more than the entirety of the forecasted increase. The efficiency and electrification interventions in Tiers 1, 2a, and 2b yield the largest energy use reductions relative to 2050 BAU in the iron and steel (0.97 EJ); nonferrous metals (0.56 EJ); and food, beverage, and tobacco (0.30 EJ) industries. Tiers 3, 4a, and 4b increase energy demand by 7 percent; this increase is almost entirely generated from the nonmetallic minerals (0.11 EJ) and iron and steel (0.05 EJ) industries.

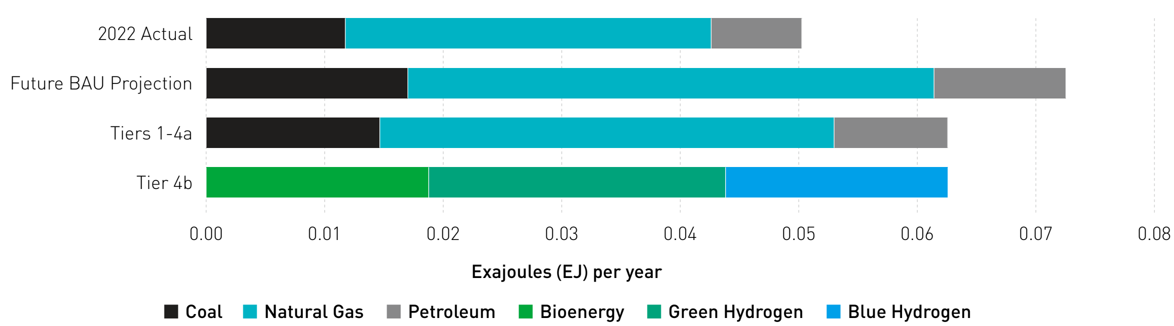
Manufacture of chemical products in Indonesia is predicted to grow 45 percent by 2050 in our BAU scenario, requiring an equivalent, and annual, rise in feedstock energy. Industrial decarbonization in Tiers 1 through 4a reduce this projected demand by 14 percent, while Tier 4b shifts these feedstocks to clean alternatives **(FIGURE 3.10)**.

FIGURE 3.9 Annual industrial energy use in Indonesia by subindustry



Note: Industrial sector energy use is displayed for historical and BAU scenarios as well as the cumulative addition of each industrial decarbonization intervention tier. Note that each tier's energy use incorporates the effects of the earlier tiers. Colors denote the type of subindustry utilizing the energy.

FIGURE 3.10 Annual chemicals industry feedstock uses in Indonesia by energy type



Note: The "Natural Gas" category includes natural gas liquids like ethane, propane, and butane. Industrial sector feedstock energy use is displayed for historical and BAU scenarios as well as the cumulative addition of industrial decarbonization intervention Tiers 1–4a and Tier 4b. While the prior interventions reduce the required energy for chemical feedstocks by 14 percent, Tier 4b does not change energy requirements but does get chemical feedstocks entirely away from fossil fuels, instead drawing solely from bioenergy and hydrogen sources.

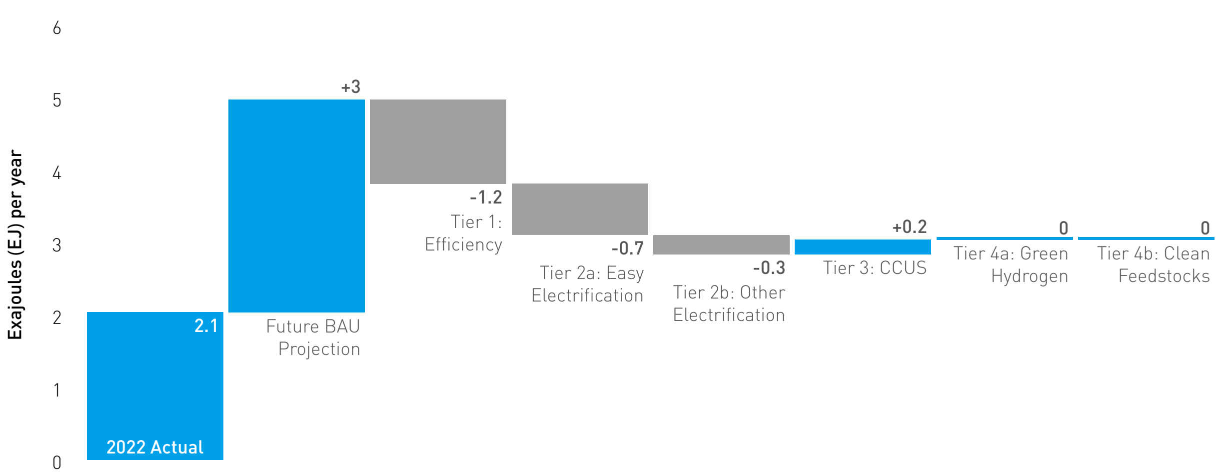
Viet Nam

Viet Nam's industrial sector accounted for about 51 percent of the country's final energy use in 2022. The sector's energy use is projected to rise by 143 percent in the 2050 BAU scenario **(FIGURE 3.11)**. Investing in efficiency and electrification (Tiers 1–2b) will reduce industrial final energy use by 43 percent and fossil fuel use by 78 percent compared to the 2050 BAU scenario **(FIGURE 3.12)**. Fully decarbonizing the sector through the energy-consuming strategies in Tiers 3 through 4b still produces forecasts of energy use 38 percent lower than the 2050 BAU scenario.

Electricity demand in Viet Nam's industrial sector leaps between 2022 and 2050 in a BAU scenario, increasing 380 percent from its 2022 levels on the path to full decarbonization **(FIGURE 3.13)**. Electricity for green hydrogen accounts for 15 percent of the sector's demand.

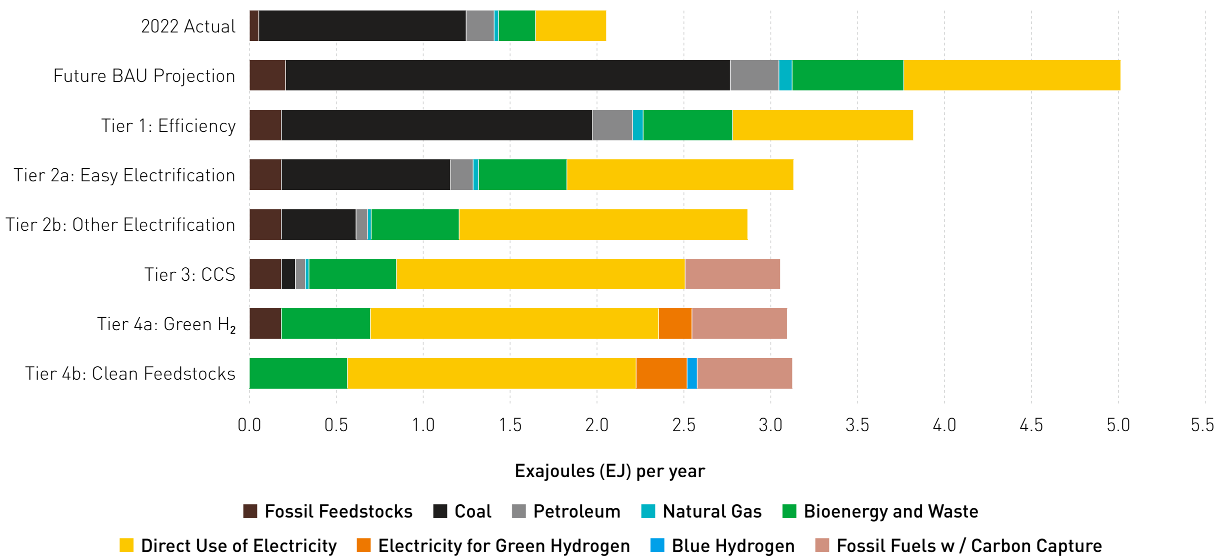
Five industries account for 67 percent of Viet Nam's final energy use: nonmetallic minerals (which utilize the majority of the sector's coal); iron and steel (which utilize most of the sector's coke); textiles, food and beverages; and chemicals **(FIGURE 3.14)**. Owing to the efficiency and electrification interventions in Tiers 1, 2a, and 2b, the greatest drops in energy use relative to 2050 BAU are in iron and steel (0.64 EJ), nonmetallic minerals (0.32 EJ), and nonferrous metals (0.23 EJ). Tiers 3, 4a, and 4b increase energy demand by 9 percent; this increase is found almost entirely in nonmetallic minerals (0.16 EJ).

FIGURE 3.11 Annual industrial sector final energy use in Viet Nam across intervention tiers



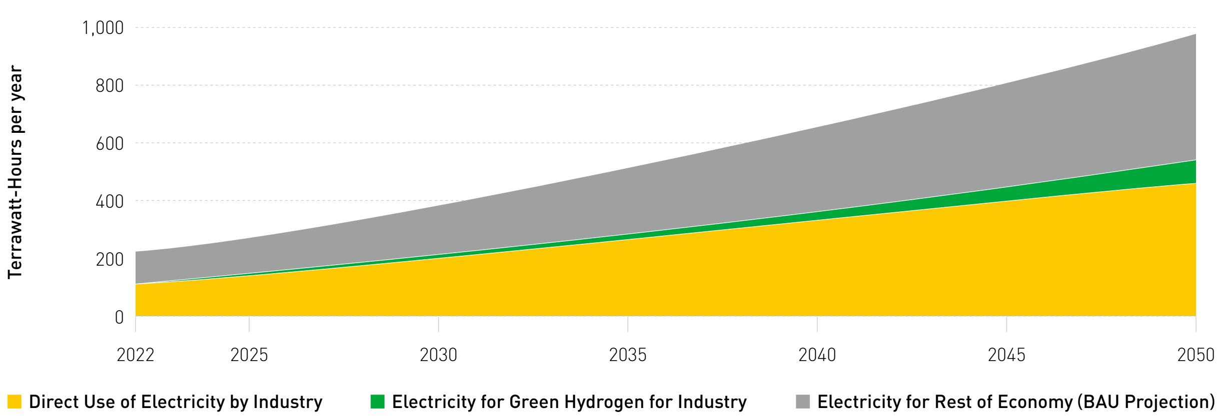
Note: This waterfall chart displays the considerable reductions in industrial sector energy use compared to the projected 2050 BAU scenario in the first two intervention tiers (efficiency and easy and other electrification approaches), as well as nominal increased energy demands from CCUS, green hydrogen, and clean feedstock interventions necessary to reach net zero. Combining these interventions results in a 38 percent reduction in final energy use compared to the 2050 BAU scenario.

FIGURE 3.12 Annual industrial sector final energy use in Viet Nam by energy type



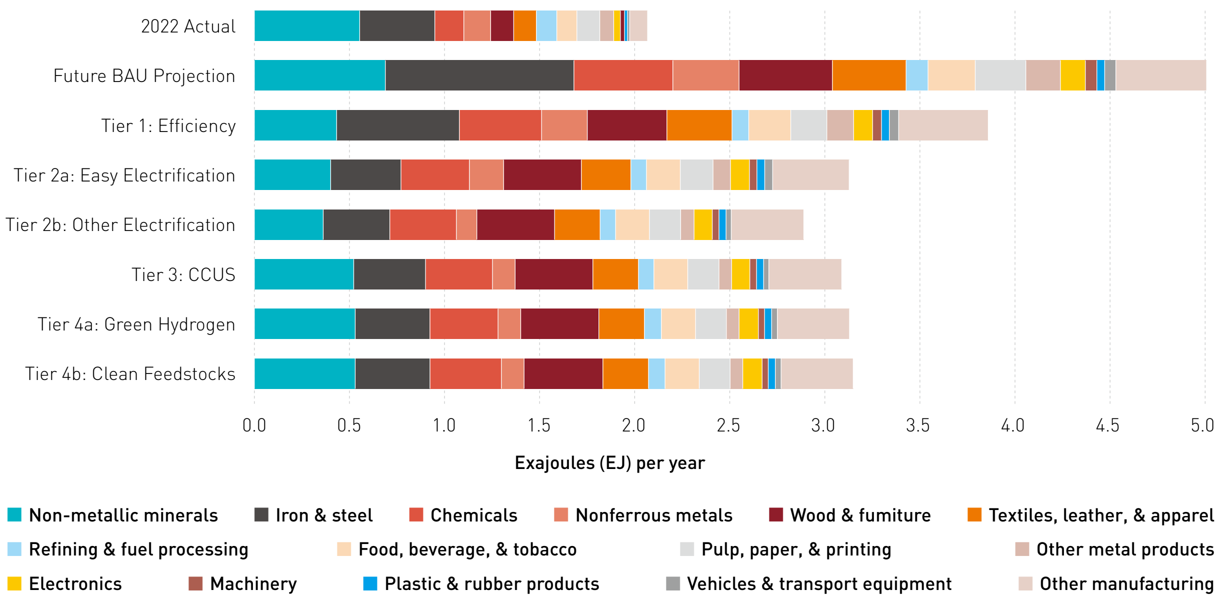
Note: Industrial sector energy use is displayed for historical and BAU scenarios as well as the cumulative addition of each industrial decarbonization intervention tier. Note that each tier's energy use is visualized here while incorporating the effects of the earlier tiers. Colors denote the type of energy resource utilized. Rather than depict green hydrogen use itself, the graph depicts electricity used to make green hydrogen to demonstrate the total electricity demand of industrial decarbonization.

FIGURE 3.13 Industrial sector electricity demand in Viet Nam



Note: The sector's electricity demand is expected to jump 380 percent compared to 2022 historical data in order to decarbonize. The industrial sector is forecast to require 543 TWh to decarbonize by 2050 compared to its historical 113 TWh demand.

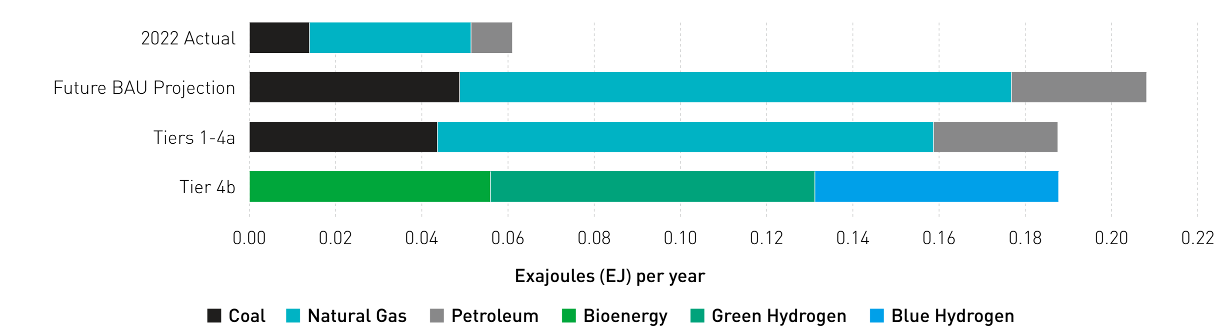
FIGURE 3.14 Annual industrial energy use in Viet Nam by subindustry



Note: Industrial sector energy use is displayed for historical and BAU scenarios as well as the cumulative addition of each industrial decarbonization intervention tier. Note that each tier's energy use incorporates the effects of the earlier tiers. Colors denote the type of subindustry utilizing the energy.

The manufacture of chemical products in Viet Nam is predicted to grow by over 240 percent by 2050 in our BAU scenario. Accordingly, the annual feedstock energy demand would rise at the same rate. Industrial decarbonization interventions in Tiers 1 through 4a achieve declines of only 10 percent from this BAU scenario, while Tier 4b shifts feedstocks to clean alternatives **(FIGURE 3.15)**.

FIGURE 3.15 Annual chemicals industry feedstock uses in Viet Nam by energy type



Note: The "Natural Gas" category includes natural gas liquids like ethane, propane, and butane. Industrial sector feedstock energy use is displayed for historical and BAU scenarios as well as the cumulative addition of industrial decarbonization intervention Tiers 1-4a and Tier 4b. While the prior interventions reduce the required energy for chemical feedstocks by 10 percent, Tier 4b does not change energy requirements but does shift chemical feedstocks away from direct use of fossil fuels, instead drawing solely from bioenergy and hydrogen sources.

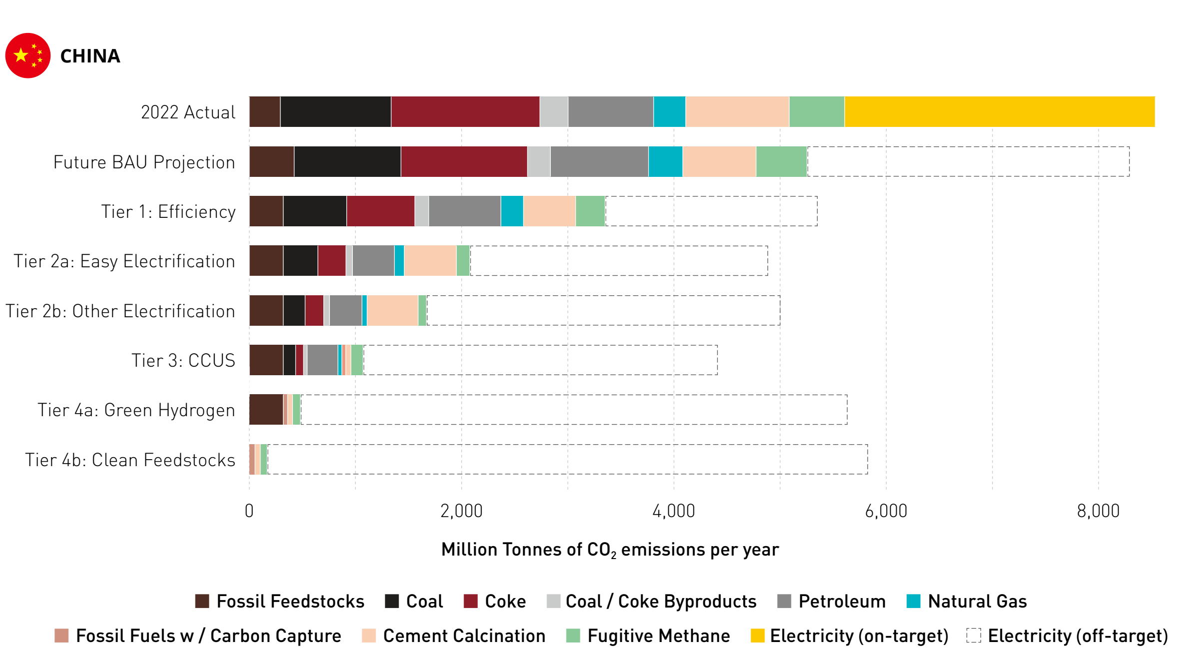
Emissions

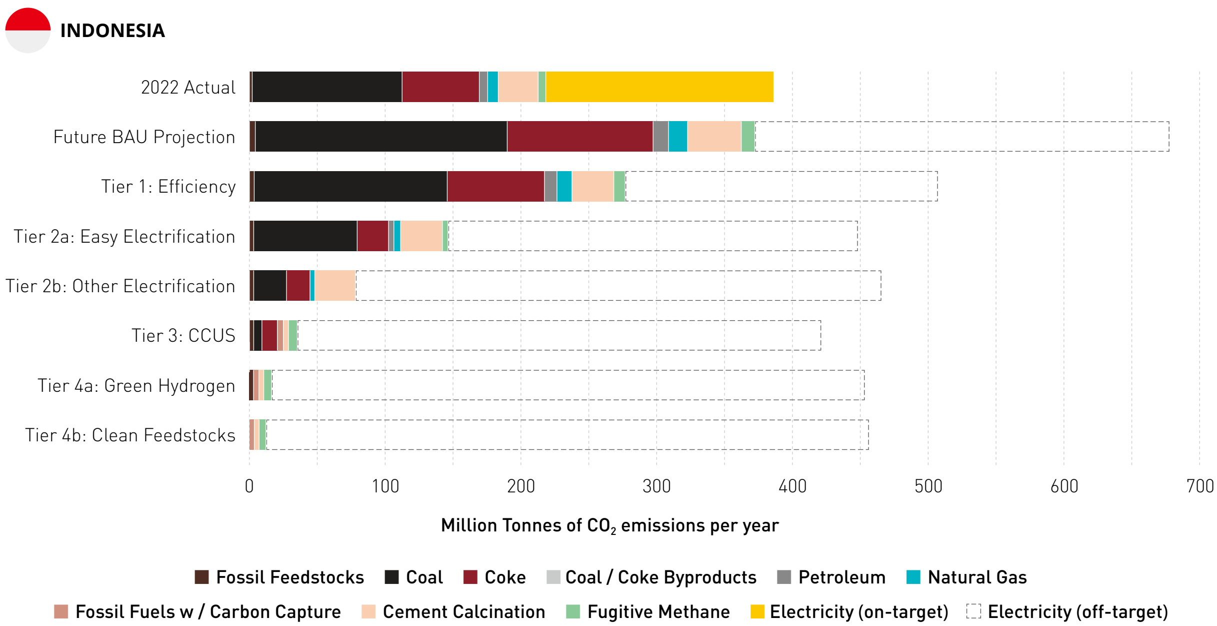
Under BAU conditions, future industrial sector CO_2 emissions depend on physical demand for industrial products as well as the country's progress on clean grids.

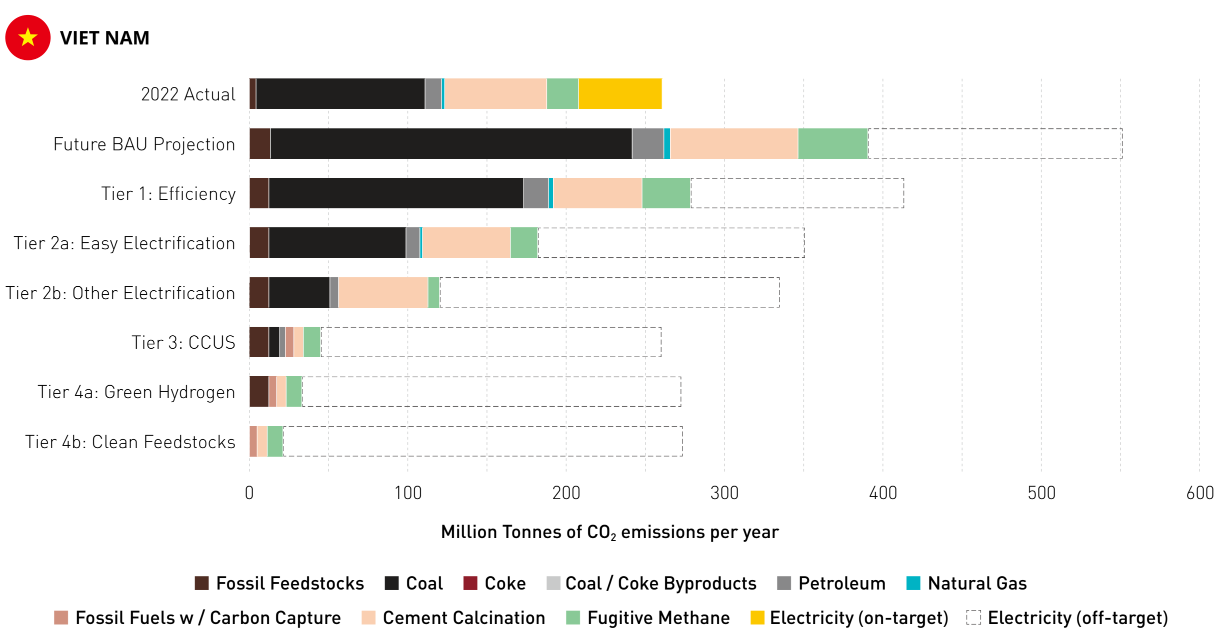
When assuming the power grid will be fully decarbonized, our analysis shows that China and Indonesia's CO_2 emissions from the industrial sector under BAU are forecast to fall by 48 percent and 4 percent by midcentury, respectively, compared with 2022 levels **(FIGURE 3.16)**. A combination of factors is at work, such as declines or slower growth in population, slowing economic growth (e.g., the real estate industry in China), and demand leveling off in buildings and infrastructure systems. Yet BAU projections show that Viet Nam's industrial sector CO_2 emissions are expected to rise 50 percent, driven by population growth, better living standards, and urbanization.

When the electricity sector is "off target," however, industrial CO_2 emissions from Indonesia and Viet Nam increase under the BAU projections. The dashed boxes in **FIGURE 3.16** show indirect CO_2 emissions from industrial electricity demand in a BAU case, where no additional decarbonization efforts are made in the power sector (i.e., if the CO_2 grid emission factors were to stay at 2022 levels). Specifically, by 2050, industrial CO_2 emissions would rise 175 percent or 212 percent of their 2022 levels, respectively, in Indonesia and Viet Nam, while China's emissions would dip 3 percent.

FIGURE 3.16 Annual CO_2 emissions in China, Indonesia, and Viet Nam by energy type







More importantly, the analyses show the CO_2 reduction potential across the technology adoption tiers **(TABLE 3.1)**. In all three countries, the results show that implementing Tier 1 measures—such as improving energy and material efficiency and extending product lifetimes of buildings and vehicles—can deliver significant CO_2 savings, in the range of 26 percent to 36 percent. Notably, even when the power sector is not decarbonizing, the CO_2 reduction potential from efficiency measures remains about the same, about 25 percent to 35 percent. This is because these measures can reduce energy demand, material demand, or both.

TABLE 3.1 Percent reductions in emissions by technological tier relative to the BAU scenario in China, Indonesia, and Viet Nam

	China	Indonesia	Viet Nam
1a: Efficiency	36	26	29
2a: Easy electrification	24	35	25
2b: Other electrification	8	18	16
3: CCUS	11	12	19
4a: Green hydrogen	11	5	3
4b: Clean feedstocks	6	1	3
Residual emissions	3	4	5

Note: Residual emissions of 3–5 percent exist because carbon capture (Tier 3) captures only about 90 percent of the CO_2 in exhaust gas streams and does not address fugitive methane associated with the production of gas and coal used in CCUS-equipped industrial facilities.

Implementing Tier 2a (Easy Electrification, such as industrial heat pumps, electric motors, and electric arc furnaces) not only brings greater energy efficiency to manufacturing processes but it also slashes CO_2 emissions, especially when accompanied by grid decarbonization. Results show an additional reduction in industrial CO_2 emissions, compared to the 2050 BAU scenario, of 24 percent to 35 percent across the three economies, assuming a decarbonized grid. Even when industrial electrification does not have a clean grid, CO_2 emissions would still fall, driven by improved energy efficiency, albeit at a much lower level—in the range of just 6 percent to 12 percent additional CO_2 reduction when compared to 2050 BAU emissions.

Tier 2b entails adopting electrification technologies for higher-temperature processes, such as in the pulp and paper and chemicals subindustries. The potential for CO_2 reductions depends on each country's industrial structure. When supported by a clean electricity grid, Tier 2b reduces CO_2 emissions an additional 8 percent to 18 percent of the 2050 BAU levels in the analyzed countries. However, if the electricity generation mix remains the same, emissions from additional electricity demand may not be offset by the relatively small improvements in efficiency of the higher-temperature technologies. Without a clean grid, implementing Tier 2b would increase CO_2 emissions by 1 percent of 2050 BAU levels in China and 2 percent in Indonesia, while Viet Nam's emissions would drop 3 percent.

Adopting CCUS in targeted processes like limestone calcination and primary ironmaking may be necessary to achieve net-zero by midcentury. In this study, CCUS adoption was considered in the nonmetallic minerals, iron and steel, and nonferrous metals industries. The results showed that by 2050, CO_2 emissions can be further reduced by 11 percent to 19 percent of their forecasted BAU levels when accompanied by a clean grid. The emissions impact would be far less (only a 6 percent reduction in Indonesia, 7 percent in China, and 13.5 percent in Viet Nam) when electricity is not decarbonized.

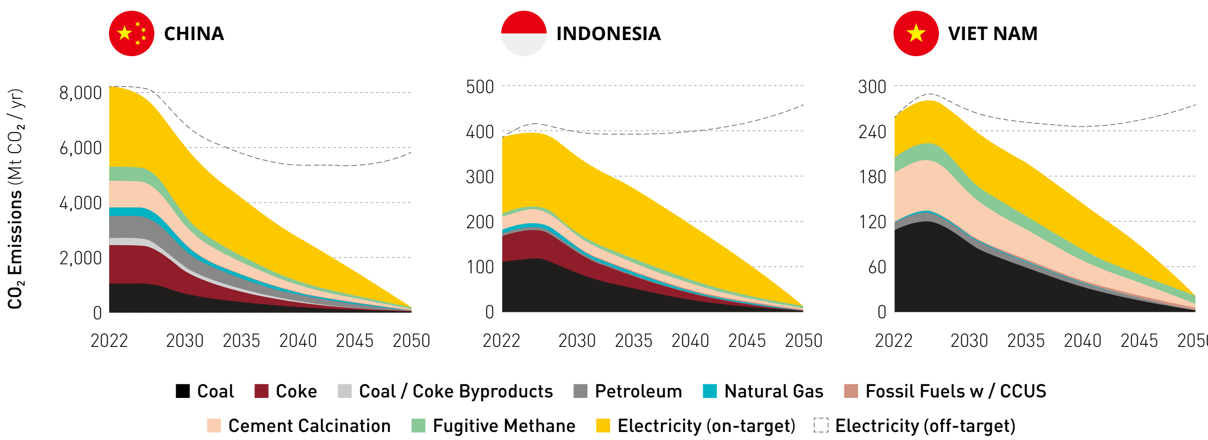
Tier 4a—using green hydrogen as a clean fuel—can play an important role in energy-intensive industries that require high temperatures, such as refining, chemicals, nonmetallic minerals (cement and glass), and iron and steel. Green hydrogen is specifically adopted in these sectors to replace the remaining fossil fuel use after implementing Tiers 1 through 3. Green hydrogen requires production backed by zero-carbon electricity; thus, it is critical to have clean power. The results show that when the power sectors are decarbonized, Tier 4a can reduce industrial sector CO_2 emissions by 3 percent to 11 percent of projected 2050 BAU levels in the analyzed countries. If the power sector maintains today's generation mix, however, the use of electrolytic hydrogen would actually drive CO_2 emissions up 2 percent, to 14 percent of 2050 BAU levels.

By replacing the fossil fuel–based feedstocks (which are used to make chemicals and refining products) with clean feedstocks like green hydrogen or bioenergy, CO_2 emissions decline downstream of the products' value chain, as with product applications (e.g., of fertilizers), end-of-life disposal, and decaying processes associated with, for example, tires and plastics. In this study, we assume the CO_2 contained in these feedstocks eventually contributes to emissions. With a decarbonized power sector, clean feedstock production can help lower emissions by up to 6 percent of 2050 BAU levels. If the power sector maintains its energy generation mix, however, then CO_2 emissions can rise up to 2 percent.

FIGURE 3.17 illustrates industrial CO_2 emissions in China, Indonesia, and Viet Nam, including emissions from on-site fossil fuel use as well as from emissions associated with electricity purchased by the sector after it has implemented all six interventions (Tier 1 through Tier 4b). Industrial CO_2 emissions could reach zero by midcentury if the power sector is on track to be zero-carbon. But if the power sector remains at today's emissions intensity through 2050, then industrial CO_2 emissions would increase by 18 percent over 2022 levels in Indonesia and 5 percent over 2022 levels in Viet Nam; China's industrial CO_2 emissions would fall by 32 percent. (China achieves some reduction because of declines in demand in certain coal-using subindustries, particularly steel and cement, in China's future BAU case.)

FIGURE 3.17 also shows the evolution of industrial fossil fuel demand for each country in a transition to a non-emitting industry. Industrial sector CO_2 emissions from coal, coke, or other coal- and coke-related byproducts level off by 2025 in China. In Indonesia and Viet Nam between 2022 and 2025, coal-related CO_2 emissions in the industrial sector are estimated to increase by 2.7 percent and 4.1 percent per year, respectively. The tiered approach—which implements measures ranging from efficiency to industrial electrification, CCUS in targeted processes, and replacement of the remaining fossil fuels with clean hydrogen—greatly mitigates industrial CO_2 emissions. From 2025 to 2030, industrial CO_2 emissions (including emissions from electricity purchases, assuming the grid becomes decarbonized by 2050) decrease by 15 percent, 2.8 percent, and 3 percent on average per year, respectively, in China, Indonesia, and Viet Nam. This trend continues in all three countries until they attain net zero emissions.

FIGURE 3.17 CO_2 emissions from the industrial sector and from electricity purchased by industry



Note: *In China, the figure pertains to Scope 2 emissions (2022–50). "Electricity (on-target)" refers to industrial scope 2 emissions if the electricity sector is decarbonized in line with national targets, while the upper dashed line, "Electricity (off-target)," shows industrial scope 2 emissions if the electricity sector retains its 2022 emissions intensity throughout the modeled timeframe.*

Costs

As discussed in Chapter 2, this study estimates energy costs and capital investment costs associated with the transition to clean industry but does not include other types of costs such as labor and maintenance of the equipment.

Energy costs

Electricity prices for industrial buyers today are several times higher than coal or even natural gas prices in China, Indonesia, and Viet Nam. For instance, electricity costs for Chinese industry are $27 million per petajoule, compared to $15 million for petroleum diesel, $13 million for natural gas, and just $3.3 million for coal (Hasanbeigi et al. 2023).

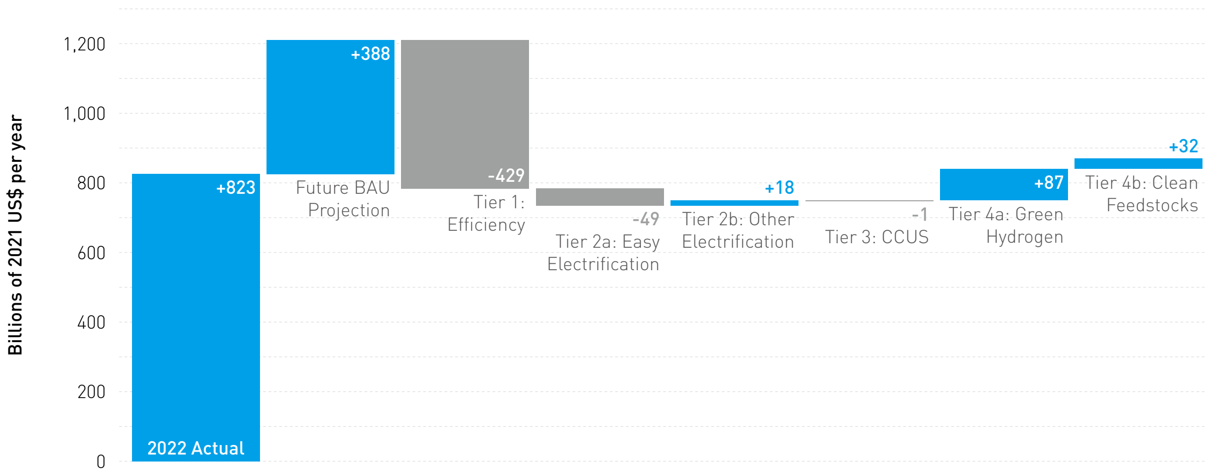
Electricity is used more efficiently than fossil fuels because it avoids important energy loss modes. For example, a natural gas–burning industrial furnace can lose 25 percent to 75 percent of the energy in the fuel as hot exhaust gas and latent heat in formed water vapor, depending on the temperature of the furnace and whether waste-heat recovery technology is employed (Mickey 2017). Electricity does not form combustion exhaust or water vapor. In certain cases—those covered in Tier 2a (heat pumps, electric motors, and secondary steelmaking)—electrified technologies can overcome the electricity price premium:

- Heat pumps can have exceptionally high efficiency (for reasons discussed in Chapter 6).
- Electric motors compete with diesel engines, not with coal-based process heating. They can be more than twice as efficient as diesel engines, which rely on one of the most expensive fossil fuels.
- Energy costs for electric arc furnaces (EAFs) are higher than the energy costs of blast furnaces per tonne of steel produced, but EAFs can nonetheless be competitive when scrap steel is available at low cost. EAFs are a mature technology that competes with primary steel in many countries.

As a result, total industrial sector energy costs decline in Tier 1 (efficiency) and Tier 2a (the most cost-effective forms of electrification). Other tiers increase energy costs, especially those reliant on green hydrogen (Tiers 4a and 4b), which is formed from electricity and suffers from the same heat loss modes as fossil fuels when combusted **(FIGURE 3.18)**. In China, total energy costs for a non-emitting industrial sector are 28 percent less than the costs of the future BAU industrial sector, almost entirely owing to the efficiency interventions in Tier 1. This highlights the importance of energy efficiency, material efficiency, and product longevity as core elements of a climate solution.

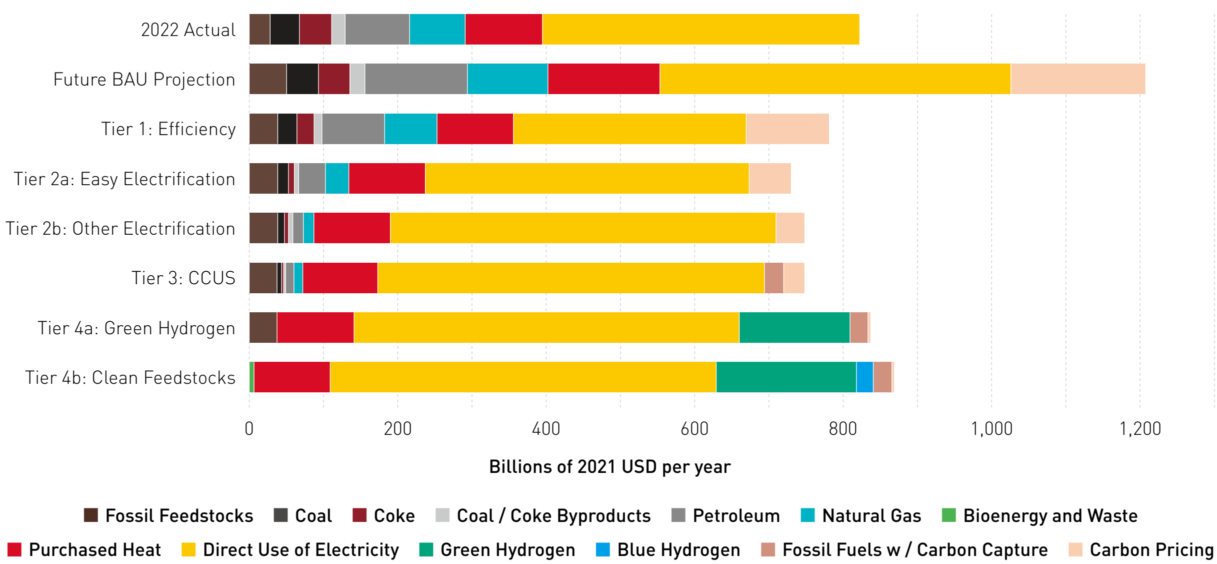
It can also be useful to look at the composition of energy costs within each tier, highlighting the growing shares of electricity and green hydrogen in total energy costs **(FIGURE 3.19)**.

FIGURE 3.18 Annual industrial energy expenditures in China by technology tier



Note: This figure includes the percentage effects of carbon pricing, broken out in figure 3.19.

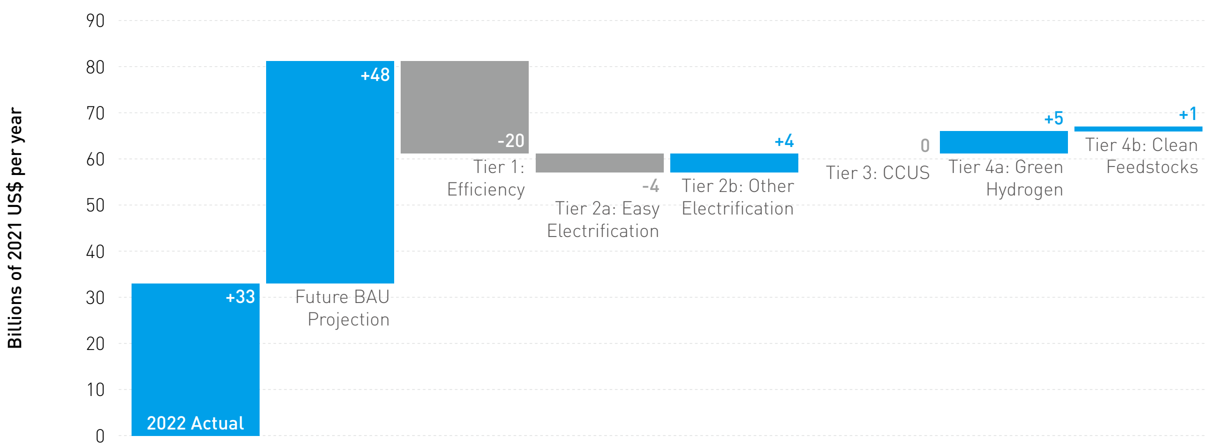
FIGURE 3.19 Annual industrial energy expenditures in China by energy type



Note: Tiers are cumulative, so the energy costs shown in any tier are inclusive of interventions from all prior tiers. To see the effect of a single tier's technologies on energy costs, compare that tier with its immediate predecessor, as in figure 3.18.

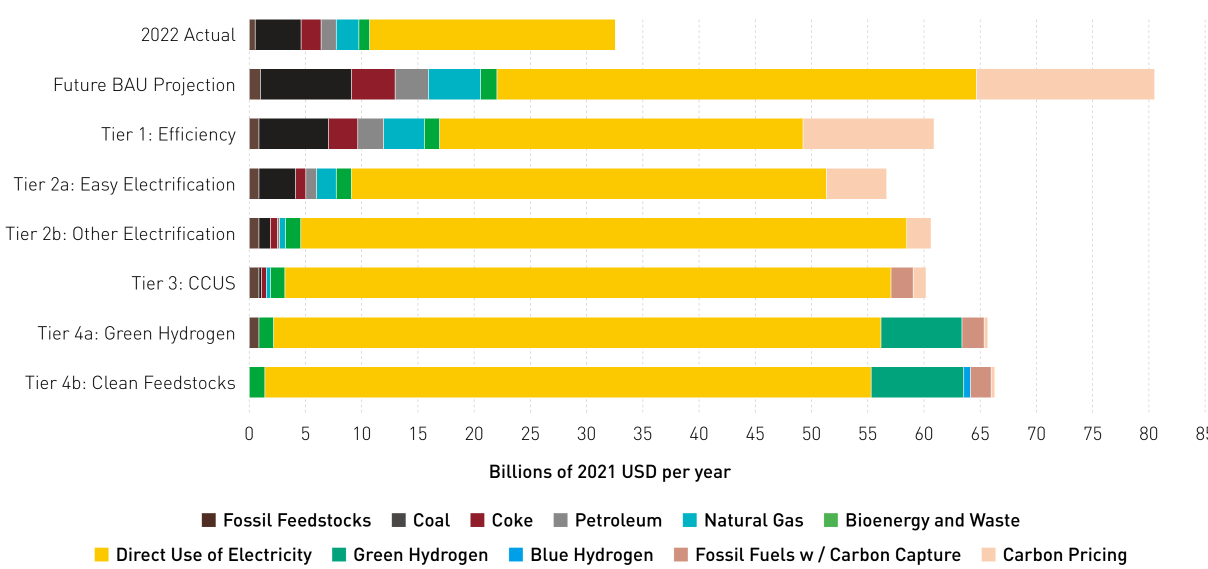
The results are similar for Indonesia **(FIGURE 3.20 and 3.21)**, where energy costs would decrease by 18 percent after the implementation of all tiers and compared to the BAU scenario—though Indonesia sees a larger cost increase for Tier 2b because a larger share of its industrial sector (especially nonferrous metals) requires high-temperature heat. (China also requires a lot of high-temperature heat for its steel and cement subindustries, but steel is partially addressed by shifting primary steel production to secondary steel production in Tier 2a, while cement is largely addressed via carbon capture in Tier 3, so these subindustries have less impact on Tier 2b electrification costs than the nonferrous metals subindustry.)

FIGURE 3.20 Annual industrial energy expenditures in Indonesia by energy type



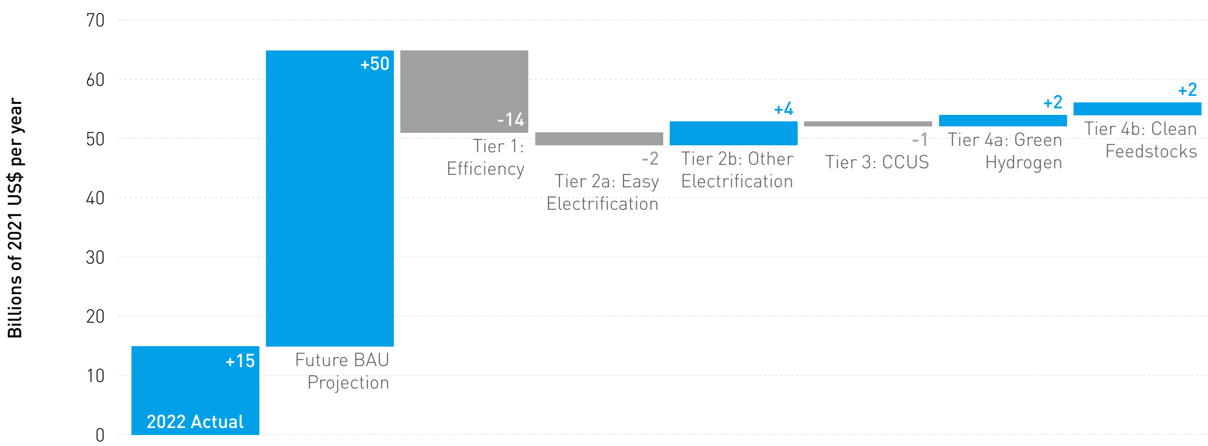
Note: Includes the effects of carbon pricing, broken out in figure 3.21.

FIGURE 3.21 Annual industrial energy expenditures in Indonesia by energy type



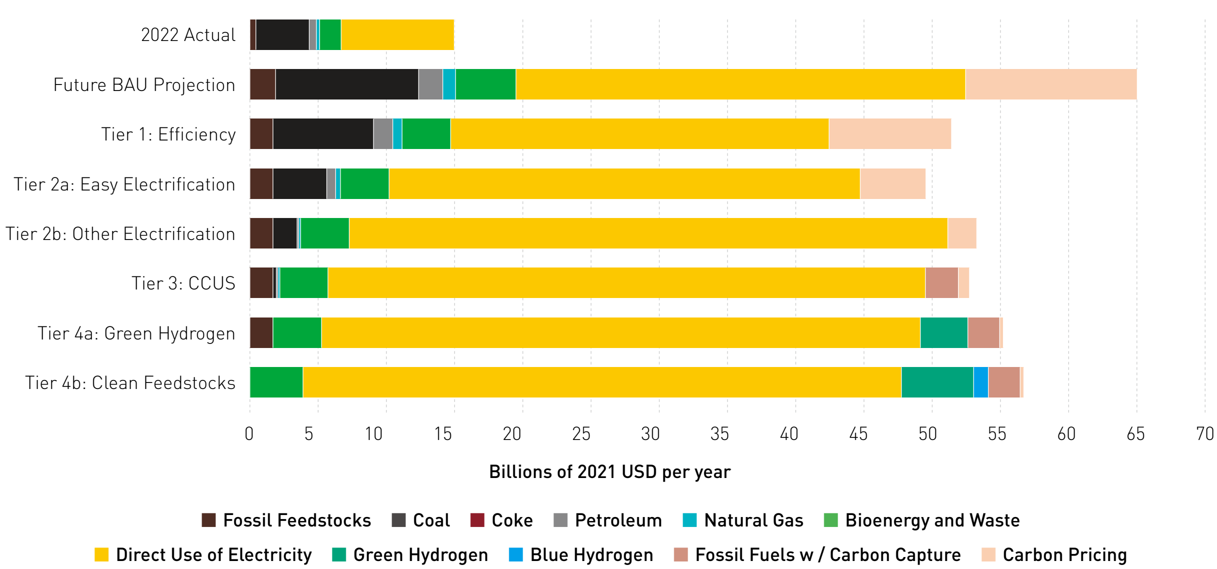
The pattern for Viet Nam **(FIGURE 3.22 and 3.23)**, is similar to that of Indonesia, including the huge drop in annual energy use from efficiency (Tier 1), smaller reductions from "easy electrification" (Tier 2a) and carbon capture (Tier 3), and increases from other technologies, ultimately achieving a 13 percent cost reduction from a fully decarbonized industrial sector when compared to the future BAU projection (Tier 4b).

FIGURE 3.22 Annual industrial energy expenditures in Viet Nam by energy type



Note: Includes the effects of carbon pricing, which is broken out in figure 3.23.

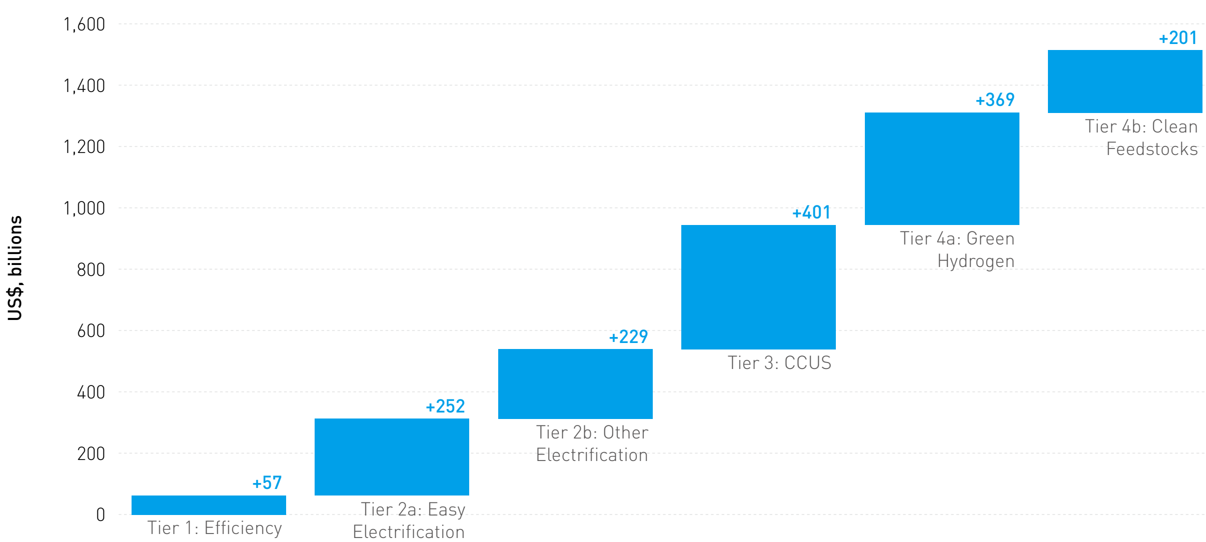
FIGURE 3.23 Annual industrial energy expenditures in Viet Nam by energy type



Capital equipment investment needs

The total need for capital investment in industrial equipment to decarbonize industry in China is around $1.5 trillion **(FIGURE 3.24)**, about 6 percent of China's 2022 GDP. This includes energy-using equipment such as boilers and furnaces, as well as electrolyzers to produce the hydrogen demanded by industry. However, it does not include investments in the electricity sector (such as power plants and transmission lines). Efficiency measures (Tier 1) have the lowest capital costs because they are often not capital-intensive relative to the less-efficient equipment in the future BAU case. The first two tiers, which encompass 65 percent of total industry sector GHG reductions in China, cost only around $300 billion, or 20 percent of total capital equipment expenditures.

FIGURE 3.24 Capital equipment investment needs in China by intervention tier



Capital expenses can also be disaggregated by subindustry and by technology tier. **FIGURE 3.25** illustrates how overall capital expenses tend to be dominated by certain technologies in certain subindustries, especially equipment to produce clean chemical feedstocks for the chemicals industry, carbon capture equipment in the nonmetallic minerals industry, and equipment for green hydrogen production and combustion in the refining and chemicals industries.

Per unit of GHG abatement delivered by that equipment annually, capital costs increase monotonically in Tiers 1–3, reflecting the fact that tiers were generally ordered from lower to higher levels of technological maturity and cost. Green hydrogen tiers (4a and 4b) are comparable to but slightly cheaper than CCUS (Tier 3) **(FIGURE 3.26)**.

FIGURE 3.25 Capital equipment investment needs in China by subindustry and by intervention tier

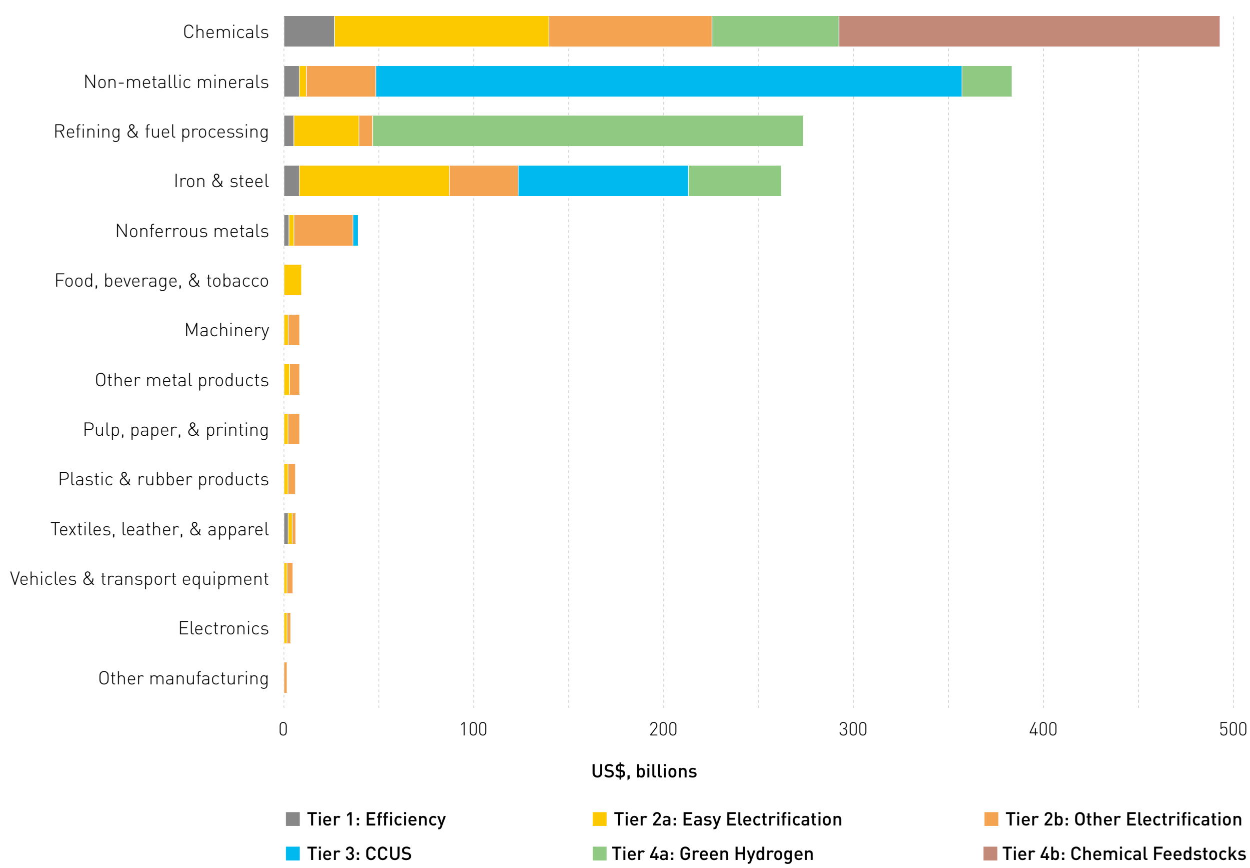
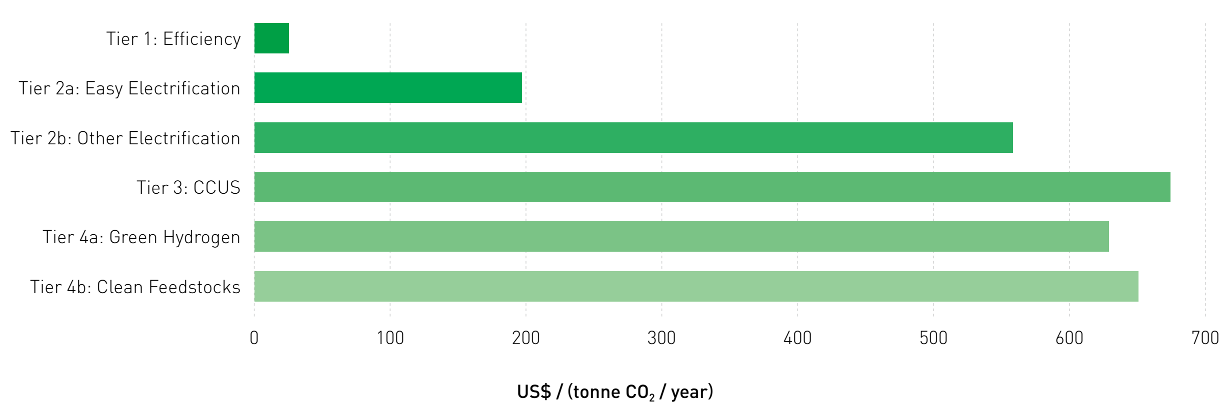


FIGURE 3.26 Required capital investment per unit of GHG abatement in China



Note: The investment needed is calculated per unit of GHG abatement delivered annually by intervention tier.

In Indonesia, which has a smaller chemicals industry but a large nonferrous metals industry, Tier 4b (chemical feedstock) equipment costs are minimal, while high-temperature electrification costs (Tier 2b) are high. Total investment need in the industrial sector is about $122 billion, roughly 9 percent of Indonesia's 2022 GDP **(FIGURE 3.27)**. Nonferrous metals, nonmetallic minerals, and iron and steel account for the vast majority of Indonesia's decarbonization capital equipment investment costs **(FIGURE 3.28)**.

Like China, Indonesia's capital costs per unit of annual abatement increase monotonically across Tiers 1–3, with somewhat lower costs for green hydrogen tiers (Tier 4a and 4b) than other electrification (Tier 2b) or CCUS (Tier 3) **(FIGURE 3.29)**.

FIGURE 3.27 Capital equipment investment needs in Indonesia by technology tier

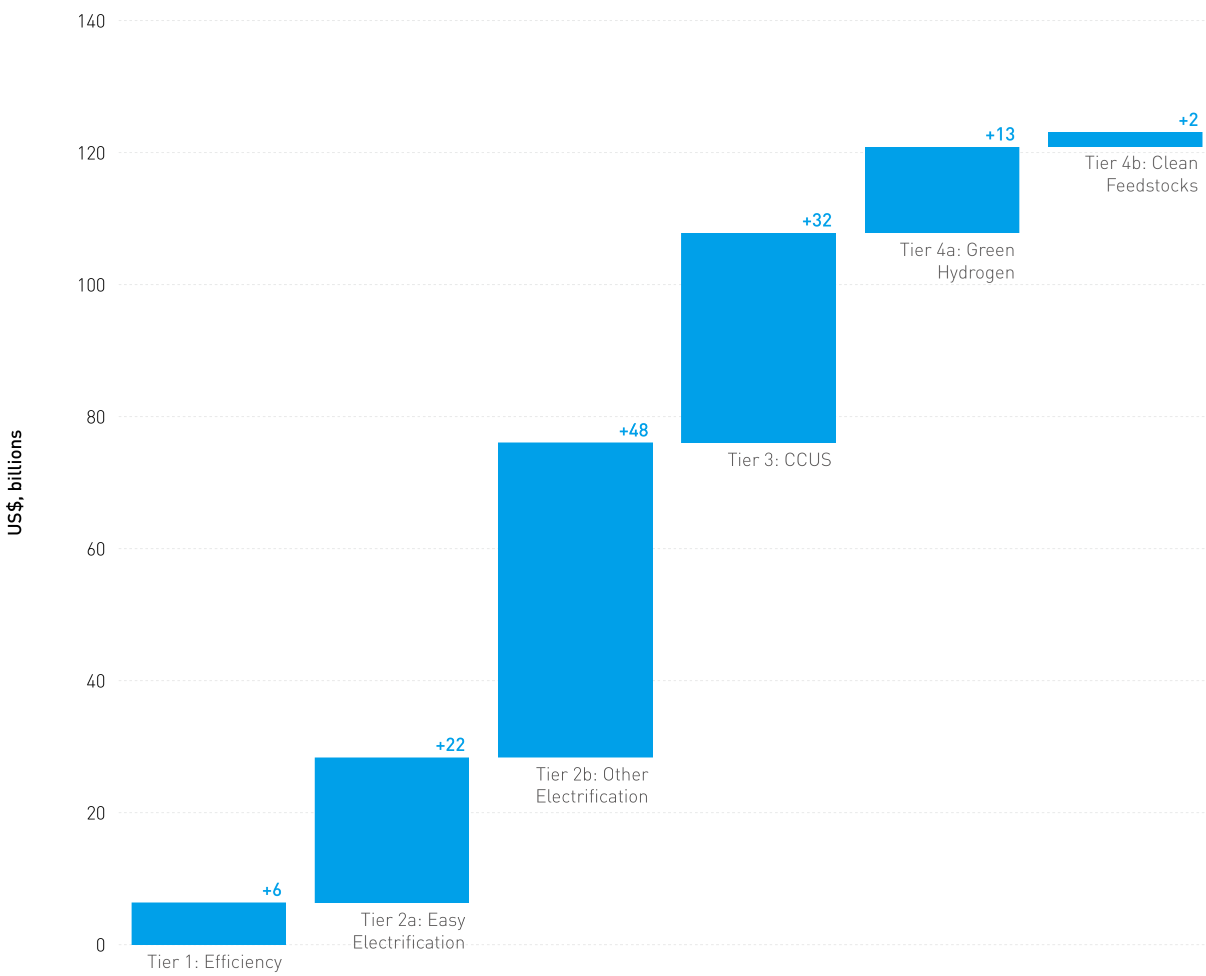


FIGURE 3.28 Capital equipment investment needs in Indonesia by subindustry and by technology tier

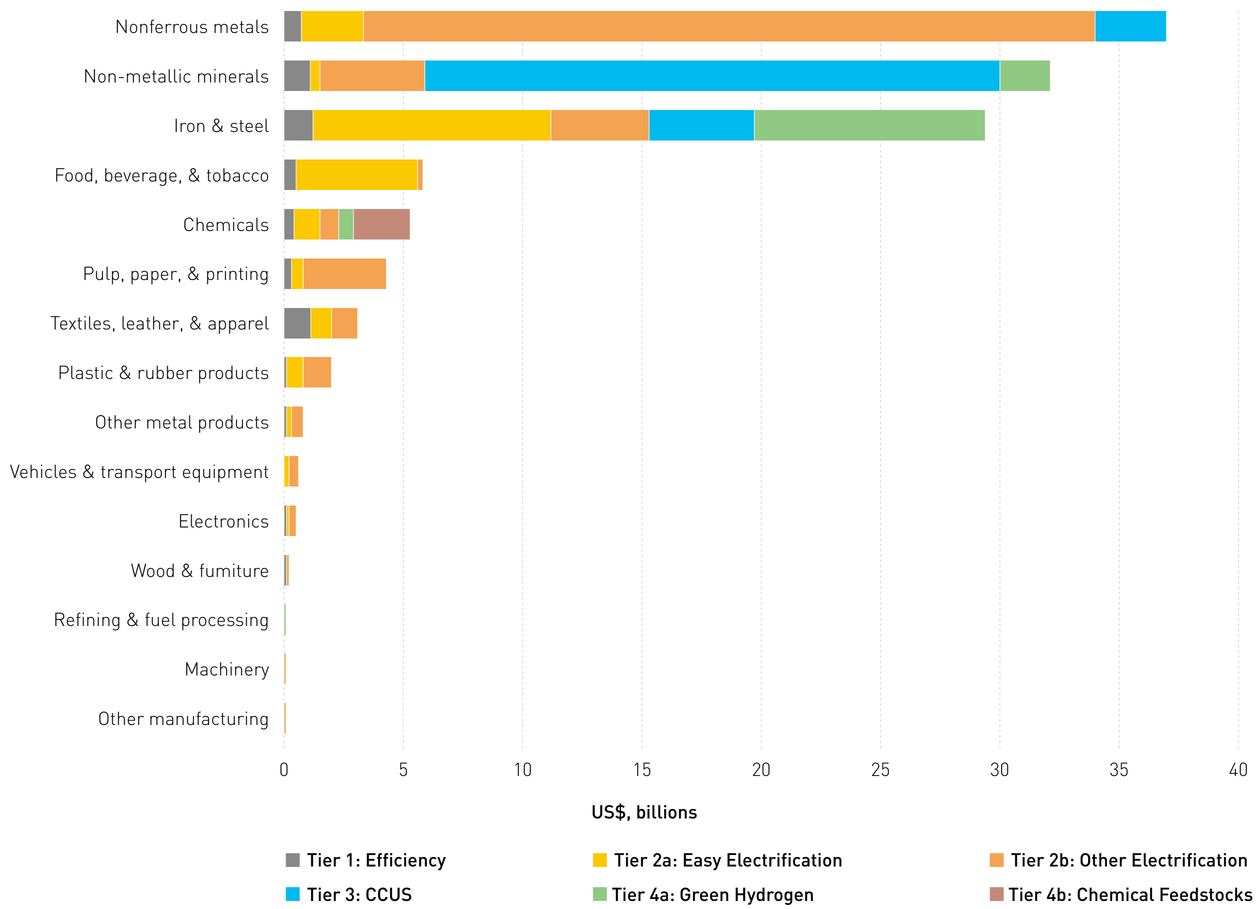
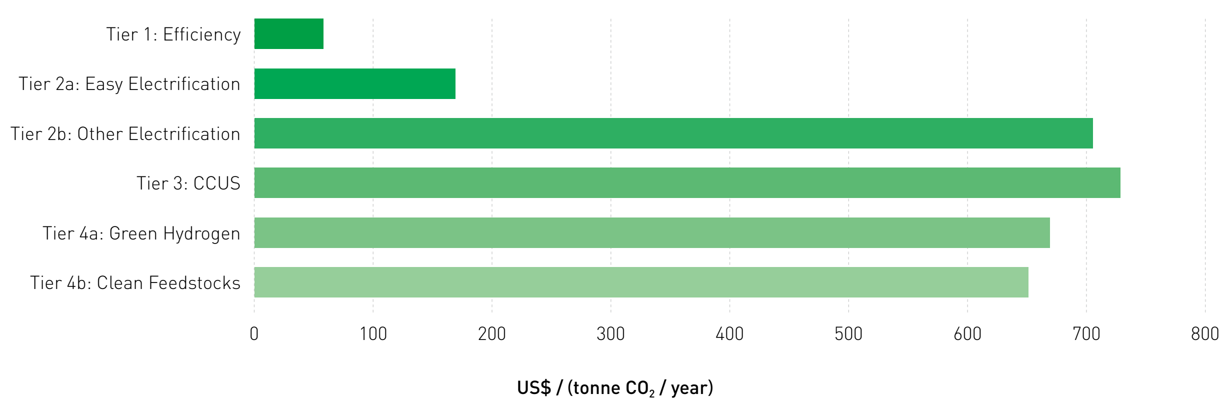


FIGURE 3.29 Required capital investment per unit of GHG abatement in Indonesia by technology tier



Note: The investment needed is calculated per unit of GHG abatement delivered annually by intervention tier.

In Viet Nam, total capital investment needs are also around $120 billion **(FIGURE 3.30)**, about 29 percent of Viet Nam's GDP. The cost is dominated by CCUS (Tier 3) because this is the main strategy used to address emissions from nonmetallic minerals. In terms of energy use and CO_2 emissions, nonmetallic minerals formed Viet Nam's largest industry in 2022 (inclusive of CO_2 from limestone calcination). Energy use requirements are forecast to grow 25 percent in the 2050 BAU scenario. Capital costs are higher as a share of GDP than for China or Indonesia because CCUS is a comparatively capital cost-intensive technology and Viet Nam relies on it more heavily than China or Indonesia. Graphs breaking out Viet Nam's capital needs by subindustry and per unit of abatement (analogous to **(FIGURE 3.25)** and **(FIGURE 3.26)**) appear in Appendix A.

While the nonmetallic minerals industry dominates investment costs for Viet Nam's capital equipment, investment needs are also substantial for iron and steel ($24 billion) as well as nonferrous metals and chemicals (at about $12 billion each) **(FIGURE 3.31)**.

Viet Nam's required capital investment per unit of abatement increases monotonically across the non–green hydrogen tiers (Tiers 1–3), with green H_2 (Tier 4a) and clean feedstocks (4b) being marginally less costly than CCUS (Tier 3) **(FIGURE 3.32)**.

FIGURE 3.30 Capital equipment investment needs in Viet Nam by technology tier

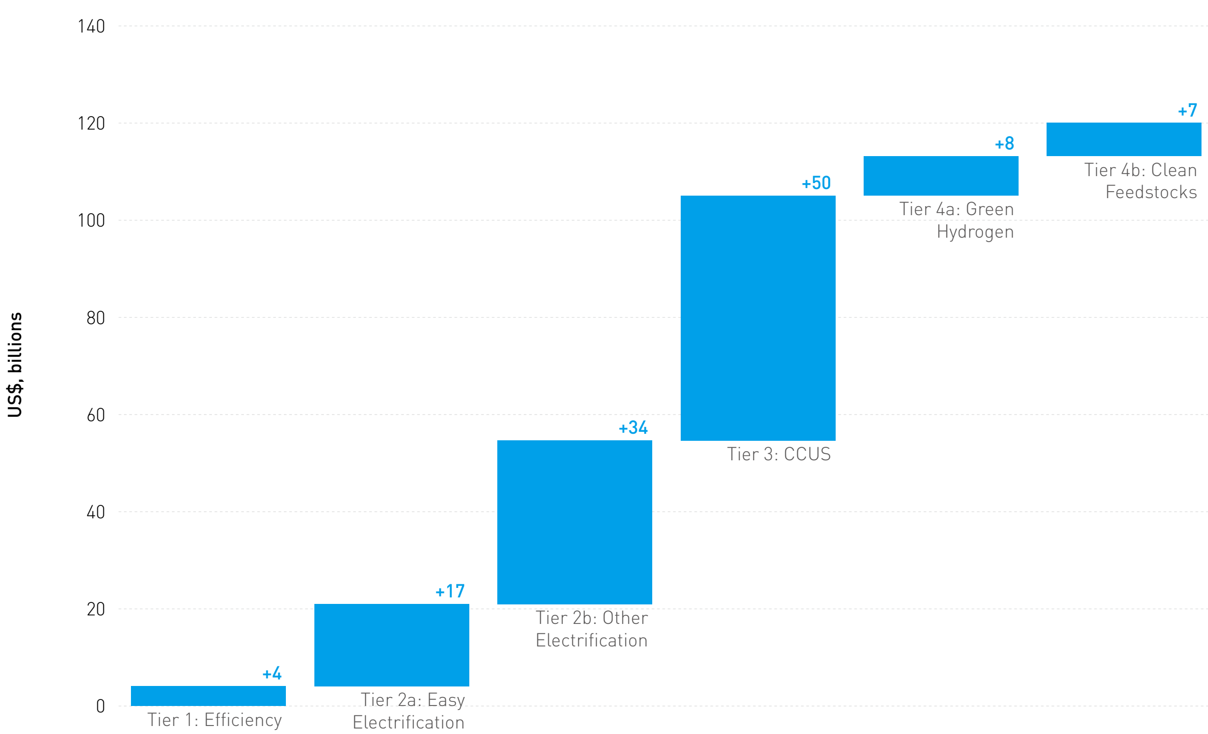


FIGURE 3.31 Capital equipment investment needs in Viet Nam by technology tier

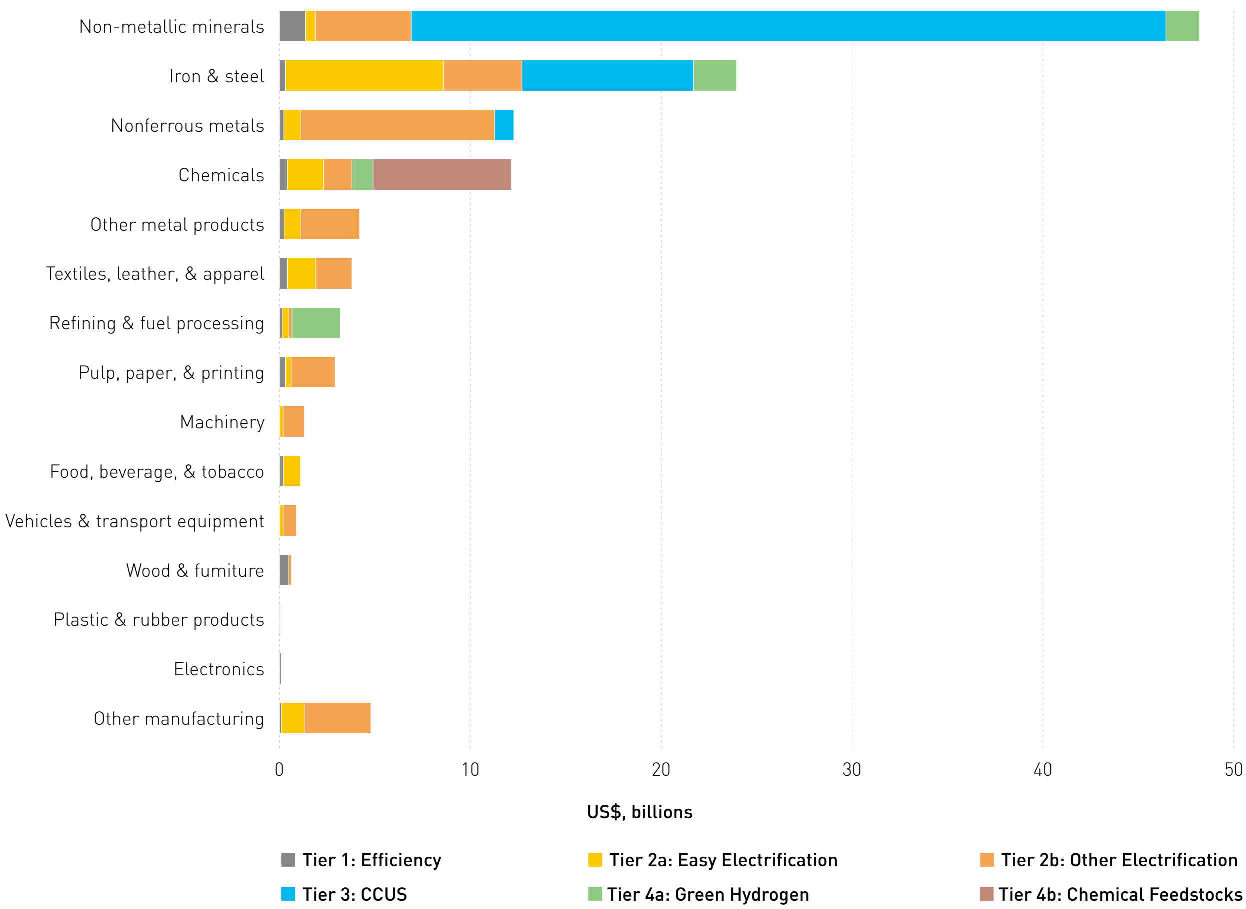
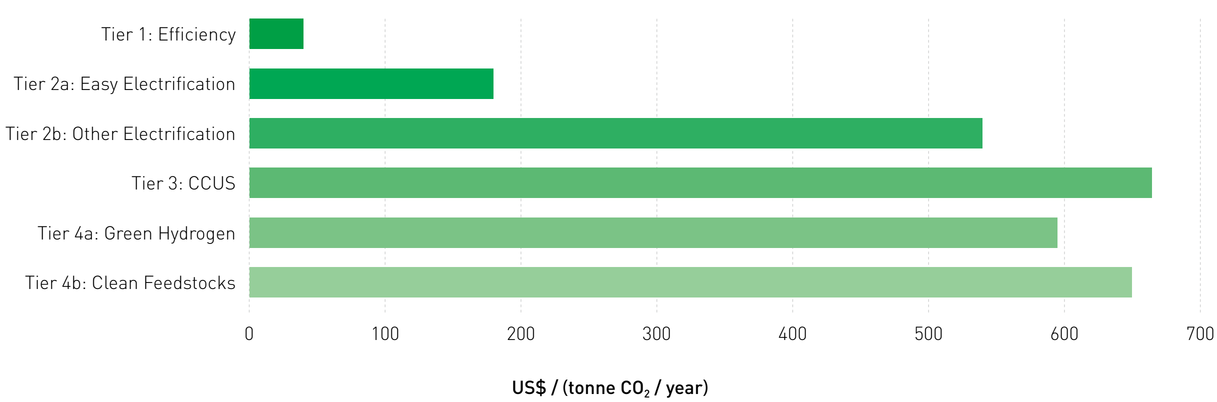


FIGURE 3.32 Required capital investment per unit of GHG abatement in Viet Nam by technology tier



Note: The investment needed is calculated per unit of GHG abatement delivered annually by intervention tier.

Combined capital and energy costs per unit of abatement

Energy and capital costs can be visualized on the same chart by annualizing capital costs over the lifetime of the industrial equipment. This study assumes a 30-year lifetime and 7 percent discount rate (though these can be customized in the model). Graphs showing these costs for each country appear in Appendix A.

The combined annualized costs for each tier can be divided by the amount of greenhouse gas abatement provided by that tier to get a sense of the cost-effectiveness of each tier (TABLE 3.2).

TABLE 3.2 Annual abatement cost of each technological tier (in US$/$tCO_2$) in China, Indonesia, and Viet Nam

	Tier 1: Efficiency	Tier 2a: Easy electrification	Tier 2b: Other electrification	Tier 3: CCUS	Tier 4a: Green H_2	Tier 4b: Clean feedstocks
China: Energy	-225	-39	43	-1	147	105
China: Capital	2	16	45	54	50	52
China: Total	-223	-23	88	53	198	157
Indonesia: Energy	-201	-32	58	-11	287	187
Indonesia: Capital	5	14	57	59	54	52
Indonesia: Total	-196	-19	115	48	341	239
Viet Nam: Energy	-122	-19	61	-8	186	135
Viet Nam: Capital	3	14	44	54	48	52
Viet Nam: Total	-119	-5	104	46	234	187

Note: The calculations use annualized capital costs (assuming 30-year equipment lifetime and a 7 percent discount rate). Negative values indicate savings and positive values indicate costs. Energy values are inclusive of the effects of the modeled scenario's \$50/tCO_2 carbon price, which is why CCUS achieves energy cost savings despite increasing fossil fuel consumption.

This result for China, shown in FIGURE 3.33, indicates that efficiency investments save \$223 per tonne of CO_{2e} abated, Tier 2a electrification saves \$23 per tonne abated, Tier 2b costs \$88/tonne, Tier 3 costs \$53/tonne, Tier 4a costs \$198/tonne, and Tier 4b costs \$157/tonne. Costs per unit abatement for Indonesia (FIGURE 3.34) are similar to China's for some technologies, although Tier

2b electrification is 30 percent more expensive and clean hydrogen strategies are much costlier: Tier 4a is 72 percent more expensive, and Tier 4b's clean feedstocks are 52 percent more expensive. Viet Nam **(FIGURE 3.35)** is broadly similar to China, though Tier 2b electrification and the Tier 4 clean hydrogen strategies are 18 percent to 19 percent more expensive than in China. China's Tier 2b costs per tonne of CO_2 are lower than Viet Nam's Tier 2b costs because China's natural gas and petroleum prices are higher, so displacing these fuels with electricity results in greater savings. China's Tier 4a and 4b costs, which are related to green hydrogen, are lower than costs for the other countries because China has access to cheaper electrolyzer hardware and low-cost renewable energy in its western provinces.

In all three countries, interventions in Tiers 2b, 4a, and 4b (electrification of medium- and high-temperature heat, the deployment of green hydrogen in specific processes, and the use of low-carbon feedstocks) will cause firms' production costs to increase substantially. Therefore, the real-world implementation of these interventions will rely on energy efficiency and emission standards, policies to reduce supply-side costs (e.g., renewables deployment, carbon pricing) and policies to hike demand for low-carbon products (e.g., green public procurement), which are covered in Chapter 5.

FIGURE 3.33 Energy costs and annualized capital investment needs per unit of annual abatement in China

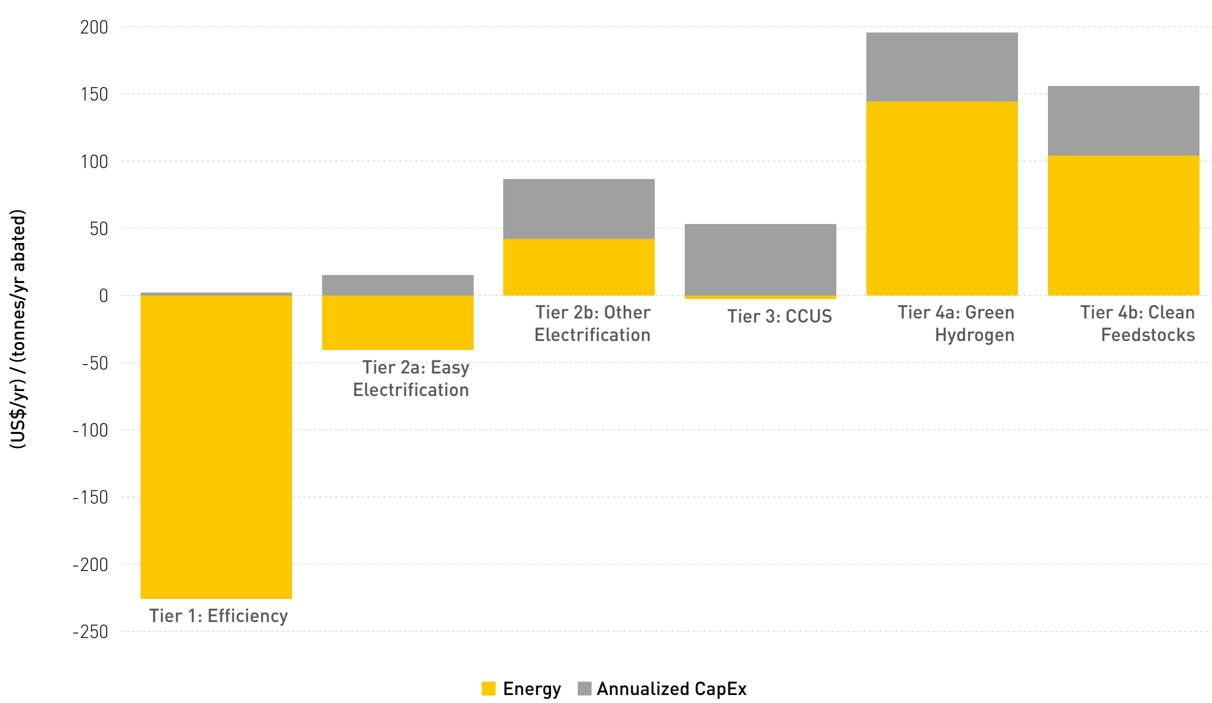


FIGURE 3.34 Energy costs and annualized capital investment needs per unit of annual abatement in Indonesia

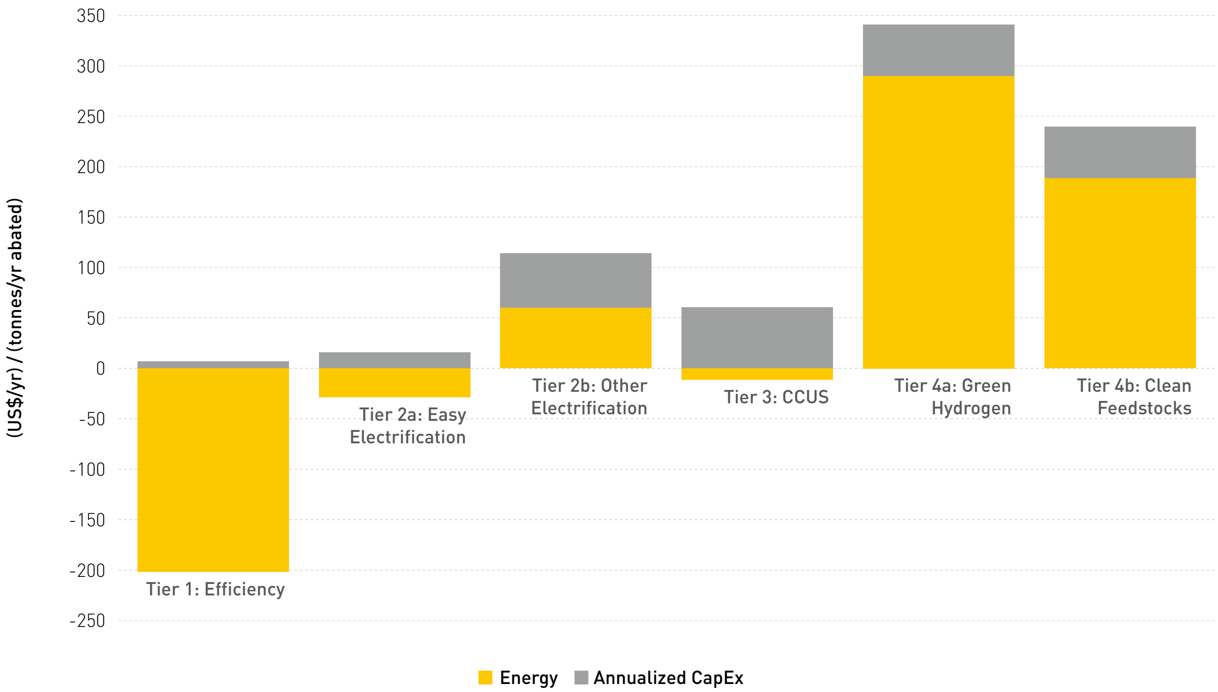
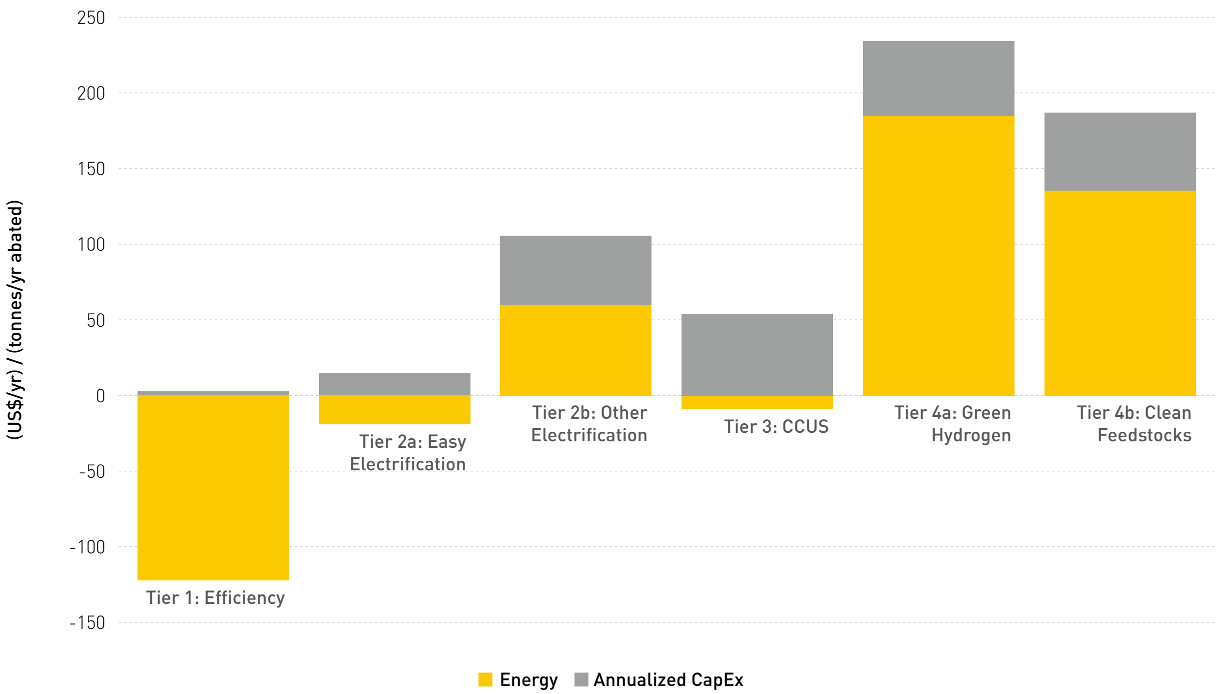


FIGURE 3.35 Energy costs and annualized capital investment needs per unit of annual abatement in Viet Nam



Sensitivity analysis

The computer model used in this study supports sensitivity analysis for a range of variables (energy use, electricity prices, clean hydrogen prices, and carbon prices, among others), as described in Chapter 2. Sensitivity settings can produce hundreds of variants of each graph in this study, so it is necessary to be selective about which sensitivity results to present. Therefore, this section prioritizes illustrating the trade-offs between electricity pricing and carbon pricing because of the relevance of those variables to financing clean industrial development.

Most forms of public and private sector finance require repayment with interest. Therefore, one key to unlocking financing for clean industrial technology is to ensure that clean industry earns a better return—from a combination of lower operating costs and higher revenues—than traditional, polluting manufacturing. There are two ways to reduce this operating cost gap: (1) make cheap, clean electricity more available through the aggressive deployment of renewable energy, and (2) carbon pricing.

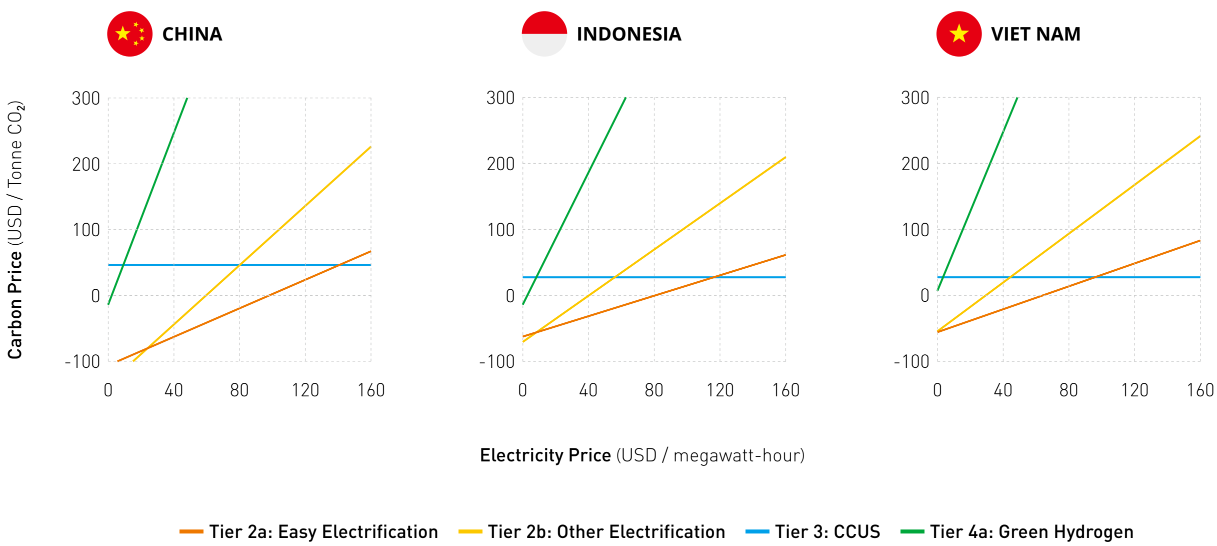
FIGURE 3.36 depicts the combination of electricity and carbon pricing that results in a zero annual energy cost premium for technology Tiers 2a, 2b, 3, and 4a in China, Indonesia, and Viet Nam. (Tier 1 is not shown because efficiency achieves energy cost savings irrespective of the electricity price or carbon price, and Tier 4b is not shown because carbon pricing is not assessed on emissions from feedstocks, which largely occur downstream in the use and the end-of-life of industrial products.)

In China, an electricity price under $80 per megawatt-hour and a carbon price of $50 per tonne of CO_2 are sufficient to make electrification and CCUS cost-competitive with traditional industry. However, green hydrogen combustion would require even cheaper electricity or carbon prices. Exceptionally low- or zero-cost electricity may be available in certain regions and during certain hours of the day, such as sunny or windy hours in western China.

Reducing the cost gap between fossil fuels and clean electricity is critical for industrial decarbonization, and many of our recommendations aim to boost renewable energy generation and make sure industrial firms have access to clean electricity at affordable prices (see Chapters 5 and 6).

In the long term, if operating cost gaps cannot be closed, governments may consider technology-neutral emissions standards, which require industrial firms to cover the costs of cleaner manufacturing. In those cases, firms are likely to pass those costs through to buyers of industrial goods, providing the incremental revenue needed to make the projects financeable (often with minimal increases in the costs faced by individual buyers). Standards can also help position a country as a technological leader and facilitate exports to regions with carbon border adjustment mechanisms, such as the EU.

FIGURE 3.36 Breakeven carbon pricing and electricity cost combinations in China, Indonesia, and Viet Nam



Note: Calculations show price combinations that achieve breakeven annual energy costs for various technologies.

Case Studies of International Industrial Decarbonization

This chapter explores five distinct case studies that pertain to industrial decarbonization in high-emitting sectors. Although global in scope, these case studies contain valuable lessons for developing countries, demonstrating how different funding sources—both private and public—can drive industrial decarbonization efforts.

The first case study examines the decarbonization efforts of a medium-sized steel producer in India. By leveraging both its export-oriented business model and its existing electric arc furnace (EAF) infrastructure and integrated company structure, this steel producer is taking advantage of India's new renewable energy open-access policy to produce India's first "green" steel despite the lack of targeted government support.

The second case study focuses on the hub for steel production in northern Sweden using green hydrogen–powered direct reduction of iron (DRI), while the third case study explores the world's first full-scale carbon capture and storage (CCS) facility in the cement sector, located in Norway. These two case studies emphasize the crucial role of public-private partnerships with significant government support as well as a coordinated expansion of enabling infrastructure, including grid infrastructure, clean power supply, and CO_2 transport and storage systems.

The fourth case study highlights China's rapid deployment of a 100 percent renewable energy–supplied industrial park, enabled through industrial load aggregation and the integration of abundant renewable energy and battery storage.

Finally, the fifth case study investigates various ammonia projects worldwide, demonstrating that renewable ammonia is emerging as a scalable end-use case for green hydrogen, either as fertilizer or as a clean fuel for shipping and power, as exemplified in Saudi Arabia. This case underscores the importance of public infrastructure planning, particularly around ports, pipelines, and power, as well as the necessity for public-private partnerships to make renewable ammonia projects viable.

Case study 1 | Bottom-up decarbonization of India's medium-sized steel producers

India's steel industry, now the world's second largest after China, is undergoing rapid growth driven by infrastructure expansion, industrialization, and rising domestic demand. As with the East Asian region generally, the steel sector has become one of India's most emissions-intensive sectors, contributing roughly 10–12 percent of national greenhouse gas emissions. Recognizing the urgent need for decarbonization, the Indian government is planning major initiatives such as the Rs 15,000 crore ($1.8 billion) Green Steel Mission. In December 2024, India became the first country to officially define "green steel" by introducing the Green Steel Taxonomy **(TABLE 4.1)** (Ministry of Steel, Government of India 2024a). This initiative classifies steel products based on their carbon emissions per tonne of finished steel, setting clear benchmarks for low-carbon steel production.

TABLE 4.1 India's Green Steel Taxonomy

Star rating	Emission intensity (tCO_{2e}/tfs)	Classification
★★★★★	Below 1.6	Ultra-low emissions; highest green rating
★★★★	1.6 – 2.0	Moderate emissions; mid-level green rating
★★★	2.0 – 2.2	Acceptable emissions; minimum green rating
-	Above 2.2	Not classified as green steel

Note: *The taxonomy's thresholds are subject to review every three years to accommodate technological advancements and industry practices. This structured approach is part of India's broader strategy to achieve net-zero emissions by 2070 and to position itself as a leader in green steel production. tCO_{2e}/tfs = tonnes of CO_2 equivalent per tonne of finished steel.*

India's decarbonization efforts provide critical insights into how major developing economies are balancing the dual imperatives of growth and sustainability with limited resources. India's steel industry is characterized by a diverse mix of large, medium, and small enterprises. The private sector accounts for approximately 82 percent of India's total crude steel production, with the remaining 18 percent produced by public sector units like the Steel Authority of India Limited. Within the private sector, large integrated steel producers such as Tata Steel, JSW Steel, and Jindal Steel and Power dominate the market.

Small and medium-sized enterprises, including numerous mini steel plants, collectively account for about 50 percent of India's steel production and employ close to 2 million people. These smaller players are vital for regional employment and cater to more specialized market demand but are often overlooked in government-supported decarbonization policies. Persistent challenges—including low profit margins, limited access to public support and concessional financing, and the inability to achieve the economies of scale necessary to reduce technology costs—constitute a significant barrier to industrial decarbonization by small and medium-sized enterprises in developing countries.

Founded in 1973 and headquartered in Pune, Kalyani Group exemplifies evolving, bottom-up decarbonization efforts. The midsized, family-owned steelmaker has a capacity of 900,000 tonnes (well below industry giants) and specializes in high-grade steel for the automotive and engineering sectors. It pioneered India's first branded green steel, Kalyani FeRRESTA, using renewable energy and recycled scrap. **TABLE 4.2** compares the emissions intensity of India's major steel producers, including Kalyani.

TABLE 4.2 Comparison of annual capacity and emission intensity: Kalyani Group and top Indian steel producers

Company	Crude steel capacity (millions of tonnes per year)	Emissions intensity (tCO_2/tcs)[11]	Category
JSW Steel	28.00	2.36	Large private firm, internationally operating
Tata Steel (India)	21.00	2.32	Large private firm, internationally operating
Steel Authority of India Limited	19.50	2.49	State-owned, major domestic player
Jindal Steel and Power	9.60	2.59	Large private firm, internationally operating
Kalyani Group's FeRRESTA steel	0.25	0.19	Medium-sized private firm

Source: Ministry of Steel, Government of India 2024b.

[11] tCO_2/tcs = tonnes of CO_2 emitted per tonne of crude steel

Kalyani FeRRESTA: A rapid transition driven by European market demand and executed by strong leadership

In 2022, the Kalyani Group launched its first green steel brand, Kalyani FeRRESTA (Saranga and Gupta 2024), through its specialty-steel arm Saarloha Advanced Materials. Saarloha's steel plant, located in Pune, has an annual capacity of 250,000 tonnes. It primarily produces alloy steel–based long products[12] for the automotive, defense, and energy sectors. Notably, 50–70 percent of Saarloha's steel is used in end products exported to Europe and the United States. The green steel initiative, entirely self-financed by Kalyani Group, was driven by growing pressure for decarbonization and demand for low-emissions materials around the world.

The initiative benefited from strong board support and leadership alignment, including the creation of the Green Steel Taskforce by the managing director. Headed by the chief financial officer and composed of product strategists and GHG accounting experts, this taskforce moved swiftly from concept to launch within the same year. Although Saarloha's plant could produce green steel at full capacity, only 50,000 tonnes were produced in 2022; there are plans for gradual increases in production to full capacity in the coming years (Khan 2022).

Leveraging existing technologies and ecosystems: EAF powered by self-generated renewable energy and using scrap from sister company

The company leveraged its existing EAF technology, which already had a lower carbon footprint than traditional blast furnace–basic oxygen furnace (BF-BOF) methods and required no workforce reskilling for the transition to green steel production. To decarbonize the electricity-intensive process, Saarloha invested Rs 4 billion in clean electricity generation, including a 74 megawatt (MW) solar power plant and an 8 MW wind power plant (Gupta 2022). Additionally, all fossil-fuel-based furnaces were electrified and, where fuel was required for processing, biodiesel replaced traditional furnace oil.

When the company's management decided to transition its EAF operations to 100 percent renewable energy, it consulted with renewable energy developers and power sector experts to evaluate available options. India's Green Energy Open Access (GEOA) Rules (2022) enabled commercial and industrial consumers to procure renewable electricity directly from renewable energy developers **(BOX 4.1)**. However, in Maharashtra state, where the steel plant is located, the initial implementation of the policy included a 30 MW cap on open-access purchases, primarily due to constraints in grid and distribution infrastructure.

[12] Long products refer to rolled steel shapes with a length significantly greater than their width or thickness. Common long products are steel bars, rods, rails, beams, etc.

BOX 4.1 **Power sector policy milestone enables 100 percent renewable energy: India's Green Energy Open Access (GEOA) Rules, 2022**

India's GEOA Rules, introduced in 2022 under the Electricity Act, mark a pivotal step toward expanding renewable energy access for commercial and industrial consumers. By lowering the eligibility threshold from 1 MW to 100 kW, the policy would allow micro, small, and medium enterprises to participate as well.

The GEOA framework has helped accelerate market development, with the open-access renewable energy market reaching 18.7 gigawatts by FY2024 and annual growth exceeding 45 percent since FY2022. It also introduces regulatory improvements such as time-bound approvals, banking provisions, and removal of certain surcharges to lower transaction costs.

To achieve economic viability at the desired scale, Saarloha opted to self-develop both solar and wind energy assets, despite its lack of experience in renewable project development. Land constraints at the plant site meant the company had to establish renewable facilities elsewhere in Maharashtra state, and wheel[13] via grid to supply the steel plant. One of the company's most capable operations managers was assigned to lead the development. That manager is said to have navigated dozens of administrative approvals and signatures required by the many layers of government and utility agencies.[14]

The company bridged the remaining clean energy needs using their local utility's Green Tariff program, which allowed it to purchase renewable electricity directly from the utility at a premium over the standard industrial rate. This combination of self-generation and green tariff procurement has enabled the company to achieve 100 percent clean electricity consumption for its steelmaking operations.

Much of Saarloha's green steel production goes directly to Bharat Forge, a sister company within the Kalyani Group that processes the steel into finished automotive components for export. This close integration between Saarloha and Bharat Forge facilitates efficient scrap collection and sorting at the source and has enabled Saarloha to increase the scrap content in its green steel to 70 percent, replacing more carbon-intensive raw materials such as pig iron and direct reduced iron.

These combined efforts slashed the carbon intensity of FeRRESTA crude steel to 0.19 tonnes of CO_2-equivalent (tCO_{2e}) per tonne of steel, much lower than the 2.5–2.85 tCO_{2e} per tonne for conventional BF-BOF steel in India. Customers purchasing FeRRESTA steel products receive Green Steel Certificates, verified by a third-party agency, which they can use to claim reductions in their Scope 3 emissions.

[13] This refers to transmitting electricity from one system to another through a third-party interconnecting network.

[14] World Bank interview with Kalyani Steel in Pune, Maharashtra, October 2024.

The challenges and strategies of securing a green premium

But the green steel initiative did not come without cost and productivity challenges. Higher prices for steel scrap and biodiesel, along with longer production times to accommodate scrap processing, raised input costs and reduced output. Nevertheless, the shift to solar power proved cost-effective, with solar electricity priced at Rs 6,000 (around $68) per megawatt-hour (MWh), compared to Rs 8,500 (around $91) per MWh for coal-dominated grid electricity. Consequently, FeRRESTA remained competitive in the high-grade alloy steel segment,[15] although it struggles to compete with BF-BOF-produced crude steel, which carries no green premium, especially in India's cost-sensitive domestic market.

Saarloha's target market therefore extends beyond India, focusing on export-oriented domestic companies or subsidiaries of global companies based in India that purchase green steel to manufacture products for international markets. In particular, the wind energy sector and electric vehicle manufacturers in Europe have been early adopters of green steel. Saarloha further expects that the EU's Carbon Border Adjustment Mechanism (CBAM), set to take effect in January 2026, will level the playing field and enhance the cost-competitiveness of green steel exports. As such, the use of green steel therefore ensures business continuity for Saarloha's clients, shielding them from emerging carbon duties in global markets.

The need for policy support to drive domestic demand and innovation

Furthermore, the company is advocating for policy measures to stimulate domestic demand for green steel in India, such as mandating the use of green steel in government projects. With approximately 50 percent of India's steel produced through electric arc or induction furnace methods, this sector presents a significant opportunity to transition to green steel via the adoption of renewable electricity. Saarloha is also exploring the use of green hydrogen in steel production and has installed two electrolyzers at its research and development facilities to produce it. At present, the high cost of green hydrogen makes it unviable for commercial steel production.

Lessons for developing countries

The Indian case illustrates how a medium-sized steel company in a developing country can strategically navigate the emerging and complex landscape of green steel. Despite operating with fewer resources than industry giants, Saarloha leveraged its core strengths—specialization in high-grade alloy steels for export markets with its existing EAF infrastructure and integrated production facilities—to pioneer green steel products.

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[15] High-grade alloy steel is made in smaller batches that undergo further refinement and use additional metals, making EAF more cost-effective than BF for such production. BF's larger batch sizes and economies of scale make it more competitive for crude steel.

In the absence of targeted public support, smaller firms like Saarloha have nonetheless taken the initiative to decarbonize, aiming to serve higher-end buyers in foreign markets where strong policies and carbon pricing create incentives to procure green steel (i.e., Germany). This case underscores the spillover effect of European climate policy on emerging markets. It also highlights the importance of enabling smaller firms in developing countries to build decarbonization capacity, as capacity bolsters competitiveness and international industrial collaboration.

The India case also shows that renewable energy procurement policies enable industries to take radical steps to reach 100 percent clean power. And by meeting their own energy demands with cheaper clean sources, firms create broader economic co-benefits, like boosting the supply of renewable energy and helping the grid decarbonize. More and more firms in India are adopting these practices today, and power market reforms will further strengthen this virtuous cycle.

At the same time, Saarloha's experience reflects the challenges smaller players face, particularly in securing a green premium and accessing the policy and financial support needed to scale up innovations, especially for early-stage technologies such as green hydrogen.

The India case offers valuable lessons: medium-sized firms, through forward-looking leadership and strategic use of their business ecosystems, can be agile innovators in the sustainability transition. The broader success of the steel industry will depend, however, on a supportive policy environment, market recognition of low-carbon products, and firms that align decarbonization goals with their core business strategies.

Case study 2 | Northern Sweden's green industrial hub

Northern Sweden is rapidly emerging as a global leader in green industrial transformation. Leveraging its rich natural resources and abundant renewable energy, the region is spearheading a shift toward industrial decarbonization. Traditionally focused on mining and forestry, it is now becoming synonymous with green hydrogen, fossil-free steel, and clean energy ecosystems. The scale of investment, the sophistication of stakeholder coordination, and the speed of development are unprecedented. Projects like Stegra and HYBRIT (hydrogen breakthrough ironmaking technology) that produce zero-carbon steel using hydrogen DRI are not only reshaping the industrial landscape but also testing the limits of infrastructure, energy systems, and workforce capacity.

Energy and natural resource foundations

Northern Sweden is uniquely attractive for green industrial investment for several reasons, chief among them its abundant renewable energy and iron ore endowments (Vendt and Wallmark 2022):

- **Abundant renewable energy:** Northern Sweden generates more than 80 percent of the country's hydroelectric capacity, providing stable, fossil-free electricity. The region is also rapidly expanding onshore wind capacity and is evaluating possibilities for offshore wind capacity to support the energy needs of large-scale green industrial projects.
- **Low electricity cost:** The abundance of renewables has produced some of Europe's lowest industrial electricity prices. When Stegra and HYBRIT launched their projects, power purchase agreements signed by companies were typically in the range of €30–35/MWh ($34–39/MWh), greatly undercutting continental Europe.
- **High-grade iron ore:** Northern Sweden possesses Europe's largest high-grade iron ore reserves, mostly in Kiruna, Gällivare, and Malmberget and primarily operated by LKAB. These deposits supply over 80 percent of the EU's iron ore, with annual output above 26 million tonnes and iron content averaging 60–70 percent—offering a key feedstock advantage for hydrogen-based green steel.
- **Strategic location:** Proximity to key European markets and planned cross-border hydrogen pipelines (Nordic Hydrogen Route) further enhance northern Sweden's industrial appeal.

Strong policy directionality and high carbon pricing create an enabling environment

Sweden's ambitious climate targets and supportive regulatory framework have created powerful incentives for industrial decarbonization. Predictable policy, high carbon pricing, financial support, and an innovation ecosystem generate strong market signals that favor early movers, helping anchor major projects like Stegra's green steel plant and the HYBRIT initiative in northern Sweden.

- **Clear directionality:** Sweden has committed to achieving net-zero greenhouse gas emissions by 2045, one of the earliest national targets globally. These are enshrined in its legally binding Climate Policy Framework adopted in 2017, after the Paris Agreement was reached in 2015. The Climate Policy Framework provided clear directionality for the Swedish iron and steel industry toward deep decarbonization, while the Fossil Free Sweden initiative formalized coordination between businesses and policy makers. By working with companies, industries, municipalities, and regions, Fossil Free Sweden produces roadmaps that include policy recommendations to speed the transition to a strong, fossil-free industrial sector.

- **Strong carbon price:** The Swedish steel sector falls under the European Union's Emissions Trading System (EU ETS) with an average carbon price of €80–90/tonne. This strengthens the competitiveness of low-carbon industrial products like green steel and renewable hydrogen.
- **Targeted financial and regulatory support:** The government offers tax incentives for clean technologies, direct subsidies through programs like Industriklivet (Industrial Leap), and streamlined permitting for renewable and hydrogen projects.
- **Innovation ecosystem:** Strong public-private collaboration, access to world-class research institutions, and a tradition of industrial innovation create a stable, dynamic environment that attracts large-scale green investments.

Financing zero-carbon steel: Public leadership and private sector momentum

The Swedish government and the EU have played key roles in financing and de-risking this transition through multiple channels (Tucker et al. 2024). The scale of public sector investment is massive, involving diverse instruments and public sector entities. Examples from the green steel sector's two flagship projects, HYBRIT and Stegra, are outlined in TABLE 4.3.

- **Public sector–led HYBRIT:** Launched by the Swedish steelmaker SSAB together with the state-owned mining company LKAB and power utility Vattenfall, HYBRIT initially focused on research into the technical and market aspects of green steel in 2016. In 2020, it opened a pilot plant for hydrogen-based DRI steelmaking and set ambitious investment plans: LKAB announced a SKr 400 billion ($40 billion) investment to shift from iron ore to DRI production, and SSAB committed SKr 45 billion ($4.5 billion) for steel decarbonization.
- **Private sector-led Stegra:** Founded in 2020 by Harald Mix and Vargas Holding, Stegra (formerly H_2 Green Steel) is a start-up aiming to produce 2.5 million tonnes per year of green hydrogen–based DRI steelmaking. The company secured major offtake agreements early, selling 1.5 of its initial 2.5 million tonnes in advance. Production is scheduled to start in 2026 with a gradual increase in capacity to 5 million tonnes per year by 2030.

Stegra shows both scale and sophistication in its financing schemes (TABLE 4.4). To achieve its planned Phase I production of 2.5 million tonnes per year of near-zero carbon steel, Stegra has secured total financing of approximately €6.5 billion (around $7 billion). Private investors provided a critical early capital base, contributing €2.1 billion (around $2.3 billion) in equity across multiple funding rounds. The public sector institutions have played an even larger role, de-risking and financing over 60 percent of the project through loans, guarantees, and grants. This blended financing structure demonstrates strategic public-private alliances, where state-backed financial instruments unlock significant private sector investment to drive industrial decarbonization at scale.

TABLE 4.3 Swedish public sector investment instruments for green steel projects

Public finance instrument	Entity	Support provided	Beneficiary projects
Industrial leap subsidies	Swedish Energy Agency	• SKr 30 million (about $2.8 million) grant for early technical work at Stegra • SKr 3.1 billion (about $285 million) grant approved for HYBRIT	HYBRIT, Stegra
Green credit guarantees	Swedish National Debt Office (SNDO)	• Guarantee covering 80 percent of a €1.2 billion (about $1.3 billion) loan to lower financing costs	Stegra
Export credit support	Swedish Export Credit Agency (SECA) + Euler Hermes (Trade credit insurance)	• Part of €3.5 billion (about $3.8 billion) debt package backed by export guarantees	Stegra
Financial policy adjustments	Swedish Government (Owner of LKAB)	• Raised net debt/equity limit to <0.6 • Reduced targeted return on equity from 12 percent to 9 percent to enable green investments without subsidies	LKAB transformation program
European Investment Bank loans	EIB (EU's climate bank)	• €750 million (about $815 million) senior debt funding for green steel plant	Stegra
EU Innovation Fund grants	European Commission	• €143 million (about $155 million) grant to HYBRIT • Grant share in €3.6 billion (about $3.9 billion) fund pool to Stegra	HYBRIT, Stegra

TABLE 4.4 Financing structure of Strega

Source	Amount	Nature of financing
Private sector	€2.1 billion (about $2.3 billion)	Equity investment (private placement, multiple rounds)
Public sector (debt + guarantees)	€3.8 billion (about $4.1 billion)	Loans supported by state guarantees (Swedish National Debt Office, Swedish Export Credit Agency, and European Investment Bank, among others)
Public sector (grants)	€250 million (about $270 million)	Nonrepayable grants (EU Innovation Fund, Swedish Energy Agency)

Energy infrastructure: A critical enabler—and a bottleneck

The decarbonization of heavy industry in northern Sweden hinges on the rapid development of energy infrastructure. In fact, the region is already facing infrastructure bottlenecks, with urgent needs for rapid renewable energy expansion, accelerated grid reinforcements, and coordinated hydrogen network development to keep pace with the explosive growth in electricity demand (BOX 4.2).

BOX 4.2 **From abundance to bottleneck: How infrastructure shapes the pace and scale of industrial decarbonization in northern Sweden**

When HYBRIT and Stegra launched their projects in Northern Sweden between 2016 and 2020, they benefited from an electricity oversupply of 20–25 terawatt-hours (TWh), low prices, and a strong, over-dimensioned grid. Around 20 TWh of new onshore wind capacity was also in the pipeline. Early movers in the region could expect to sign long-term power purchase agreements at around €30–35/MWh for their first-phase operations to 2035, with no major costs for balancing or grid upgrades needed.

The balance shifted after 2018, when industrial electricity demand in Northern Sweden surged with expansion of industrial decarbonization projects. HYBRIT and LKAB's 2045 plan added another 45–55 TWh of future demand, while multiple new electrofuel plants, fertilizer factories, and data centers entered the market. National electricity demand projections doubled from 150 TWh in 2020 to nearly 300 TWh by 2045. This has also meant that expected future power prices have gone up. Several later-stage projects were withdrawn due to the inability to secure affordable and reliable power in the region but also because of uncertain market development for green commodities.

For future expansions, the lack of grid capacity has become a critical bottleneck. In the case of LKAB's green iron production in Kiruna, discussions have emerged over who should finance the necessary grid investments—the company or the public. Swedish state-owned TSO initially classified the grid expansion investment as a company-specific need, which added substantial costs to LKAB's investment plans. LKAB's green iron expansion is delayed until sufficient electricity access can be guaranteed.

- **Renewable energy expansion:** Northern Sweden's abundant hydropower, combined with major new wind projects, underpins its appeal for green industrial investment. Public utilities like Vattenfall and Skellefteå Kraft are expanding capacity rapidly. Flagship projects include the Markbygden Wind Farm, set to reach 4,000 MW and generate up to 12 TWh annually, equivalent to around 8 percent of Sweden's electricity demand. Overall, renewable output in the north is expected to more than double by 2045.
- **Grid reinforcements:** To accommodate massive new industrial loads, Svenska Kraftnät is investing heavily under its 2024–2033 Grid Development Plan. This includes more than 20 new transmission projects in northern Sweden (SE1 region), major cross-border upgrades like the Aurora Line to Finland, and adoption of smart-grid technologies (e.g., dynamic line

rating, power flow control). It is estimated that the region's grid hosting capacity must triple, or even increase sixfold, by 2050 to support announced decarbonization projects.[16]

- **Hydrogen infrastructure integration:** Northern Sweden is pioneering the integrated development of electricity and hydrogen networks. The Nordic Hydrogen Route will link production hubs like Boden-Luleå to industrial users across Sweden and Finland. Stegra's project alone will house one of the world's largest electrolyzers (over 700 MW capacity), directly tied to green steel production (LTU CH2ESS 2025).

Workforce and social challenges

Northern Sweden's green industrial boom is driving strong demand for skilled labor, creating workforce shortages across sectors such as engineering, construction, and energy systems (Milne 2024). Companies like Stegra, Grupo Fertiberia, and HYBRIT face mounting competition for talent, straining local education systems and infrastructure. At the same time, large-scale renewable energy and industrial developments are encroaching on traditional reindeer-grazing lands managed by the Indigenous Sámi communities. Expansion of wind farms, mining, and transmission networks presents challenges to land use, cultural preservation, and local livelihoods (Dini and Tramonte 2024). As northern Sweden advances its green transition, aligning industrial expansion with workforce readiness and local stakeholder engagement will be essential to support inclusive and sustainable development.

Lessons for developing countries

Northern Sweden offers one of the most compelling real-world laboratories for understanding how industrial decarbonization can happen at scale—and what it takes to make it sustainable. First, it demonstrates that large-scale clean hydrogen-based DRI steelmaking is technically feasible, and that, with appropriate financial and infrastructural support, a viable business model can be established in practice.

The Swedish case also highlights that industrial decarbonization hinges on the synchronized expansion of grid infrastructure and clean power supply, requiring close and proactive coordination between the power and industrial sectors.

The success of industrial decarbonization depends on a high carbon price, strong political support, environmentally conscious investors, and end-product buyers, along with strong public-private partnerships, robust R&D ecosystems, and a skilled workforce.

[16] Guest contribution by Max Ahman, Lund University

Case study 3 | Full-scale zero-carbon cement in Norway

Heidelberg Materials' cement plant in Brevik, Norway, is home to the world's first full-scale carbon capture and storage (CCS) facility in the cement industry **(FIGURE 4.1)**. This project is a cornerstone of Norway's "Longship" initiative, which integrates CO_2 capture at industrial sites with transportation and permanent storage in the North Sea. The Brevik CCS plant utilizes on-site waste heat to capture about 400,000 tonnes of CO_2 per year (roughly 50 percent of the plant's emissions) and then transports it by ship to the Northern Lights CO_2 storage hub on Norway's west coast (Heidelberg n.d.a).

FIGURE 4.1 Heidelberg Materials CCS project in Brevik, Norway

Photo: Hongyou Lu.

Public and private investment partnership

The Brevik CCS project relies on government investment. Two-thirds of the total cost (about NKr 16.8 billion of NKr 25.1 billion, or \$1.88 billion of \$2.82 billion) is covered by direct subsidies to Heidelberg Materials (capture) and Northern Lights (transport and storage) (Heidelberg n.d.a, n.d.b). For the capture portion of the project, Heidelberg Materials covers the remaining capital and operational costs not subsidized by the state. The company's financial commitment was bolstered by its corporate climate strategy (aiming for carbon-neutral concrete by 2050) and years of internal R&D on CCS technology.

Northern Lights, a joint venture of Equinor, Shell, and TotalEnergies, covers the unsubsidized CO_2 transportation and storage costs. Northern Lights leaned heavily on state support to co-finance the development of CO_2 ships, an onshore terminal, and an offshore CO_2 storage reservoir (Northern Lights 2025). This public-private risk-sharing model was crucial: industrial stakeholders invested capital and expertise, while the government de-risked the venture with funding and guarantees.

Additionally, Norway participates in the EU ETS and imposes its own carbon tax for sectors outside the ETS. But even Norway's high carbon price is still below the cost, per tonne, of first-of-a-kind carbon capture. Thus, carbon pricing alone could not finance the project, although it did signal long-term economic value in CO_2 reduction, complementing the direct subsidies.

Stakeholder, technological, and regulatory readiness

High-level political commitment and aligned stakeholders have been instrumental from the outset in advancing this project. The Norwegian government has treated CCS as a strategic climate initiative for years. Gassonova SF was developed as a Norwegian state enterprise in 2005 under the Ministry of Energy, dedicated to advancing CCS technologies (Gassnova n.d.). On the industry side, Heidelberg Materials spent over two decades developing the CCS project. Technological readiness, embodied by Aker Carbon Capture's proven post-combustion amine technology, also played an important role in aligning stakeholders. All parties—the government, Heidelberg, and Aker—shared a "first-mover" mindset, accepting the higher risks of a pioneering project in exchange for real-world experience. This championing of a public-private endeavor created a united front to propel the project over the expected hurdles.

Furthermore, Norway's robust regulatory framework for CCS eased stakeholder concerns. The country's decades of offshore CO_2 storage experience in the Sleipner field meant clear, long-established regulations on CO_2 transport and storage, reducing project risk. The government took on long-term liability for stored CO_2 under international agreements, removing a major uncertainty for the private actors. Finally, broad support for climate action among the Norwegian public helped the project clear hurdles related to community buy-in that industrial projects often face.

Creating market demand and bridging the cost gap

The value proposition of Brevik's CCS project lies in the creation of future market demand for low-carbon cement. Heidelberg Materials has branded the cement produced with carbon capture as “evoZero,” marketed as the world’s first net-zero concrete solution. Supported by policies such as green procurement, green public infrastructure projects, and certification systems that value CO_2 reductions, Heidelberg expects that customers will pay a “green premium” in the future.

In the interim, direct subsidies from the Norwegian government will keep the project afloat, covering the costs of CO_2 capture, transport, and storage. This can be seen as a form of contract-for-difference or output-based aid: Heidelberg builds and operates the CCS facility, and the government helps protect against losses by offsetting additional operating costs. In return, the government expects knowledge spillovers and cost reductions that will benefit other sectors of the economy.

Meanwhile, the Northern Lights joint venture has agreed to accept and permanently store the Brevik CO_2. While not a commercial buyer in the traditional sense, Northern Lights provides a guaranteed service for the captured carbon, underwritten by the government in the demonstration phase. As the Northern Lights system opens to other customers (e.g., agreements signed with Yara and Ørsted), it plans to charge fees for CO_2 storage. This points to a future “storage-as-a-service” model to handle CO_2 from various emitters and countries. For the Brevik project, as an early part of an integrated CO_2 network, its captured carbon has a secure destination, effectively de-risking the “storage/outlet” side of the equation.

Timeline and execution challenges

The Brevik CCS project progressed through a series of preparation and execution milestones over nearly two decades. The timeline was as follows (Heidelberg Materials n.d.b).

- **2005:** Full-scale desk study
- **2011:** Pre-engineering
- **2013:** Project initiation
- **2014:** Technology testing
- **2016:** Concept and feasibility studies
- **2018:** Front-end engineering design (FEED) study
- **2019:** Government approval
- **2021:** Construction
- **2025:** Commissioning

Implementing the Brevik project presented several technical, financial, and regulatory challenges. Retrofitting CCS onto an existing cement plant involves dusty flue gases, variable process flows, and limited space—all of which necessitates dedicated and precise engineering. The project team had to install massive equipment (e.g., absorber columns, refrigeration units for CO_2 liquefaction, storage tanks) on a brownfield site. Ensuring worker safety and avoiding interference with cement production was critical. Being the first full-scale CCS project in the cement industry, there has been a learning curve for everything from engineering to operation. The project team had to incorporate contingency plans and flexibility to learn by doing and troubleshoot unforeseen issues. The long project horizon (20 years) requires sustained commitment from all parties and cost management. In addition, the project had to secure various permits for CO_2 capture, approvals for CO_2 transportation, as well as alignment with Norway's regulations and international law for offshore CO_2 storage.

Lessons for developing countries

The Brevik CCS project shows that, while CCS is costly and complex, persistent public-private alignment can deliver world-first projects. Specifically, the project shows that:

- **Strong government leadership is crucial.** Large-scale CCS projects require committed government support. Government can act as an enabler, providing policy direction, funding, and institutional support.
- **Public-private partnerships and funding models are necessary.** The Brevik CCS project relied on financial support from the government, while private companies contributed capital, operational costs, and technical expertise.
- **Integrated value-chain planning is required.** The Longship project supported not just carbon capture but also CO_2 transport and storage. For countries that may not have proper geological CO_2 storage capacity, Norway's Northern Lights provides an example where it is open to CO_2 from various countries, providing storage as a service.
- **Technical know-how and an experienced workforce are the backbone of clean industrial projects.** Norway has decades of experiences in CCS technologies and engineering practices. This shows the importance of developing experienced technical institutions and workforce know-how to design, test, and build CCS projects.
- **Regulatory frameworks and institutional capacity are needed.** Norway is one of the "early movers" in establishing an enabling regulatory environment for CCS projects, providing rules and protocols for CO_2 monitoring and verification, CO_2 transportation and storage, and liability frameworks. The experiences and lessons learned can help other countries looking to develop similar regulatory expertise and frameworks.

The Heidelberg Materials Brevik CCS venture illustrates how political will, financial innovation, stakeholder alignment, and technical expertise can combine to realize a groundbreaking climate project. For developing nations, the case highlights that, while CCS projects are complex and capital-intensive, they can be pursued with strategic public-private partnerships, innovative financing models, technical and workforce capacity, and a strong vision for long-term sustainable development.

Case study 4 | Zero-carbon industrial parks in China

Industrial clusters, or parks, are powerful enablers of the clean energy transition. By co-locating production facilities with shared infrastructure for energy and logistics, such clusters can help reduce energy costs by providing economies of scale, sharing infrastructure, improving operational efficiency, optimizing energy systems, and allocating risks. They also aggregate energy demand to enable more cost-effective investments in clean energy, including renewable energy and green hydrogen production. These advances can reduce the green premium for low-carbon products and make clean energy more accessible for industrial users (World Economic Forum 2025). A unified vision at the cluster level is critical for realizing these benefits. It involves strong governance frameworks, transparent data sharing, and robust public-private collaboration (World Economic Forum 2025).

Industrial clusters also support streamlined emissions accounting and certification by enabling co-located supply chain activities and consolidated power purchase agreements. These features can help products qualify for green public procurement programs and enter low-carbon global markets (World Economic Forum 2025).

Industrial parks facilitate resource aggregation and emissions reporting

One exemplary case is the Ordos-Envision Net-Zero Industrial Park in Inner Mongolia, China. Jointly developed by Envision Group and the Inner Mongolia government, this 73 square-kilometer park integrates renewable energy generation, energy storage, and advanced manufacturing. Development began in 2020, with Phase 1 operations starting in 2021. The initiative was driven by mounting pressure on the Inner Mongolia government to reduce Ordos's reliance on coal. Ordos accounts for approximately 16 percent of China's coal production, making it a focal point of China's energy transition strategy. The industrial park represents a strategic effort to diversify Ordos's economy and shift toward cleaner energy (IEA 2023d).

The park supports industries across the clean energy value chain—including battery production, electric vehicles, hydrogen fuel cells, and photovoltaics—while consuming 5 TWh of renewable electricity annually (Inner Mongolia Department of Science and Technology 2024, World Economic Forum 2025). Of this, 80 percent is generated on-site from wind and solar, with the remaining 20 percent sourced from the grid. A dedicated renewable electricity company was established to manage procurement and operations (Inner Mongolia Department of Science and Technology 2024). In addition, the park produces green hydrogen and supports industries that use it (China Daily 2022b).

To support emissions monitoring and optimization, the Ordos park has developed a shared digital emissions monitoring system used by over 50 companies. It tracks real-time electricity usage and enables energy system optimization, which can help to lower emissions while facilitating accurate emissions accounting (Inner Mongolia Department of Science and Technology 2024). The park also collaborates with local authorities to co-develop standards for clean electricity and emissions reporting, helping local products gain international recognition (Inner Mongolia Department of Science and Technology 2024).

A replicable model comes from Yancheng, Jiangsu, where industrial parks in Sheyang, Defeng, and Binhai overcome limits in on-site renewable generation by building direct-line connections to external renewable energy facilities. These dedicated transmission lines link wind and solar farms to substations that exclusively serve the parks, powering manufacturing activities and producing green hydrogen within the industrial parks themselves (NDRC 2024). This approach can facilitate the real-time tracing of renewable electricity and robust emissions accounting, helping the parks meet the standards required for international green markets (Yancheng City Government 2025).

Lessons for developing countries

Taken together, these examples illustrate the strategic value of cluster-based industrial configurations, especially those that involve electricity access, green hydrogen production, digital emissions tracking, and public-private collaboration. As countries accelerate their net-zero transitions, China's industrial parks offer a scalable, exportable model to align economic development with energy sustainability.

Case study 5 | From fertilizer to fuel—the dual role of ammonia in clean hydrogen adoption

Ammonia—fuel and fertilizer—straddles both the industrial and energy transitions. As of 2025, nearly half of all announced clean hydrogen projects worldwide centered on ammonia production, reflecting its unique role as both a consumer of clean hydrogen and a vector for its commercial uptake (World Bank 2025a). Today, around 85 percent of global ammonia demand is for nitrogen fertilizer production (IRENA and AEA 2022), but the future of ammonia is likely to be far more versatile. It is being explored as a clean fuel for shipping and power, making it a possible cornerstone of zero-carbon supply chains. In this dual role, renewable ammonia is becoming a scalable end-use case for clean hydrogen.

Existing ammonia production is highly energy intensive and deeply integrated into global trade. China remains the largest supplier—primarily for domestic fertilizer use—at 27 percent of global production. Russia, the United States, and India are the three next-largest producers, at 11 percent, 10 percent, and 8 percent of global production, respectively. No other country accounts for more than 3 to 4 percent (Saygin et al. 2023). Globally, about 8 percent of ammonia is traded across borders—representing a $9 billion market—while ammonia-derived nitrogen fertilizers are traded more extensively, with approximately 46 percent of their global production entering international markets (Mingolla and Rosa 2025). The leading ammonia exporters include Trinidad and Tobago (26 percent), Saudi Arabia (19 percent), Canada (12 percent), and Indonesia (12 percent). On the import side, the largest markets are the United States (15 percent), followed by the European Union (15 percent), India (14 percent), and Morocco (10 percent) (OEC 2025, Mingolla and Rosa 2025).

With the exception of China, where 85 percent of ammonia production is based on gasified coal, ammonia production relies heavily on hydrogen derived from natural gas and is therefore concentrated in countries where gas is abundant and inexpensive. Still, the industry is highly sensitive to price fluctuations in gas markets because gas accounts for 70 to 90 percent of total production costs. Transitioning to renewable hydrogen, which relies on green hydrogen rather than volatile fossil fuels, can therefore offer economic advantages in addition to environmental ones (Mingolla and Rosa 2025). The geographic distribution of ammonia production may shift as renewable hydrogen becomes cost-competitive, enabling countries with high solar or wind potential, such as Indonesia and Viet Nam, to enter the ammonia market through renewable routes.

A multi-sector solution

Ammonia's energy intensity has also made it a promising decarbonization solution for other sectors. In addition to fertilizer producers, the shipping and power sectors are now major emerging off-takers, creating a new class of project developers. Several shipping companies are already investing in ammonia production facilities to secure future fuel supply, reflecting growing confidence in ammonia's role as a clean maritime fuel (World Bank 2025a).

As of March 2025, more than 130 ammonia-fueled vessels had been ordered or announced, including 27 ammonia carriers and 27 bulk carriers. Small-scale applications such as tugboats had already entered operation in Japan and Korea. A further 225 vessels had been classified as "ammonia-ready," with 28 already operational (AEA n.d.b). In parallel, the World Bank and other institutions are supporting port authorities, particularly along major trade corridors, to prepare for ammonia bunkering infrastructure. Recent Bank-supported technical assistance spans Colombia, Morocco, Panama, and South Africa, with new studies underway across Southeast Asia (World Bank 2025a). These initiatives demonstrate the momentum behind ammonia as a clean shipping fuel, which is bolstered by the revised climate targets of the International Maritime Organization (IMO) for the shipping sector.

Ammonia is also gaining traction in the power sector. As of April 2025, at least 43 ammonia-to-power projects were under development globally. These include 10 ammonia-fueled gas turbines and 31 projects involving ammonia co-firing in thermal power plants, which boast a combined generation potential of 7.8 gigawatts (GW) from ammonia and projected fuel demand of 33.8 million tonnes of ammonia per year (AEA n.d.a). Most of these projects are in East Asia—particularly Japan and Korea—where government support and industrial collaboration have accelerated deployment. In 2024, Japan successfully demonstrated 20 percent ammonia co-firing in a 1 GW coal plant over multiple months, proving technological viability and de-risking deployment (AEA n.d.a). In Singapore, a 60 MW ammonia gas turbine is under development at Jurong Port. These efforts illustrate ammonia's potential as a long-duration energy storage medium (LDES) and peaking solution in decarbonized power systems.

A landmark renewable ammonia initiative is the NEOM Green Hydrogen Project in Saudi Arabia. Developed by the NEOM Green Hydrogen Company—a joint venture between ACWA Power, Air Products, and NEOM—the $8.4 billion project aims to produce 600 tonnes of green hydrogen per day, which will be converted into approximately 1.2 million tonnes of green ammonia annually. Scheduled to commence operations by 2026, the facility will be powered by 4 GW of renewable energy from solar and wind and is backed by a 30-year exclusive offtake agreement with Air Products (Bhatt 2025). The project illustrates how integrated clean hydrogen and ammonia infrastructure can be deployed at scale, setting a global benchmark.

Challenges to scaling renewable ammonia production

Despite this growing momentum, renewable ammonia remains much more expensive than conventional production. Prices for conventional ammonia have been volatile—ranging from $900 per tonne in September 2024 to $350–400 per tonne by March 2025 (Argus n.d.). By contrast, best-in-class renewable ammonia costs are around $700 per tonne, while smaller-scale projects in Latin America report production costs of $1,500–2,000 per tonne (World Bank 2025a). Exceptions include agriculture-dominant countries with no domestic gas production, where renewable ammonia can substitute for costly imports. Likewise, in remote regions, where transportation and logistics can double fertilizer costs, decentralized renewable production is more attractive (Mingolla and Rosa 2025). Overall, areas with abundant renewable energy, limited domestic production, and high import or distribution costs are strong candidates for decentralized, renewable ammonia systems.

Blue ammonia, produced from fossil fuels with CCS, tends to be cheaper but offers smaller emissions reductions, depends on the availability of CO_2 storage (World Bank 2025a), and remains reliant on natural gas, making it vulnerable to market volatility.

Large-scale renewable ammonia projects require substantial enabling infrastructure and resources, including grid assets, land and water supply, pipelines for hydrogen and ammonia, and port facilities. Studies in Mauritania, for example, showed that exports of renewable hydrogen and ammonia will require highway reinforcements and infrastructure upgrades. And, according to the World Bank, producing 1 million tonnes of green hydrogen would require 10 GW of electrolyzer capacity, 20 GW of renewable energy, and $30 billion in investment (World Bank 2025a).

Common-user infrastructure—shared pipelines, terminals, and storage—can reduce costs and improve access, unlike project-specific investments (World Bank 2025a). A more difficult challenge may be the land and water requirements of renewable ammonia production, which can be orders of magnitude higher than those of conventional fossil-based methods (Mingolla and Rosa 2025, Mingolla et al. 2024), posing constraints and potentially adding to existing land-use pressures and water stress in certain regions.

China, Indonesia, and Viet Nam are at varying stages of developing ammonia as a clean hydrogen derivative. China is the world's largest ammonia producer, but most of its production is coal-based. Select provinces with abundant renewable resources and water availability are exploring green ammonia pilot projects. Indonesia is positioning itself as a future exporter of renewable ammonia, with projects planned in Sulawesi and East Nusa Tenggara that target both fertilizer and marine fuel markets. Viet Nam is examining ammonia's potential role in the power sector, particularly for balancing offshore wind through ammonia-based energy storage or co-firing solutions. Each country must also address grid planning, certification of renewable energy, and access to concessional finance.

Lessons for developing countries

The evolving landscape for ammonia offers important lessons for developing countries. First, ammonia production will likely be the most commercially viable use of clean hydrogen in the near term. Second, public infrastructure planning—particularly around ports, pipelines, and power—will determine project viability. Third, international certification, trade policy alignment, and bilateral partnerships will be essential for export competitiveness. Finally, public-private collaboration is vital if bottlenecks around power procurement, grid access, and affordability are to be resolved. As the market for clean ammonia matures, countries that combine resource endowments with enabling infrastructure and policy clarity will be best placed to benefit from the global ammonia transition.

Recommendations

Policy makers can accelerate the transition to clean industry in affordable ways that enable financing from international financial institutions (IFIs) and domestic investors. If investors are to fund upfront capital improvements (such as electrified or hydrogen-using industrial equipment), they will require a return on that investment. This means that ongoing operating costs for clean technology must be lower than those for fossil-based alternatives. Given that governments in the East Asian region are likely reluctant to shoulder large, ongoing subsidies for industrial use of clean energy, this study recommends achieving cost parity or a cost advantage for clean industry without resorting to subsidies. Our recommendations aim to minimize the “green premium” for low-carbon products by reducing the costs of clean manufacturing. Although the issue of securing off-takers for products that do have a green premium falls outside of the scope of our analysis, the issue is nonetheless important for investors and policy makers.

In this section, we first focus on how policy makers can create an environment conducive to clean industrial investment. Under the right conditions, the technologies in Tier 1 (efficiency) and Tier 2a (heat pumps, electric motors, and secondary steelmaking) can be cost-effective even given current market prices for electricity and fossil fuels. They are thus the easiest place for policy makers to start, beginning with energy efficiency and emissions standards, industry-specific targets, loans and loan guarantees, workforce development, and policies to facilitate a circular economy.

Other technologies that rely on electricity directly (in Tier 2b) or produce green hydrogen (in Tiers 4a and 4b) will cost firms more money than emitting alternatives, given today’s electricity prices. A large expansion of renewable energy on the grid is key to lowering the cost to operate those technologies, while industrial firms can further lower costs by providing distributed renewable energy resources and grid services such as demand response.

Carbon capture (Tier 3) ties additional fossil fuel consumption to the business as usual (BAU) case. Absent carbon pricing, it can save costs only if the captured carbon dioxide (CO_2) is sold for use. We first discuss CO_2 use options and technological pathways, then consider carbon pricing as a means of improving the financial viability of clean industrial technology in all tiers, including carbon capture, utilization, and storage (CCUS).

The final recommendations in this section are aimed at investors, especially IFIs. We first explore the amounts of international climate finance targeted to industry today relative to industrial investment needs. We then address how investors can tailor their investment strategies to best support industrial decarbonization in East Asia.

In addition to the recommendations in this chapter, Chapter 6 offers additional recommendations on how to enhance the availability of clean electricity for industrial electrification and to help industrial firms access that clean electricity. Though those recommendations are part of the deep dive on industrial electrification in China, they contain many strategies that may be useful across the East Asian region.

Policies for the first steps in industrial decarbonization | Tiers 1 and 2a

The efficiency improvements in Tier 1 and the easy electrification solutions in Tier 2a (e.g., heat pumps, electric motors, and secondary steel) are the most practical, cost-effective, and scalable industrial decarbonization interventions today. Policies that can remove barriers to their adoption need not entail a high cost to government. They should be among the top priorities for countries aiming to decarbonize their industrial sector. Such policies include energy efficiency and emissions standards, industry-specific targets, supporting innovative business models, public financing support, workforce development programs, and circular economy support measures.

Energy efficiency and emissions standards

Technology performance standards for industrial equipment can drive decarbonization by establishing thresholds for energy efficiency and greenhouse gas (GHG) emissions. They can overcome barriers to adoption that are not responsive to financial incentives and are less visible than taxes (fees on inefficient models are more noticeable than the absence of inefficient models from the marketplace).

Standards should be designed to become more stringent over time, promoting continual innovation and the phase-out of underperforming equipment. By building such a “ratcheting” mechanism into standards, policy makers can ensure that standards do not require repeated assessment, debate, and approval, and firms can have a reliable forecast of future expectations. Wherever possible, standards should be paired with small financial incentives that reward better-performing technologies, to encourage manufacturers to go beyond the standards’ minimum threshold requirements.

Energy efficiency standards are traditionally designed for components such as motors or pumps, but, in most countries, many types of industrial equipment are not subject to energy efficiency standards. While standards can cover specific pieces of equipment, applying them to entire industrial facilities may be more pragmatic for some products, limiting the energy or emissions related to producing a given product. This approach is well suited for commodity products such as specific grades of steel or bulk chemicals. In the case of more specific non commodity products, standards for a facility can be tied to that facility’s historical baselines or current energy use and emissions, with standards requiring improvements relative to that baseline. Even when using a historical baseline, care must be taken to relate these standards to productivity. This mitigates scenarios where facility production is ramped down to meet requirements only to trigger ramped-up production at another, unregulated industrial facility (possibly owned by the same firm).

Emissions standards permit a firm to take a flexible approach to decarbonization while ensuring that conventional pollutant emissions (e.g., PM, SOx, NOx) improve. They are a strong complement to energy efficiency standards, which would need to exclude all combustion technologies, including biomethane and green hydrogen, to eliminate emissions on their own.

A technology-neutral clean heat emissions standard would allow firms to select the most practical energy sources and equipment to comply with lowered limits on industry's heat-related GHG and pollutant emissions. The standard would need to encompass new and existing equipment, taking into account the long lifetimes of industrial heating equipment, as well as the technological maturity of equipment for providing heat in a specific temperature range or for a specific industry. While ideally such a standard might impose limits that decline to zero in 10 to 15 years for new equipment and 30 to 40 years for existing equipment, these timelines may need to be less stringent depending on the specific country or industry. Moreover, an emissions standard for clean industrial heat would complement the efficacy of financial policies like carbon pricing or clean heat subsidies, should such policies be pursued.

Standards can also be applied in a more limited fashion to ensure a market for lower-carbon goods. Green public procurement (GPP) programs set standards for materials purchased for government-funded projects. Due to the scale of government infrastructure projects, this can create a large-scale market with stringent emissions standards that impact major industrial goods such as steel, cement, and glass. GPP can also drive low-carbon manufacture of finished products for government buyers ranging from military and construction equipment to electronics and office supplies. Public procurement often accounts for a significant portion of gross domestic product (GDP), averaging 12 percent in the countries of the Organisation for Economic Co-operation and Development and up to 30 percent in developing countries (UNEP 2017). Because manufacturing products to GPP standards is voluntary, GPP programs can kick in earlier in the technology life cycles, helping to motivate the adoption and scaling of clean technologies that are not yet cost-competitive against their historical counterparts.

Industry-specific targets

In order to align industrial actions with national climate goals (e.g., Nationally Determined Contributions or long-term strategies) and promote the scale-up of cost-effective technologies, governments can establish industry-specific targets for emissions in each industrial subsector. While targets do not mandate emissions reductions, they can serve as market signals, encouraging firms to plan for equipment replacements and facility upgrades that ease the risk of stranded assets in the long term. Industry-specific goals also enable more targeted policy design, facilitate resource allocation, and enhance accountability, especially in countries like China and Viet Nam with central planning and government influence over industrial activities.

Industry-specific targets are already part of China's strategy to achieve its 2030 carbon peaking for coal. Last year, China's State Council launched an action plan that outlined several subindustry-specific decarbonization targets to be achieved by the end of 2025, including specific energy use and emissions reduction goals in the primary metals, refining, and petrochemicals industries (Yin et al. 2024). Other targets included increasing the share of electric arc furnace (EAF) steel in primary steel production to 15 percent, boosting the share of renewable energy in the aluminum industry's electricity use to 25 percent, limiting primary refining to 20 million barrels per day, and capping clinker production (for cement) at 1.8 billion tonnes per day.

Indonesia and Viet Nam have established industry-specific decarbonization targets, though they are not very comprehensive or ambitious. Indonesia set a broad target of lowering industrial sector emissions by 9 million tonnes of carbon dioxide equivalent ($MtCO_{2e}$) by 2030, but the country has not announced goals for specific subindustries (Climate Action Tracker 2024). Viet Nam identified energy efficiency targets for certain industries to reach by 2030, including a 10 percent reduction in energy consumption in the chemicals industry (compared to levels in the 2015–18 period) and a close to 7 percent reduction in the cement industry (compared to 2015 levels) (Climate Action Tracker 2023). In pursuing additional subindustry-specific targets (e.g., reductions in energy use and emissions, or the deployment of specific decarbonization technologies) aligned with realistic decarbonization pathways for each industrial subsector and the country's overarching climate goals, governments can nudge investments toward the proper industrial decarbonization projects.

Innovative business models for heat pump adoption

Business models to incentivize heat pump adoption include heat-as-a-service (HaaS), wherein the heat pump manufacturer provides the equipment and handles engineering, installation, and maintenance. This is an evolution of the energy service company (ESCO) model, where clients can repay the investment out of shared energy savings. Newer HaaS models also include electricity procurement and infrastructure management in service provision (see Appendix B for case study examples).

Policy makers can encourage HaaS ventures by promoting ESCO partnerships and pilot programs, motivating providers to incorporate renewable energy procurement and pairing HaaS with public subsidies. Additional policy measures can help HaaS ventures overcome common barriers to their success. For example, if the balance sheets of heat pump manufacturers are too meager to support HaaS contracts, governments can establish public HaaS ventures or finance programs that purchase HaaS receivables. Governments can also offer monitoring and verification guides to improve the enforceability of HaaS contracts, as well as risk guarantees to improve the creditworthiness of industrial firms interested in signing HaaS contracts.

Appendix B offers more detail on methods to promote the adoption of industrial heat pumps.

Addressing capital and installation costs

This section examines financing mechanisms for both capital and installation costs of heat pumps and similar clean industrial equipment. Appendix B provides a more detailed look.

The high upfront costs of industrial equipment may not be the main barrier to cleaning up industry, but firms may lack the capital to cover them, and investors might perceive new industrial technologies (even commercial ones, like energy efficiency technologies) as too economically or technologically risky to finance. Technological innovation that improves and standardizes components (e.g., compressors and heat exchangers) can cut capital costs and help to scale production. Policies that advance research, development, and demonstration, which are important enablers of innovation, are examined later in this chapter.

Direct public funding (e.g., investment tax credits, grant programs) can also help to cover upfront capital costs, along with financing mechanisms such as traditional lending, sustainability-linked financing, private equity investment, and development bank financing (Appendix B).

In addition to private finance, governments, and quasi-public institutions like green banks can invest directly in clean industrial projects and offer policy solutions to reduce investment, drawing additional private finance to new technologies. (A later section in this chapter addresses policy options to accelerate investment in decarbonizing industry and details how IFIs can support policy design and implementation.) Subsidized interest rates and concessional loans, as well as co-lending between a private firm and public entities (e.g., blended finance and public-private partnerships), can help to scale up commercial technologies that already have some private sector interest (IEA 2025d). For higher-risk projects, like those that involve newer technologies or highly leveraged firms, public entities can offer a range of financing mechanisms. For one, they can take a direct equity stake in projects, as is common in China (Ban and Li 2025). They can also aggregate small loans to an array of clean industrial projects to mitigate the exposure of individual investors, and they can provide loan loss reserves or public guarantees that also reduce lenders' exposure in the event their loans are not repaid (IEA 2025d). Finally, governments can indirectly lower the risk of investing in newer industrial technologies by boosting demand for cleanly made products. Examples include GPP programs (described earlier in this chapter), where the government serves as a reliable and potentially long-term off-taker, as well as government-led corporate emissions accounting systems compatible with existing financial databases (combined with mandates on corporate emissions disclosure and climate-related financial risks).

In some cases, installation costs can be higher than the cost of the equipment, particularly for relatively affordable equipment (such as heat pumps and electric boilers), if the industrial facility requires retrofits that provide more electricity capacity (Appendix B). To mitigate installation costs, supportive policies include initiatives to develop modular, standardized plug-and-play heat pump designs and streamlining of the regulatory and permitting processes.

Workforce development

Naturally, any new technologies installed to support industrial decarbonization need a workforce well versed in their installation, operation, and maintenance. Workforce development and training resources can ensure the supply of highly skilled workers while making certain that recent graduates and displaced workers have high-quality job opportunities. Such training can be built into the funding provisions for industrial decarbonization projects. To ensure training is relevant to real-world settings, education on decarbonization technologies for industrial decision-makers could be handled by industrial trade groups. As an example, the China Energy Conservation Association and China Heat Pump Alliance together run an annual conference and provide educational materials on industrial heat pumps. For more detailed recommendations on policy options to ready the workforce for industrial decarbonization, see the last section in this chapter.

Facilitating the circular economy

Smart policies that support the circular economy and encourage product longevity are relevant to early-tier material efficiency measures. They are an important facet of moderating demand while meeting consumers' daily needs. This can include right-to-repair legislation, which mandates that manufacturers offer reasonable access to documentation and tools for third parties to repair their goods. Products may furthermore be evaluated and labeled with a "repairability index," as implemented in France (Jourdain 2025). Incentives can further promote repair services, such as Sweden's approach of reducing value-added taxes and providing income tax reductions when consumers use these services (Dalhammar, Richter, Almén, et al. 2020).

Policies can also address how goods are handled at the pre- and post-consumer stages. Returned and unsold goods are frequently destroyed, especially in luxury brands, but France passed legislation that banned this practice, forcing unsold inventory to be donated or deconstructed for reuse (Ministère de la Transition écologique et solidaire 2020). More widely adopted extended producer responsibility laws ensure that manufacturers handle reuse or disposal of products at the end of their life cycle. This can itself help facilitate refurbishment and remanufacturing practices by manufacturing firms, as are relatively common in the auto parts, aviation, and construction machinery industries (US International Trade Commission 2012). Creating a larger pool of remanufacturable core components is key, as are policies that facilitate a transparent, searchable inventory of such cores to facilitate their reuse. If remanufacturing or refurbishment is not practical, then products may be repurposed toward wholly new uses or recycled, though these routes have a less direct impact on demand reduction and energy and materials efficiency.

Policies for later-stage industrial decarbonization dependent on electricity | Tiers 2b, 4a, and 4b

Later-stage electrification (Tier 2b), green hydrogen solutions (Tier 4a), and the decarbonization of chemical feedstocks (Tier 4b) all require a foundation of abundant clean electricity from which to operate. Given their substantial electricity requirements, these technologies are far more expensive to operate than burning fossil fuels for heat or transforming fossil fuels into chemicals. Numerous policies can help to cut the operating cost premium for these solutions by boosting the availability of cost-competitive, clean electricity. These include policies to accelerate the proliferation of renewables on the grid and to incentivize industrial demand flexibility through the propagation of industrial energy storage, variable utility rates, and demand response programs.

Expansion of renewables on the grid

Renewables are the most cost-competitive source of electricity today. Therefore, deploying more renewables—primarily wind and solar—can reduce the cost of generating grid electricity, lowering the operating cost premium that grid-connected firms face when electrifying medium- and high-temperature heat, and cutting the costs of green hydrogen. High renewable energy penetration has been shown to make electricity cost-competitive over many hours. In China, the government has piloted “spot pricing” in key provinces, where price bidding aligns electricity prices with real time supply and demand conditions, improving renewable energy integration and resource allocation. While spot markets now account for less than 10 percent of electricity consumption in China, they offer a preview of electricity prices under China’s new market-based electricity system, where cheap renewable energy can more easily drive down electricity prices.

Among the eight regions of China in which spot pricing is or will soon be in official operation, regions with the most renewables saw the biggest dips in electricity prices at midday (Gao et al. 2024). These include the Shanxi and Shandong provinces, where the share of solar PV in total electricity generation in 2023 was 6.2 percent and 9.7 percent, respectively. That year, average spot prices (per 15 minutes) dropped below 250 RMB per megawatt-hour (MWh) ($35 per MWh) in Shanxi; in Shandong they fell below ¥200 per MWh ($28 per MWh) between 12pm and 2pm. In contrast, solar PV penetration was only 3.2 percent in the Guangdong province, where spot prices hardly dipped below ¥400 ($56) per MWh.

These are wholesale prices, not reflecting the cost of distributing that energy to industrial firms and industrial customers’ cross-subsidization of residential and agricultural customers in China.

However, the lowest spot prices in both Shanxi and Shandong are less than a third of the average electricity price in China—still higher than Chinese coal prices per unit of energy but close to Chinese natural gas prices per unit of energy. Increasing renewable energy penetration beyond current levels will likely drive further price reductions, potentially making electricity cost-competitive with coal at certain times of the day.

Numerous policy mechanisms can work to accelerate renewable energy deployment on the grid. Financial policies can help to offset the costs of renewable energy projects and provide investment certainty to renewable energy developers. For example, feed-in tariffs (FITs), which guarantee certain electricity prices for renewable energy developers over long periods, were critical for expanding solar and wind in Viet Nam in recent years. The continued decline in renewable energy prices has, however, made FITs ineffective in Viet Nam today, necessitating a more flexible alternative, such as a transparent reverse auction scheme where the government procures renewable energy at low prices (World Bank 2022b). Tax credits are another effective financial policy, rewarding renewable energy developers based on investment costs or energy production (U.S. EPA 2025).

Standards, targets, and electricity market reforms can be important policy options for governments with less budgetary freedom. Standards may include mandates on renewable energy consumption or the share of renewable energy in a grid, while targets include goals to boost renewable energy capacity or reduce coal power generation capacity, like those outlined in Viet Nam's Eighth Power Development Plan (World Bank 2022b). Electricity market reforms, like Indonesia's 2022 Presidential Regulation that removed price caps linked to the average cost of generation and introduced competitive electricity procurement principles, can also boost low-cost wind and solar (World Bank 2023a). Further reforms in Indonesia could include altering requirements around the quantity and price of output that coal producers sell to state-owned utilities and reducing domestic content requirements in Indonesian wind and solar installations. Renewable energy integration is also supported by policies that improve grid flexibility; see the section below on utility incentives, variable rates, and demand response programs.

Chapter 6 of this report explores the policies China is using to boost both renewable energy deployment and use of that energy by industrial firms in ways that signal more renewable energy deployment. In the present chapter, the section on investment strategies to support industrial decarbonization in East Asia explores how international investors can complement in-country policy support for renewables, further accelerating their deployment.

Political ambition for the policies listed above, as well as investment appetite for renewable energy projects, is likely to accelerate as electricity demand grows for end-uses like data centers, electric vehicles, and buildings. The International Energy Agency estimates that data centers' electricity demand, for example, will more than double by 2030 (IEA 2025b). Such projections could serve as a forcing function for electricity growth, encouraging policy makers and investors to plan for the rapid, near-term deployment and integration of renewable energy resources. Integrated power system planning that incorporates grid constraints, investment needs, and cost distribution can support growing and competing demand for renewables. However, more research is needed to illuminate both the opportunities and challenges that economywide electricity demand growth will present for grid decarbonization and industrial electrification.

Research, development, and demonstration

Public and private funding for research, development, and demonstration (RD&D) is of paramount importance to the emerging technologies required for industrial decarbonization. For example, industrial firms that can store thermal energy (and can be flexible about when they buy electricity) can purchase electricity at prices far below average (often about a third of the average electricity cost in both the United States and China) while helping to balance the grid (Rissman and Gimon 2023). Other technologies, such as those to utilize green hydrogen in industrial processes, require RD&D to reach commercialization and scale.

Even for technologies with commercial models available, research can continually improve performance, efficiency, and upfront costs. Today, commercial thermal batteries top out at around 300°C to 500°C, but newer models can reach 1,700°C, close to the highest temperatures used for industrial bulk heating today. Pilot projects and real-world demonstrations can help to commercialize high-temperature thermal batteries, which can serve as a low-cost electrification option for most industrial processes. Other industrial decarbonization technologies that can electrify high-temperature processes, capture carbon from dilute CO_2 streams, produce and use clean hydrogen, and enable low-carbon cement production are even more nascent and need the support of both laboratory research and real-world demonstration projects. Ultimately, all industrial decarbonization pathways can benefit from demonstration projects, such as the 28 industrial decarbonization projects originally selected to receive awards from the US Department of Energy's (DOE's) Office of Clean Energy Demonstrations (U.S. OCED 2024). They provide proof-of-concept and private sector buy-in with data that validate the technologies' cost-effectiveness and performance.

Government labs, such as the Chinese Academy of Sciences, could provide a home for industrial decarbonization research. Public-private research partnerships, such as the US DOE's Innovation Hubs, can combine government, academic, and private firm resources for technology development. Germany's Frauenhofer-Gesellschaft network of seventy-six applied research institutes is another example, garnering only 30 percent of their funding from federal and state governments and relying on private contracts for the remainder. The network yields important technology discoveries in green hydrogen, bioplastics, hydrogen-to-methanol, and other areas (Rissman 2024).

Once technologies have been successfully demonstrated, public entities (including green banks) can bridge the deployment gap that occurs when projects are too technologically mature to receive government RD&D support but too new to attract low-cost private sector financing. (For more information on public financing support for industrial decarbonization, see the section of this chapter on policy options to accelerate investment in decarbonizing industry.)

Research and development (R&D) of low-carbon technologies has recently become more of a priority in China, which in 2019 accounted for nearly a quarter of the world's energy-related R&D investments (World Bank 2022a). Policy reforms are needed if the quality of research is to keep pace with the quantity. China's rate of patenting high-value, low-carbon inventions lags that of the United States and Japan. Reforms could include enhanced review and evaluation of research, incentives designed to reward research based on its quality, and greater emphasis on R&D of technologies that, if commercialized, would have decarbonization potential.

Utility incentives, variable rates, and demand response programs

Electric utilities could offer discounted rates for industrial firms to encourage the use of clean electricity. At the same time, incentivizing flexible energy demand may present an even greater benefit to both utilities and firms. Many industrial facilities already have weekly and seasonal fluctuations in their production patterns: a survey of smart meter data of over 21,000 industrial facilities in Guangdong province showed that only about a quarter of its factories worked through the weekend, varying by subindustry (Khan et al. 2016). If industrial firms can flexibly adjust their patterns of energy use, they can lower peak demand on the grid and reduce the utilities' cost to generate and deliver that electricity. In this context, industrial customers would aim to use electricity when energy resources exceed demand and wholesale electricity costs are low.

Utilities could provide daily granularized rates for time-of-use (TOU) that penalize usage at peak hours. China's government has offered industrial firms TOU pricing since the early 1990s, although the exact policies have changed over time. Today, rather than one national TOU price for all utilities and customer types, individual cities and provinces design their own TOU rates; in Beijing, the ratio of peak electricity prices to off-peak prices is now 4.3 to 1 (ESMAP 2024). Utilities could also provide block and index pricing, where a customer buys a block of power at a fixed rate, then buys additional power or sells back their remainder at a real-time price, which exposes customers to the wholesale electricity price. This real-time pricing method is being used in Pennsylvania, where large industrial customers can access a growing pool of cheap, clean electricity (Pennsylvania Public Utility Commission 2021) .

Industrial firms could take better advantage of such rate designs both by adjusting their operating patterns and by investing in energy storage. Industrial thermal batteries permit firms to bank energy during the hours when it is cheapest and the grid is oversupplied and then utilize the banked energy during times of expense and scarcity. This would smooth grid demand curves and allow utilities to sell excess electricity from renewable sources that would otherwise have been curtailed. Thermal batteries would ideally benefit from highly transparent and granularized TOU rates on the order of 15 minutes or even higher frequency, but many TOU rates offered today are broken into fairly generalized multi-house blocks.

Even when time-varying rates are not offered, industrial facilities with energy storage could access lower rates or gain additional revenue by providing flexibility services for the grid. By participating in demand response programs where they shift their electricity usage to off-peak periods, firms may qualify for a lower electricity rate or compensatory payments for reducing strain on the grid. Viet Nam has explored a range of demand response programs for industrial loads and even established targets to increase demand response to 600 MW by 2030. But legal challenges (e.g., utility-side restrictions on incentive payments for demand response and national government restrictions on electricity tariff changes) have limited the country's ability to implement such programs (ESMAP 2024). Therefore, legal and regulatory reforms could help unlock incentives for demand-response in Viet Nam.

For a deeper look at the use of demand-side resources in a clean industrial transformation, see Appendix C.

Policies to support carbon capture and use or storage | Tier 3

Although direct electrification is the best solution for the vast majority of industrial GHG emissions, CCUS can be important for certain processes that are difficult to electrify or that release significant process emissions. To limit the risks of industrial CCUS deployment—including the long-term lock-in of fossil fuel infrastructure and upstream emissions from fossil fuel extraction—our model applies CCUS only to some process heat in the nonmetallic minerals, iron and steel, and nonferrous metals industries. The modeling results indicate that, for emerging economies in the East Asian region, CCUS can reduce the CO_2 emissions remaining after the implementation of Tiers 1 through 2b (efficiency and electrification) by another 50 percent or more **(FIGURE 3.16)**. However, the capital costs of CCUS per unit of annual abatement are higher than those of interventions in Tiers 1 through 2b, at $600 to $700 of upfront costs per tonne of CO_2 captured and stored (inclusive of capture, transport, and storage equipment) **(FIGURE 3.26)**. CCUS's energy costs are relatively modest **(FIGURE 3.36)**, but if aggressive renewable energy deployment overcomes the operating premium for industrial electrification and green hydrogen deployment, CCS could end up being the only industrial decarbonization approach that raises industrial energy costs. While technological advancements can help to reduce CCUS's capital costs and improve its energy efficiency, these by themselves are not enough to make CCUS a cost-saving technology. Therefore, standardization and new business models can become powerful tools for driving market adoption and ensuring CCUS users achieve financial returns.

Standards

Standardization is important for the proper evaluation, adoption, and interoperability of CCUS technologies (China Building Materials Federation 2024). Multiple stages of the CCUS value chain could benefit from better standards in the East Asian region and in the process drive investment and technology adoption. For CO_2 capture, standards can cover specific capture technologies like post-combustion capture and oxy-fuel combustion, equipment and system design, specific technology components like solvents and sorbents, system energy efficiency, and operational protocols. For CO_2 transportation, standards should cover the pretreatment of CO_2 and robustness of CO_2 pipelines (e.g., leakage prevention and safety). Standards for CO_2 utilization can cover specific CO_2-using industrial processes and technologies, while CO_2 storage standards should consider pre-injection treatment of CO_2 and ensuring the long-term integrity of CO_2 storage reservoirs and wellbores. Finally, standards for measurement and reporting can help governments and carbon market stakeholders verify the amount of CO_2 captured and utilized or stored, energy consumption of the CCUS process, and safety metrics.

Business models

New business models can be instrumental in establishing and growing a market for industrial CCUS. Traditionally, most CCUS projects have relied on a “full chain,” or vertically integrated, model. This involves a single entity developing, owning, and operating the entire value chain for a CCUS project, including CO_2 capture, transportation, and underground storage. Many types of CCUS projects have adopted this model, from commercial enhanced oil recovery (EOR) projects to demonstration and “first-of-a-kind” projects that are publicly funded (IEA 2023b). The full-chain model can reduce project development and coordination risks by limiting the number of parties involved in the project and streamlining the decision-making process, which may be critical in early-stage markets where project timelines and certainty are essential. However, the full-chain model requires the project developer to possess technical and operational expertise in all areas of CCUS, and it puts the entire capital expenditure burden on a single entity, which requires a large appetite for investment. Few entities are able to meet these requirements. This limits the number of CCUS projects that can be developed per year and inhibits market competition, which might otherwise drive down prices (IEA 2023b).

Alternative business models are emerging to better manage project risks and encourage market access. The “partial chain” model breaks up the CCUS value chain, such that separate entities can own, develop, and operate CO_2 capture, transportation, and storage processes. This model allows CO_2 emitters to focus on their core businesses and outsource carbon management to specialized entities with relevant expertise and access to capital, reducing financial and operational risks (Oxford Institute for Energy Studies 2024). It also opens avenues for third-party infrastructure operators, fostering a competitive marketplace where different players can optimize efficiency at each stage. For instance, CO_2-capture-as-a-service may involve engineering companies providing and operating equipment at industrial sites (perhaps with capture occurring where exhaust leaves the industrial facility, avoiding the need for complex integration with existing manufacturing operations). CO_2 transport can be offered by specialized pipeline companies, and CO_2 storage can be provided by firms that own suitable sites and possess expertise in drilling, injection, and related practices. One of the key challenges for the partial-chain model is the development of CCUS infrastructure, which requires large investments and faces lengthy regulatory processes. Policy makers can help by ensuring that comprehensive regulatory frameworks are in place to streamline permitting processes and address liability concerns (e.g., around long-term storage integrity, induced seismicity, and safety) through transparent protocols and risk-sharing.

Revenue sources

Even with robust standards and smart business models in place, a CCUS project still requires a cost-effective revenue source in the absence of a steep carbon price. These sources may include: (1) selling CO_2 emissions reductions as carbon offsets; (2) selling captured CO_2 to off-takers; and (3) manufacturing and selling products that use captured CO_2, such as low-carbon cement, synthetic fuels, and chemicals (Oxford Institute for Energy Studies 2024). Carbon markets today are nascent and small relative to the magnitude of industrial CO_2 emissions, but innovation in carbon utilization technologies can help them grow. Strong, stable, and predictable carbon pricing mechanisms can also help to grow those markets by reducing revenue risks and volatility, but carbon pricing is not unique to CCUS.

Today's largest industrial use of CO_2 is to produce urea, primarily used in fertilizers. The CO_2 that goes into urea today comes from steam methane reforming or coal gasification to produce ammonia, creating CO_2 as a byproduct. If ammonia production shifts to clean feedstocks, urea production will need another source of CO_2, creating a market for CO_2 captured from industrial processes.

EOR is the second-largest user of CO_2 today, but most CO_2 used in EOR comes from naturally occurring underground CO_2 deposits. EOR stores CO_2 permanently but also results in the production of fossil fuels, which when burned will generate climate-warming CO_2. However, if the use of captured carbon displaces the use of CO_2 from naturally occurring underground CO_2 deposits (e.g., in an EOR project that is certain to move ahead with or without the use of captured CO_2), then it will reduce emissions relative to the alternative.

At smaller scales, CO_2 is also used commercially in the food and beverage industry (to form dry ice or carbonate soda), as a shielding gas in metalworking, in greenhouses to stimulate plant growth, and in novel CO_2-cured cements (Rissman 2024). With the exception of cement, these uses do not sequester the CO_2 long-term (and CO_2-cured cements may sequester less carbon naturally during and after their service lives). Nonetheless, these uses of CO_2 are economically important, and use of captured CO_2 may become indispensable as industry shifts to clean chemical feedstocks.

This shift should not only reduce the availability of CO_2 from steam methane reforming and coal gasification but also increase demand for CO_2, which is needed to transform clean hydrogen into chemicals like methanol.

Finally, revenue stacking—which combines public and private revenue sources, such as government incentives, carbon pricing, and sales or direct use of CO_2—can be effective at making CCUS financially viable. If a CCUS project is expected to achieve a financial return but needs help with upfront costs, a range of financing mechanisms can help, such as loan loss reserves, loan guarantees, favorable interest rates, senior or subordinated debt or equity, viability gap funding, and green bonds (tax-favored bonds issued by a green bank or other authority). In addition, instruments such as long-term offtake agreements or carbon contracts for difference could also provide revenue certainty. These tools can be used strategically to leverage private funding, often achieving several dollars of private funding for every public dollar invested (while delivering financial returns to both public and private investors).

Policies to level the price of fossil fuels and clean energy

To make clean power more competitive, policies must address the systematic underpricing of fossil fuels across all studied countries. One such policy is carbon pricing, which assigns a monetary value to the right to emit GHGs and requires firms to pay for the social costs of pollution. Another policy is the reduction or removal of fossil fuel subsidies, which artificially deflate the price of fossil fuels in many countries around the world, including China, Indonesia, and Viet Nam. Both policies change the cost-benefit calculus of fossil fuel combustion, reducing the cost gap between fossil fuels and cleaner alternatives. Since fossil fuel subsidy policies vary by jurisdiction, this next section focuses on carbon pricing as well as on carbon border adjustment mechanisms, a related policy that protects industrial competitiveness.

Carbon pricing

In line with the World Bank and the World Trade Organization's Working Together for Better Climate Action report, we adopt a broad definition of carbon pricing that includes both explicit and implicit mechanisms (World Trade Organization et al. 2024, World Bank 2023b). Explicit carbon pricing instruments—such as carbon taxes and emissions trading systems—directly assign a cost to greenhouse gas (GHG) emissions, creating clear financial incentives to reduce them. In contrast, implicit carbon pricing refers to policy measures that affect the cost of carbon-intensive goods and services without directly pricing emissions. Examples include fuel excise taxes, the removal of fossil fuel subsidies (which effectively impose a "negative" carbon price when in place), and tax differentials such as reduced value-added taxes on certain fuels. These instruments may not be labeled as carbon pricing tools, but they still provide important price signals that influence carbon-related behavior. International Monetary Fund studies show that de facto fossil fuel subsidies are higher when accounting for implicit carbon prices. In 2022, this subsidy amounted to $2.2 trillion (12.5 percent of GDP) in China, while Indonesia and Viet Nam each allocated over 14 percent of their GDP (Black et al. 2023). These price distortions create soaring electricity costs for industries and delay industry's shift to cleaner power, hindering decarbonization.

It is essential to recognize both explicit and implicit forms of carbon pricing to understand the climate policy landscape of each country (TABLE 5.1). Many indirect measures—originally designed for broader fiscal or social objectives—nonetheless contribute to reducing emissions. By integrating these into climate policy analysis, governments can better assess existing incentives and identify gaps and complementarities. This holistic approach enables the design of more robust, context-appropriate carbon pricing strategies that support both economic efficiency and equity regarding climate goals.

TABLE 5.1 Comparison of carbon pricing systems

Type of carbon pricing	Instrument
Explicit	• Carbon taxes • Emissions trading systems
Implicit	• Fuel excise taxes • Fuel subsidies (negative carbon prices) • Value-added tax differential for fuels

Carbon prices can be implemented through carbon taxes or cap-and-trade schemes, as well as hybrids of both systems. Carbon prices are best used for technologies that are only marginally cheaper to operate than conventional alternatives. Carbon taxes impose a fixed fee on the tonnes of CO_2-equivalent (CO_{2e}) emitted, pegging those fees to the social cost of carbon. As social costs increase, fees will rise, becoming more stringent to incentivize net zero emissions practices. The imposition of a predictable and mounting carbon price helps firms map out the feasibility of near- and long-term compliance strategies. Carbon taxes do not, however, lock in reliable emissions reductions, as firms can simply pay their cost.

Cap-and-trade or emissions trading systems (ETS) mandate that entities purchase permits to emit GHGs above a certain limit, with permit prices typically decided via auction. The number of permits typically falls to zero over time, providing certainty around the emissions reduction potential while creating uncertainty around the carbon price itself. Many ETS systems impose price controls with a floor and ceiling, limiting carbon price volatility.

Viet Nam is considering a carbon tax or ETS (Asia Foundation 2023). Indonesia implemented a hybrid ETS for emissions from coal-fired power plants above 100 megawatts (MW) in February 2023; this program will expand to cover oil and gas plants as well as off-grid coal plants from 2025 to 2030 (International Carbon Action Partnership 2023). Under the hybrid system, facilities that fail to meet their allowances will be subject to a carbon tax (International Carbon Action Partnership 2023). Carbon pricing schemes often exempt industrial emissions to protect industrial competitiveness and prevent firms from relocating to other jurisdictions. A better approach is to offer counterbalancing subsidies (e.g., based on GDP contributions and jobs created) or combine carbon prices with carbon border adjustment mechanisms, explained below.

Carbon border adjustment mechanisms

Carbon border adjustment mechanisms (CBAMs) are a means for countries to insulate domestic industry from foreign firms not subject to a carbon price. The CBAM fee is imposed on imported goods based on their embodied carbon (e.g., CO_{2e} emissions from manufacture). Conversely, domestic firms that export to regions without carbon pricing are granted rebates to maintain competitiveness. While CBAMs can beneficially incentivize firms in other regions to cut their emissions, they require international agreements on standards for measuring and reporting embodied emissions in order to work efficiently at scale. These mechanisms can be streamlined for manageability and accounting purposes; the EU's CBAM proposed a simplification of its operations in February 2025 that includes a threshold exemption of 50 tonnes mass, which would keep 99 percent of CBAM-relevant emissions in scope while exempting 90 percent of importers (Directorate-General for Taxation and Customs Union 2025).

CBAMs can safeguard firms against more than just carbon pricing policies; they can protect domestic firms from the compliance costs arising from policies like industrial emissions standards.

Investment strategies to support industrial decarbonization

The financing gap for industrial decarbonization

As mentioned earlier, industrial decarbonization accounted for only $52 billion (1.4 percent) of the $1.3 trillion in international finance allocated to climate mitigation in 2022 (Naran et al. 2024). Only 59 percent of all international climate finance ($862 billion) went to emerging markets and development economies (EMDEs), most of which went to China. Among all EMDEs in the East Asian region, China received 94 percent of climate finance in 2019 (Asian Development Bank 2023). International climate finance comes from public sources (e.g., governments, state-owned enterprises and financial institutions, and development finance institutions) as well as private sources (e.g., commercial banks, firms, and individuals) (Naran et al. 2024). Public sources and commercial banks mainly provide debt for climate projects, whereas firms and individuals mainly provide equity, although all sources use a mix of instruments.

Capital investment needs for decarbonizing industry are orders of magnitude higher than the amount of international finance now allocated to that end. In its economywide net-zero emissions scenario, the International Energy Agency projects that capital investment in global industry must rise from today's average of $158 billion per year to $477 billion in 2050, or a cumulative investment of $10 to $15 trillion (IEA 2021c, OECD 2025). According to the analysis conducted for the present report, decarbonizing industry in China, Indonesia, and Viet Nam will require a capital investment of $1.509 trillion, $122 billion, and $120 billion, respectively, with most investment needs concentrated in high-emitting subindustries that rely on high-temperature heat (e.g., iron and steel, chemicals, nonmetallic minerals, and nonferrous metals).[17]

While these capital investment needs are much higher than current investment in decarbonizing each country's industry, they are relatively small per tonne of emissions abated. Still, firms (especially in EMDEs) may struggle to cover those investment costs unless much more international climate finance is allocated to industry. Moreover, the energy costs of decarbonization will limit the bankability of capital investments unless they are deployed alongside supportive policies to narrow the price gap between fossil fuels and clean energy (see the section in this chapter on

[17] The IEA estimate is higher than that of the present study for several reasons. The IEA is considering the entire world, not just three countries of the East Asian region. The scenario designed for this study employs strong energy efficiency, material efficiency, and product longevity interventions to reduce energy use, lowering capital investment needs. The IEA includes a portion of the capital costs of stranded fossil-burning assets in the industrial sector, while this study only counts the cost of new and replacement equipment, not the costs of already purchased, retiring fossil technologies. The IEA's report, released in 2021, uses older technology cost data than this study. And the IEA includes construction as a subindustry within the industrial sector, while this study excludes construction.

policies for later-stage industrial decarbonization dependent on electricity and the section of Chapter 6 on policies to overcome the challenges of high electricity costs).

Key considerations for financing industrial decarbonization

In the East Asian region, a successful clean industrial transition depends not only on the amount of international climate finance that flows to industry but also on the strategic targeting of finance to the highest priority investment needs. Investments in cost-neutral interventions—namely efficiency and easy electrification in Tiers 1 and 2a—will generate a positive cash flow and may not need much financing support from governments and public institutions. On the other hand, projects that leverage direct electrification, CCUS, or green hydrogen to clean up medium- and high-temperature heat and eliminate process emissions are largely too expensive today to generate a return on investment.

Large-scale demonstration projects and early deployments can drive down the upfront costs and financial risks of these advanced technologies, but they require investments of multiple billions of dollars that industrial firms and private investors cannot meet without support from governments and public financing institutions. Most clean industrial demonstration projects in the United States and Europe—ranging from CCUS in cement manufacturing to hydrogen-fired direct reduced iron furnaces for steelmaking—are supported by multi-million-dollar cost-sharing grants from government funds like the US DOE's Industrial Demonstrations Program and the European Union Innovation Fund (as shown in the case study on northern Sweden in Chapter 4). (The section of this chapter on policy options to accelerate investment in decarbonizing industry offers detailed recommendations on how governments and IFIs can help direct more finance to these projects.)

Investments in industrial decarbonization should also align with the unique financing needs of industry. First, industrial decarbonization finance must accommodate higher risks and longer-term payback periods (U.S. DOE 2023b). Investing in low-carbon equipment can increase the risk of stranded assets, since industrial equipment can last multiple decades (Bataille 2022) and entail performance risks given the low technological readiness or recent commercialization of some industrial decarbonization solutions (U.S. DOE 2023b). Financing for these projects could also be constrained by fundamental issues such as firms' creditworthiness, loan durations, and collateral requirements, often made more challenging by tight profit margins and high exposure to commodity prices (U.S. DOE 2022, Dobrotkova et al. 2018). Finally, IFIs and other international entities may be wary of the foreign exchange risk associated with investing in emerging economies, as fluctuating currency values could negatively impact their return on investment (IEA 2021b).

Second, industrial equipment, processes, and supply chains are complex, heterogenous, and unstandardized. They require novel investment strategies informed by sectoral expertise. Investors may lack the data or expertise to predict cashflows for novel industrial projects, relying instead on proxies like the historical financial performance of industrial firms (IEA 2021b). Additionally, upgrades to existing facilities can present practical challenges, like the need for facility reengineering and the potential for disruption if upgrades occur outside of scheduled maintenance windows (U.S. DOE 2023b).

Third, investments within a given facility may succeed only if coordinated with other investments. These include investments in enabling infrastructure like renewable energy installations, hydrogen electrolyzers, and CO_2 storage wells, which may require the creation of industrial clusters where multiple firms share the costs and risks of low-carbon infrastructure (IEA 2021b). They also include investments to strengthen the circularity of value chains and align the changing needs of manufacturers with their suppliers.

Finally, investments in industrial decarbonization must sometimes contend with competing priorities. For example, low-carbon technologies that entail higher operating costs can lower the competitiveness of trade-exposed industries, triggering their relocation to other countries (Rissman 2024). Therefore, investments in decarbonizing a country's industry should accompany policies and other interventions that mitigate any adverse impacts, like carbon border adjustment mechanisms that protect industry's competitiveness (see the section of this chapter on carbon pricing for more information).

Additional context on financing industrial projects in the East Asian region

All around the world, government support is critical for driving investment in large-scale, high-risk deployments of advanced industrial technologies (i.e., interventions in Tiers 2b through 4b). However, government support may take different forms depending on how large industrial projects are typically financed in a given region. Advanced economies (e.g., the United States, Europe, Japan, and Republic of Korea) have developed capital markets that facilitate access to large volumes of equity and debt from the private sector (Narayanaswamy et al. 2017). In these countries, government support is most critical for overcoming the economic and technological barriers to deploying advanced industrial technologies (e.g., high energy costs and low technology maturity), since financing is broadly available for commercially viable technologies.

China is a unique case. Its capital markets are less developed than those of advanced economies. Nevertheless, as China's economy booms, its capital markets are rapidly growing. More important, China's state-managed financial system is capital-rich, equivalent to over four times China's GDP (World Bank 2022a), directing large volumes of debt and equity to industries and projects that align with national policy goals. Many large firms in China already benefit from significant government financing support, including direct investment (e.g., government equity infusions though government guidance funds) and top-down coordination of capital allocation from China's banks (especially to state-owned enterprises), in addition to grants, subsidies, and regulations that favor strategic industries (Boullenois et al. 2025). Therefore, beyond overcoming economic and technological barriers to advanced industrial deployments, the acceleration of green investment in Chinese industry is mainly a matter of adjusting national policy priorities to emphasize deep decarbonization of industry.

In addition to their undeveloped capital markets, other EMDEs like Indonesia and Viet Nam face other institutional barriers to coordinating financial support. They lack China's more centralized networks for policy implementation and administration. For example, in Indonesia, both national and provincial government budgets are small and inflexible relative to the country's infrastructure investment needs (Anbumozhi et al. 2023). In Viet Nam, foreign direct investment (e.g., foreign firms building plants or establishing joint ventures with local firms in another country) accounts for around 85 percent of products manufactured for export, implying a lack of domestic capital available for large-scale industrial projects (World Bank 2022b). To decarbonize their industrial sectors, EMDEs other than China need much more support from governments and IFIs, both to increase the availability of capital for industrial decarbonization and to direct it to the highest priority projects. Debt availability may prove the most beneficial, as indicated by Indonesian manufacturing firms' preference for debt over equity when seeking external financing (Goenawan and Wasistha 2019).

Policy options to accelerate investment in decarbonizing industry

There are two main ways for governments to accelerate investment in industrial decarbonization technologies that are not yet bankable. First, they can introduce policies to reduce the operating costs of industrial projects, helping projects generate a return on investment and thus attract private finance. Such policies include carbon pricing (see previous section on carbon pricing in this chapter), policies to lower the costs of electricity generation (see previous section on policies for later-stage industrial decarbonization dependent on electricity), and direct public funding (e.g., tax credits) to support clean production. Second, public entities can help to de-risk industrial projects through direct financing of projects, other financing support mechanisms, and policies to support the development of early markets for low-carbon products (see section on addressing capital and installation costs).

In capital-poor EMDEs like Indonesia and Viet Nam, IFIs can supplement the government support described above in a number of ways. First, to de-risk industrial decarbonization investments, IFIs can bundle small investments, foreign and domestic, and channel them to specific industrial projects, providing capital for large-scale projects and de-risking individual investments (IEA 2025d). IFIs can also contribute finance or risk guarantees to blended finance instruments, provide risk guarantees to foreign lenders, and/or facilitate cross-border guarantees to assuage foreign investors' concerns about the creditworthiness of EMDE governments or sovereign risk. To mitigate foreign exchange risk, IFIs can offer currency hedging instruments (e.g., swaps and forward contracts) or local currency finance. Second, IFIs can use their international networks to coordinate project stakeholders in EMDEs and foreign entities. This may include connecting EMDE firms and governments with international investors, establishing international cooperation agreements that allow projects to benefit from foreign technologies and technical expertise, or encouraging long-term commercial partnerships where foreign countries agree to import low-carbon goods from EMDEs. Finally, IFIs can help build the capacity of EMDE governments to financially support industrial projects. This may include helping governments to conduct risk assessments and financial analyses that inform the selection and design of de-risking policies (e.g., government equity injections, concessional loans, public guarantees), providing technical assistance to governments taking a more active role in planning and managing large industrial investments (e.g., via government equity injections, blended finance, or public-private partnerships), and helping governments create special purpose vehicles to finance industrial projects off the government's balance sheet.

Financing renewable energy and green hydrogen to meet the clean energy demands of low-carbon industry

Most of the interventions deployed in our model will increase industrial demand for electricity, whether to directly electrify processes or create green hydrogen for energy and feedstocks. By 2050, following all interventions through Tier 4b, Chinese industry will demand around 86 percent more electricity than it would have used in a BAU scenario, Indonesian industry will demand 46 percent more, and Vietnamese industry will demand 56 percent more. It is doubly challenging that these projected levels of electricity demand dwarf the clean energy capacities in each country today, given that industry can only fully decarbonize with clean electricity (IEA 2025a, 2025c, 2025e). Accelerating renewable energy deployment is no easy task, especially in the context of higher electricity demand from vehicles, buildings, data centers, and an upwardly mobile population. IFIs, including development finance institutions, can play an important role in overcoming this challenge in EMDEs.

For one, IFIs can catalyze private finance by mitigating the perceived risks of investing in renewable energy projects in EMDEs, like the risk that utilities will not be paid for their power output or the risk that local supply chains cannot support equipment needs (Laxton et al. 2024). One de-risking pathway is to invest in enabling grid infrastructure, including modern transmission and battery storage systems. This is especially important in Southeast Asian EMDEs, where public ownership and decentralized governance of grid infrastructure are barriers to private investment, leading to large renewable energy interconnection backlogs. Another pathway is to offer innovative financing mechanisms suited to the risk profile of renewable energy projects. Loan guarantees and risk insurance can reduce private investors' uncertainty about debt repayment, and blended finance tools and public-private partnerships can spread risks across more investors (Choi and Laxton 2023). IFIs can also issue "green bonds" for renewable energy projects or establish pooled investment vehicles (e.g., infrastructure investment trusts, asset-backed securities) where individual units can be sold to investors who receive a regular income (PricewaterhouseCoopers 2020).

IFIs can also coordinate among policy and financial stakeholders to create a supportive environment for renewable energy projects (Laxton et al. 2024). Those with climate and clean energy expertise can make certain financial support contingent on the passage of supportive policies in EMDEs, and they can also offer capacity-building support to national and subnational financing institutions within those countries. Additionally, IFIs can coordinate with one another around the definitions of climate finance mechanisms (e.g., green bonds) and the provision of credit enhancement support for those mechanisms. They can also work with financing institutions within EMDEs to aggregate small-scale renewable energy projects into the pooled investment vehicles described above, and coordinate with global entities to mitigate the risks associated with local currency fluctuations in EMDEs.

Green hydrogen has its own unique financing needs, in addition to its reliance on abundant renewable energy. The production of clean hydrogen (including green and blue hydrogen) may require a global investment of $700 billion in all countries other than China between now and 2030, with EMDEs accounting for up to half of that investment (ESMAP et al. 2023). Today, investors have committed just 4 percent of that $700 billion. In addition to lowering renewable energy costs, governments and IFIs can reduce these costs by helping to lower the cost of capital for green hydrogen projects, which currently account for 30 percent to 50 percent of project costs. Specifically, they can conduct project risk assessments and then offer tailored de-risking mechanisms, such as long-term hydrogen offtake agreements, risk and credit guarantees, political risk insurance, and contracts for difference. Large-scale green hydrogen demonstration projects, such as the World Bank's "lighthouse" initiative to deploy 10 gigawatts of electrolyzer capacity in EMDEs, can also de-risk and accelerate green hydrogen investments by demonstrating project viability, setting standards around supply chain considerations and project outcomes, and reducing capital costs (World Bank 2023c).

Policy options to ready the workforce for industrial decarbonization

East Asia's pathway to industrial decarbonization will be increasingly constrained without a coordinated transformation of its workforce. A widening skills gap—driven by both rapid technological change and the structural decline of fossil fuel-intensive sectors—is emerging as a critical bottleneck. Provinces facing the dual pressures of decarbonization and automation, like Shanxi and Inner Mongolia in China, are experiencing acute mismatches between the existing labor force and the evolving needs of green industries. Without deliberate, system-wide interventions, the transition risks deepening regional disparities, underutilizing labor potential, and slowing emissions reduction efforts. A targeted workforce strategy is urgently needed. It should rest on three mutually reinforcing pillars: (1) modernizing vocational education, (2) embedding digital and interdisciplinary skills, and (3) delivering targeted transition support in structurally exposed regions.

Modernizing vocational education requires reorienting the technical and vocational education and training systems across the region, which remain concentrated in traditional fields like mechanical and electrical maintenance, toward emerging green occupations. These include carbon accounting, industrial energy efficiency, emissions auditing, and renewable energy operations. Curricula should be systematically updated to reflect sector-specific decarbonization needs and delivered through modular, stackable credentials that support flexible reskilling, especially for mid-career workers. Enterprise–government–institution partnerships should be formalized to align training content with labor market demand and investment pipelines. In practical terms, this means embedding structured apprenticeships and work-based learning into industrial retrofitting, clean energy deployment, and decarbonized supply chains.

Embedding digital and interdisciplinary competencies is equally critical, as industrial decarbonization increasingly demands talent capable of navigating complex, data-driven systems that span engineering, environmental science, and policy. Yet many institutions lack the capacity to deliver digital and cross-cutting content at scale. Addressing this gap will require embedding digital fluency, systems thinking, and sustainability principles across vocational, tertiary, and continuing education systems. Applied universities and polytechnic institutes have a central role in cultivating mid-level professionals who can integrate production, compliance, and innovation functions. Partnerships with industrial parks and research institutions should co-develop curricula in areas such as carbon markets, green supply chain analytics, and industrial decarbonization technologies. Flexible delivery mechanisms—micro-credentials, blended learning, mobile platforms—are essential to reach workers in underserved regions.

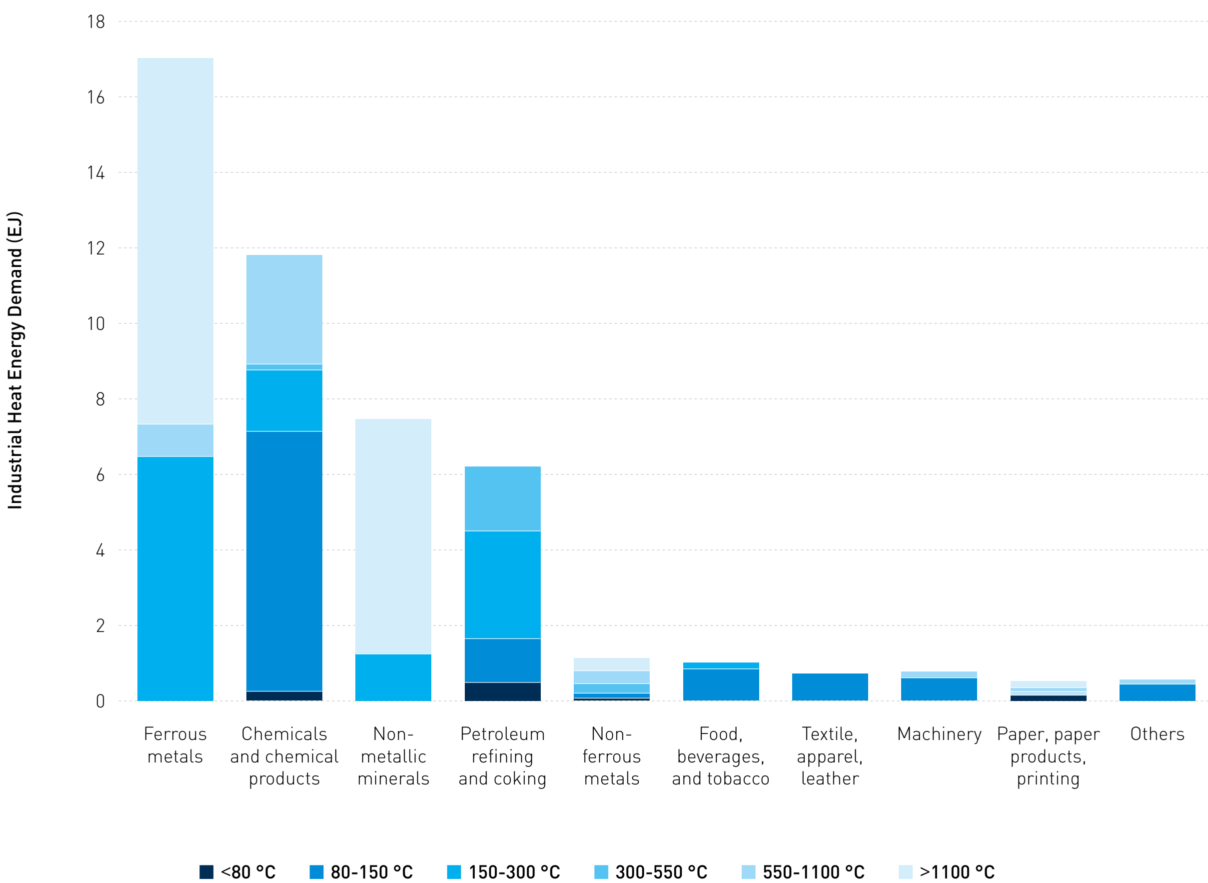
Delivering targeted transition strategies in coal-dependent provinces will be essential to managing displacement and ensuring a just transition. These regions face overlapping vulnerabilities: declining employment in extractive sectors, low skill mobility, and limited absorptive capacity in alternative industries. Transition strategies should begin with granular labor market diagnostics aligned with subnational decarbonization scenarios. These should identify at-risk worker groups and map emerging labor demand based on planned green investments. Reskilling programs must be embedded in regional industrial diversification strategies and aligned with accessible, locally relevant occupations—such as building retrofits, electrification, clean logistics, and CCUS operations and maintenance. Demand-side incentives—such as wage subsidies, retraining tax credits, and green wage top-ups—should support employer participation. Implementation responsibilities should be devolved to provincial governments, with national support in the form of financing, technical assistance, and oversight. A workforce transformation strategy built on these pillars will not only mitigate the social risks of industrial decarbonization but serve as a foundational enabler of long-term economic competitiveness and inclusive green growth.

Deep Dive: Industrial Electrification in China

China accounts for much of the industrial output and emissions in the East Asian region, and Chinese industry continues to rely on fossil fuels for 71 percent of its final energy use. It is therefore imperative to shift most of that energy demand toward renewable sources. An estimated 73 percent of China's total manufacturing energy use today is for industrial process heating, almost all of which is supplied by fossil fuels, so direct electrification is critical for decarbonizing Chinese industry (Sawe et al. 2024).

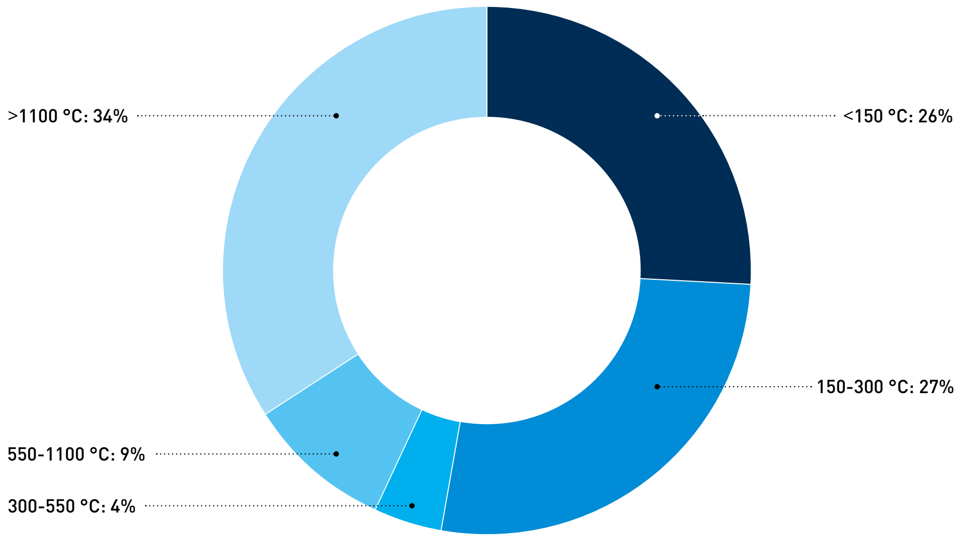
As discussed earlier, China's industrial energy use is dominated by four energy-intensive industries: iron and steel, chemicals, refining, and nonmetallic minerals, which together account for 81 percent of China's industrial emissions. These industries rely not just on large quantities of heat, but also on substantial amounts of medium- and high-temperature heat **(FIGURE 6.1)**. In fact, more than half of China's manufacturing sector process heat demand exceeds 300ºC **(FIGURE 6.2)**.

FIGURE 6.1 Industrial heat energy demand and temperature requirements in China by manufacturing subsector, 2021



Source: *Sawe et al. 2024.*

FIGURE 6.2 Process heat energy demand by temperature grade in China's manufacturing sector



Source: *Sawe et al. 2024.*

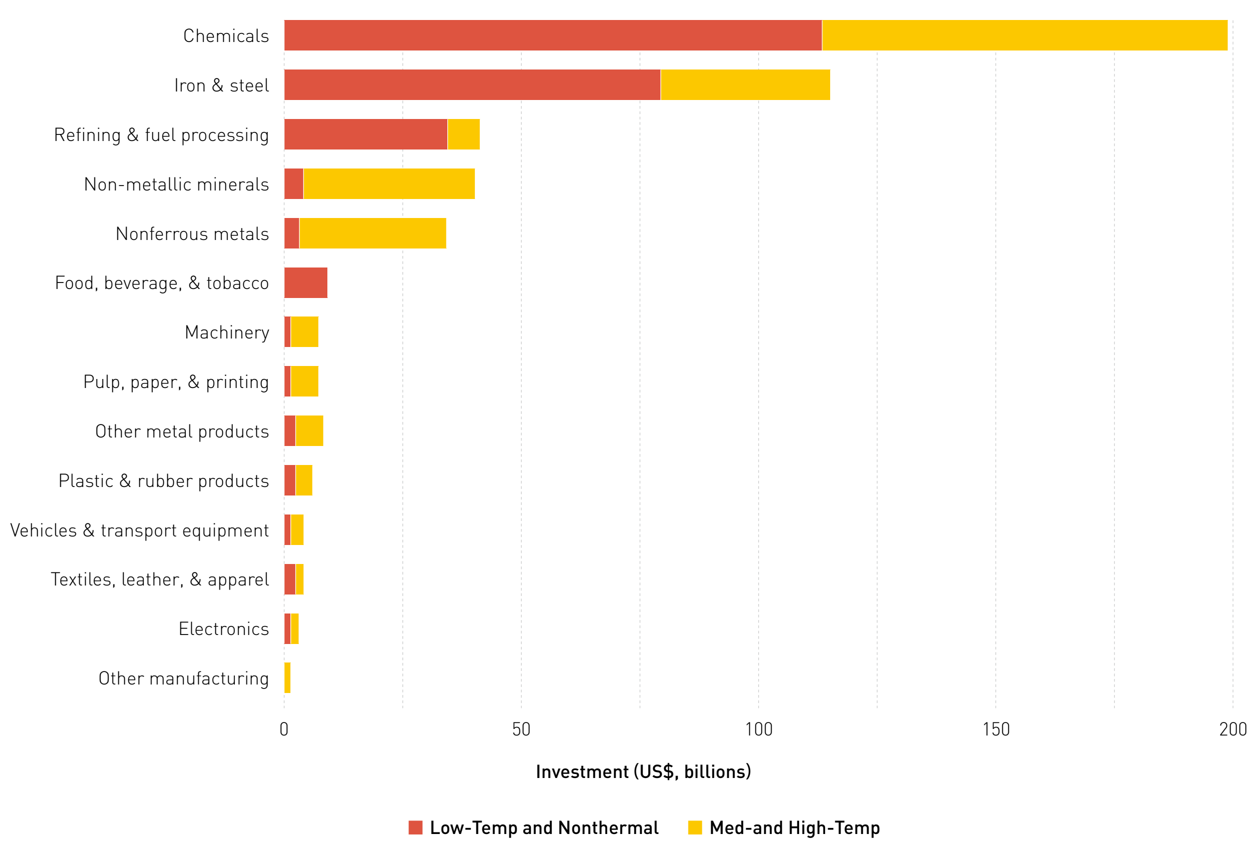
Impacts of electrification tiers on industrial energy use in China

Industrial electrification is the option with the highest impact for reducing and decarbonizing industrial energy use in China. Electrified heating has several practical advantages over other low-carbon alternatives to fossil fuel combustion (these are detailed in the section of Chapter 2 on Tier 2b). In our model, even after Tier 1 efficiency interventions are fully deployed in Chinese industry, electrification interventions in Tiers 2a and 2b still lower the remaining industrial energy use by 24 percent **(FIGURE 3.4)**. The energy use reduction impacts of easy electrification (Tier 2a) are the most significant in the iron and steel industries (40 percent); food, beverage, and tobacco (27 percent); chemicals (20 percent); other metal products (17 percent); and refining (16 percent); most other industries see reductions of 5 percent to 10 percent. The additional energy use reductions from other electrification interventions in Tier 2b are most pronounced in other metal products (9 percent), nonmetallic minerals (9 percent), nonferrous metals (7 percent), and vehicles and transport equipment (6 percent); all other industries show reductions under 6 percent.

The capital costs of electrification are not negligible, but they represent only a small share of industrial equipment's lifetime costs and are not substantially higher than the capital costs of conventional equipment. Moreover, the model's electrification tiers require lower capital expenditures than the CCUS and green hydrogen tiers, at $252 billion for Tier 2a and $229 billion for Tier 2b. After efficiency improvements, Tiers 2a and 2b also offer the best yield in terms of tonnes of CO_2 reduced annually per dollar of capital investment, at $198 and $556 per tonne per year, respectively.

Below is a breakdown of this capital investment in electrification by subindustry (FIGURE 6.3). This investment is led by China's five most energy-intensive subindustries: chemicals ($199 billion), iron and steel ($116 billion), refining ($41 billion), nonmetallic minerals ($40 billion), and nonferrous metals ($34 billion). Tier 2a interventions—including low-temperature and non-thermal electrification and secondary steelmaking—make up the majority of electrification-related capital investment in chemicals (57 percent), iron and steel (68 percent), refining (83 percent), and food, beverage, and tobacco (97 percent). Solutions for medium- and high-temperature heat (Tier 2b) take up most electrification-related capital spending for nonmetallic minerals (91 percent) and nonferrous metals (92 percent).

FIGURE 6.3 Capital investment needs for electrification in China (Tiers 2a and 2b), by industrial subsector



Existing technologies can electrify industrial process heat at all temperatures, although the equipment for high-temperature electric heating is still being developed and commercialized (Rissman 2024). The low readiness of some technologies affects their upfront costs, investment risks, and availability; these metrics will improve with continued research, development, and demonstration (see the section of Chapter 5 on this topic).

Cost-effective electrification technologies

Cost is a major obstacle to the electrification of industrial process heating, which represented an estimated 62 percent of China's manufacturing sector's final energy consumption in 2021 (Sawe et al. 2024), when the price of coal for industrial use was $12 per megawatt-hour (MWh) compared with the $97 MWh industrial electricity price (Hasanbeigi et al. 2023). Although these cost disparities can be mitigated by savings—for example, on cooling water, exhaust treatment, and maintenance of combustion equipment used for electrification—these cannot by themselves close the gap. For example, the labor and maintenance expenses for electric boilers are estimated to be 80 percent lower than those for coal boilers (Sawe et al. 2024). However, because more than half the total lifetime cost of boilers is attributed to energy costs (Zuberi et al. 2021), bridging the cost differential calls for cutting the costs of clean electricity or hiking the costs of fossil fuels for combustion in industrial settings.

Two commercial technologies can partially or fully overcome the high operating costs of industrial electrification in China: industrial heat pumps and thermal batteries.

Industrial heat pumps

Heat pumps have tremendous potential to supply most of China's needs for low-temperature process heat (addressed in Tier 2a). Heat pumps extract heat from a source (e.g., the air, or waste heat from another industrial process), manipulate its pressure to raise its temperature, and deposit that heat into a sink, akin to the systems in a refrigerator or air conditioner. Capable of outputting heat at up to 165°C, with earlier-stage models supporting up to 200°C, heat pumps are unique for their high efficiency (Sawe et al. 2024). Because they redistribute rather than generate heat, heat pumps can be up to four times more efficient than an idealized electric resistance heater that converts 100 percent of electricity into heat. No other heating technology exceeds 100 percent efficiency. While the efficiency of heat pumps declines with higher input temperatures, it remains high: a heat pump in the upper range that boosts the temperature of the input heat by 130°C is still 50 percent more efficient than an idealized electric resistance heater (Arpagaus et al. 2018).

In China's case, industrial heat pumps support temperature ranges that would address 3–15 percent of the non-electricity energy demands of industry (IEA and Tsinghua University 2024, Sawe et al. 2024). As China transitions from more energy-intensive industries (e.g., steel and cement) to others, its use of industrial heat pumps will increase in share. Food and beverages, pulp and paper, textiles, and other industries that often require hot water or steam are ideally suited for heat pump use (Arpagaus et al. 2018). Specific low-temperature applications may still be unsuitable for heat pumps, but they are niche cases. For instance, an industrial microwave used for cooking food quickly and thoroughly may have a similar temperature range but differ substantively enough in its heat delivery mechanism that heat pumps are a poor substitute.

Given their high efficiency, heat pumps can electrify large quantities of low-temperature heat without raising operating costs for firms. A techno-economic analysis found that industrial heat pumps were cost-effective when compared with conventional options and other clean technologies for temperature needs up to 100°C, second only to coal-fired boilers; however, when incorporating a 2030 estimated carbon cost, they became the cheapest option at ¥260 per megawatt-hour of thermal output (MWhth) ($38/MWhth). Higher-temperature ranges cost ¥391/MWhth ($58/MWhth), broadly comparable to natural gas boilers, but are likely to become cheaper and more cost-effective as manufacturing scales up for these higher temperature models.

The analysis also revealed that industrial heat pumps had the lowest CO_2 emissions compared to competitive technologies, with the exception of natural gas combined heat and power units that can reduce firms' consumption of electricity from China's coal-heavy grid (Sawe et al. 2024). As the country's grid becomes cleaner, the associated emissions of industrial heat pumps and other electrified options will drop to zero.

Still, industrial heat pumps present technological hurdles to their adoption. Many on the higher end of the temperature range need to pair with an existing heat source like waste heat from another industrial process, the availability of which will decline as industrial energy efficiency scales. Additionally, heat pumps are larger than steam boilers and have a lower maximum power output than high-capacity boilers, which may present challenges when incorporating them into existing facilities (IEA and Tsinghua University 2024). The power output concern can be allayed by pairing two heat pumps with an output modulated by steam demand, as well as balancing steam demand over time; this can provide energy savings compared to a large single boiler (Sawe et al. 2024). Although heat pumps are commercial technologies, continued RD&D is necessary for them to overcome these performance hurdles.

Thermal batteries

Thermal, or heat, batteries convert electricity into heat that can be stored for hours or even days. Batteries in development today can support temperatures up to 1,700°C (Rissman and Gimon 2023), hot enough to meet over two-thirds of China's industrial heating demand (although today's commercial models reach only 300 to 500°C) (Sawe et al. 2024). Naturally, thermal batteries are not the technological solution for all applications within that heat range. As discussed below, they need access to variable electricity rates, like the time-of-use (TOU) prices discussed in chapter 5, that periodically dip to low levels to make financial sense.

Thermal batteries use large quantities of thermal storage material with a high specific heat capacity (e.g., graphite or silicon dioxide). Held in an insulated shell, these batteries can lose as little as 1 percent of their heat per day (Rissman and Gimon 2023). Wires are connected to the battery's internal electrical resistance heaters, which turn electricity into heat that is absorbed by the storage material. Heat can then be extracted from the thermal battery by either pumping air or steam to be used in an industrial process through the storage material or opening shutters on the battery casing to emit infrared and visible light. Heat losses can be as low as 5 percent (Rissman and Gimon 2023).

Thermal batteries can be used in on- and off-grid configurations, both of which can significantly lower firms' electricity costs. In off-grid configurations, facilities could produce clean electricity on-site or could procure it from a nearby renewable source at prices cheaper than retail electricity from the grid. Because they can store heat for multiple hours or days, thermal batteries could smooth out variability from renewable sources, providing heat even when solar and wind production is low and can bolster industrial operations when the grid is unreliable. Moreover, by helping to avoid the curtailment of renewable electricity, they can accelerate renewable energy deployment.

In most instances, on-grid configurations may be more practical in China. Manufacturing facilities are located in the eastern provinces, where land and ability to build out new renewable generation may be limited. Grid-connected batteries lower electricity costs by allowing firms to purchase electricity when it is cheapest and bank it as heat for later use, like when the grid's electricity demand is at its peak. China's intraday prices for industrial electricity buyers vary greatly, based on province, time of year, and other factors. In some provinces, electricity prices can dip as low as 30 percent to 40 percent of the average price (Sawe et al. 2024). Modeling of thermal battery usage in China's populous Guangdong and Shandong provinces, for example, showed that thermal batteries allowed industrial firms to purchase energy at 34 percent of the cost compared with energy they needed to purchase continuously throughout the day (Sawe et al. 2024).

As with industrial heat pumps, as China's grid decarbonizes, the CO_2 emissions from thermal battery usage drop to zero (Sawe et al. 2024). With China's carbon neutrality target of 2060 (Sengupta 2020), the grid's trajectory will make thermal batteries increasingly attractive from an emissions standpoint in the coming decades.

As the production of heat represents 90 percent of industrial fossil fuel use in China (based on modeling done in this study), storing energy as heat in thermal batteries is substantially cheaper than storing electricity with lithium-ion batteries if the stored energy is ultimately used as heat. Thermal batteries are estimated to be extremely cost-effective when manufactured at scale, around $27 per kilowatt-hour (kWh) of capacity; by contrast, a lithium-ion battery runs $150 per kWh (Henze 2022, Rissman and Gimon 2023). In the technoeconomic analysis discussed earlier, the levelized cost of heat from thermal batteries fell between that from low- and high-temperature heat pumps, at ¥314/MWhth ($46/MWhth) (Sawe et al. 2024), though their ability to support far higher temperatures permits them a larger range of use cases.

Electric arc furnaces

Electric arc furnaces (EAFs) are another cost-effective industrial electrification technology, producing steel with heat generated from electric arcs. EAFs are already widely adopted globally for secondary steel production, which uses scrap steel as an input and is far less energy-intensive than the more commonly used blast furnace-basic oxygen furnace process for primary steelmaking. EAFs can also produce primary steel using direct reduced iron (DRI) or pig iron as inputs, but that steelmaking pathway is far less common. In 2023, 29 percent of the world's crude steel was produced via EAF; China's share, however, was only 10 percent (World Steel Association 2024).

One of the major challenges to scaling scrap-based EAF is the availability of high-quality scrap steel. The China Iron and Steel Association projects that scrap steel availability will reach 350 million tonnes (Mt) per year by 2030 and 500 Mt per year by 2050 (Hasanbeigi et al. 2023). Scrap steel supply and quality, however, continue to be constrained as China's steel recycling industry is fragmented and relies on small and inefficient facilities. As a result, poor-quality control introduces high levels of tramp elements into the mix (Hasanbeigi et al. 2023).

Steel recycling rates are high in the United States, averaging between 80 percent and 90 percent in recent years and reaching as high as nearly 100 percent for automobiles (Tuck 2021), with 68 percent of crude steel coming from EAFs (World Steel Association 2024). One enabling factor for the widespread use of EAFs in the United States is the vertical integration of major steel manufacturers with scrap steel collectors (David J. Joseph Company 2022), which allows manufacturers to control the source and quality of scrap. Vertical integration also allows scrap collectors to establish extensive networks of facilities. With better sorting, copper content and other tramp elements in scrap steel can be managed, which lowers the likelihood of contamination. When the tramp elements exceed technical requirements, they are commonly diluted with DRI.

Policies to overcome the challenges of high electricity costs

Although heat pumps, thermal batteries, and EAFs can in theory electrify most industrial process heat in China, certain barriers may limit their scalability (e.g., industry's access to TOU pricing, suitability for specific facility configurations). This means that electrification will entail high electricity costs in some industrial processes. Electric utilities in China can help to lower these costs with better rate designs and conditional discounts.

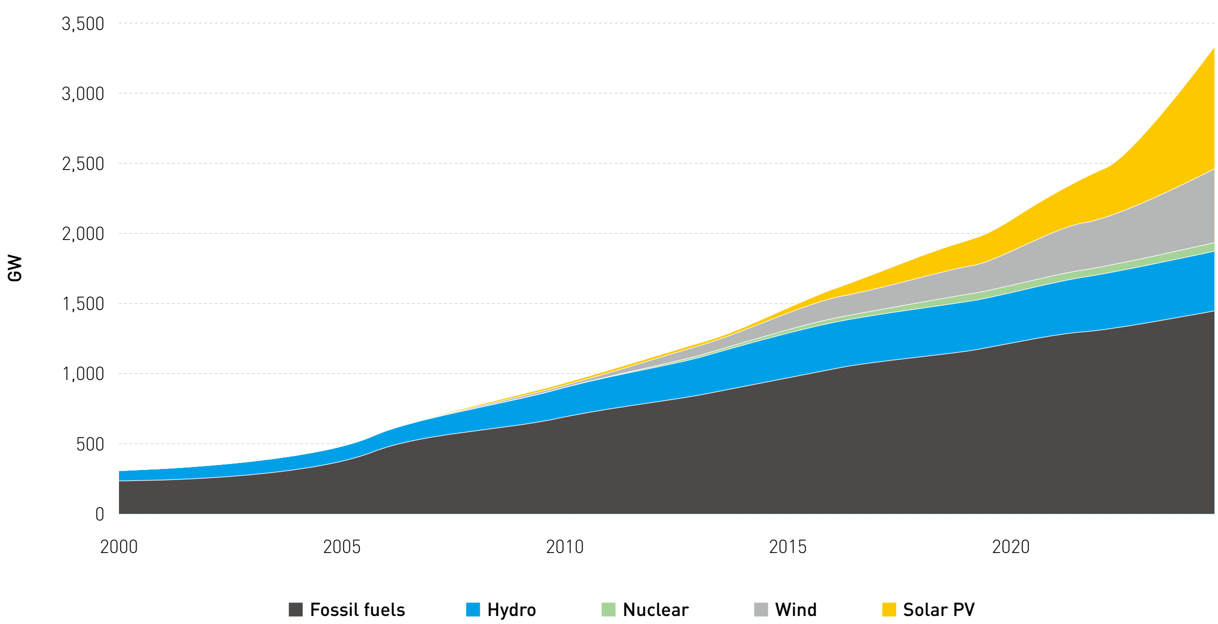
In order to subsidize consumers, China charges a higher electricity tariff for industrial customers than for residential customers. This means that industrial electricity prices are 40 percent higher than residential prices (Sawe et al. 2024), further widening the cost gap between electricity and fossil fuels and thwarting electrification.

One potential solution involves interruptible tariffs and TOU rates that encourage demand-side management (Johnson et al. 2024). These allow industrial facilities to be flexible, or to use flexible processes—pumps that recharge storage tanks and thermal batteries, for example—when electricity prices are low. Another approach involves conditional discounts to industrial facilities that meet energy efficiency performance criteria or use efficient heat pumps. Demand flexibility and energy efficiency do more than help industrial customers lower electricity bills by optimizing the time and volume of electricity consumption. They help the grid avoid curtailment and reduce peak demand (Johnson et al. 2024). In the building sectors of other countries, they are used as a grid resource to boost variable renewable energy utilization and allow deferred investments in new energy generation and storage (Langevin et al. 2021). Utilities can then pass on the savings to electricity consumers, leading to lower rates.

The availability of clean electricity for industrial electrification in China

Clean electricity is an important enabler of industrial electrification, and nowhere is it more abundant than China. China's renewable energy capacity soared over the past decades, often breaking its own records. Between 2009 and 2024, solar photovoltaic (PV) capacity grew from 0.03 to 887 gigawatts (GW) and wind power capacity grew from 17.6 to 521 GW, with average growth rates of 59 and 34 GW per year, respectively. By the end of 2024, China's cumulative renewable energy generation capacity—including hydro, solar, and wind—accounted for 55 percent of total installed capacity **(FIGURE 6.4)**.

FIGURE 6.4 China's electricity installed capacity by source, 2000–24

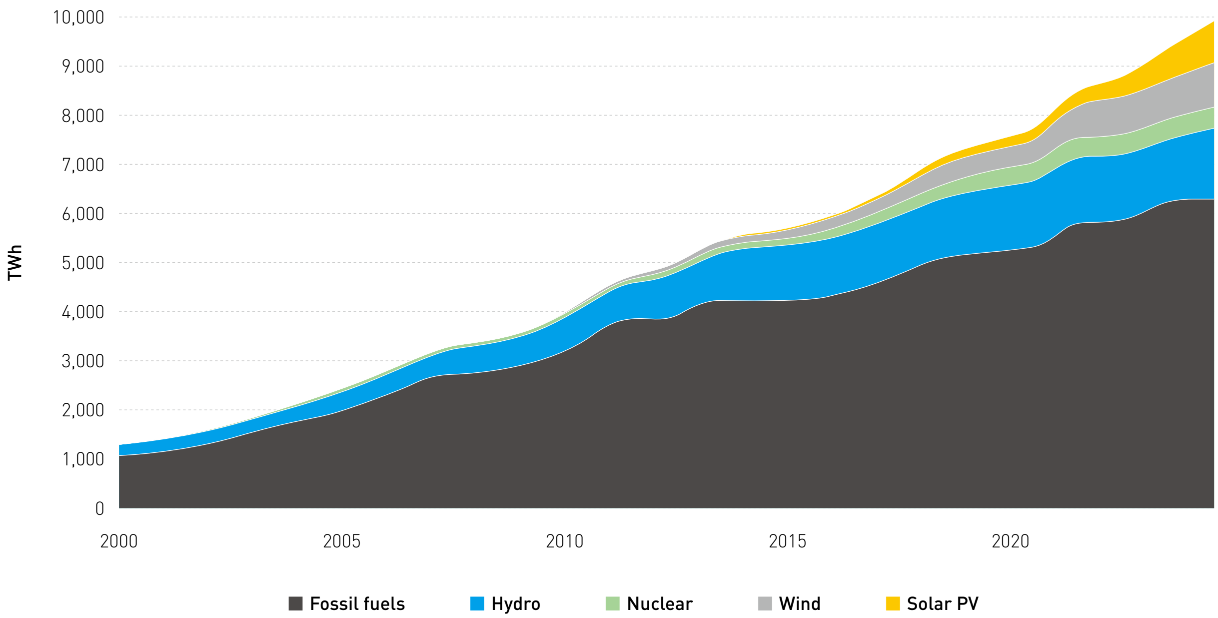


Source: *NBS 2024.*

In 2024, "new energy" power generation capacity, which includes sources like solar, wind, and biomass, reached 1,450 GW, exceeding China's fossil-based power generation capacity for the first time. That same year, newly installed wind and solar accounted for about 80 percent of newly installed capacity (355 GW). Between 2023 and 2024, wind and solar capacity grew at rates of 18 percent and 45 percent, respectively, much higher than the 4 percent growth of fossil-based installed capacity (China Electricity Council 2025).

In terms of electricity generation, the share of renewable energy production also rose, from 17 percent in 2000 to 32 percent by 2024. From 2020 to 2024, wind and solar power generation increased by an annual average of 18 percent and 35 percent, respectively, compared to only 4 percent for fossil-power generation. Between 2010 and 2024, total wind and solar power generation increased immensely, from 45 TWh to 1,764 TWh **(FIGURE 6.5)**.

FIGURE 6.5 China's electricity production by source, 2000–24



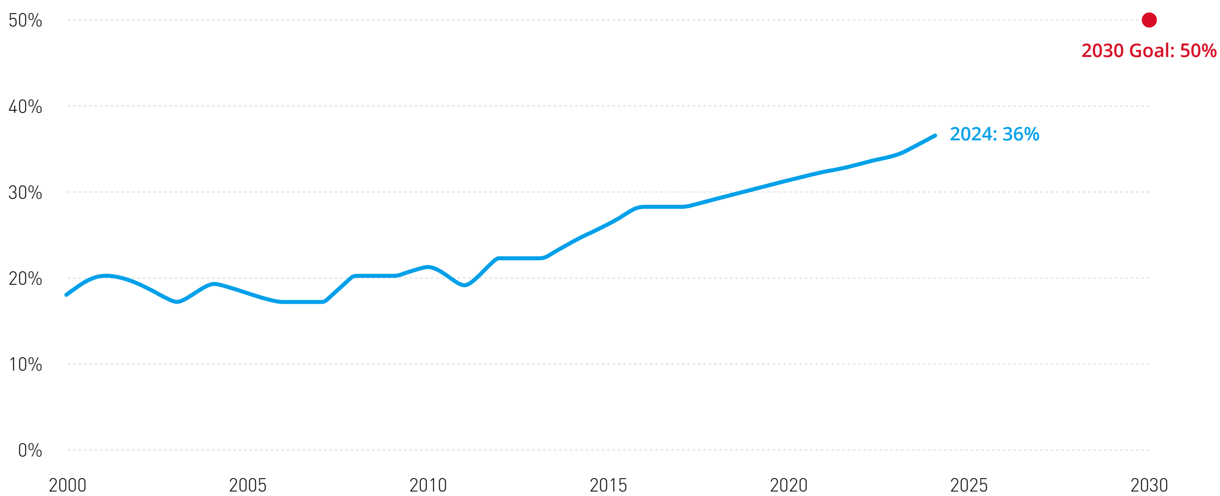
Source: China Electricity Council 2025.

Government plans and goals for further renewable energy deployment

Ambitious policies and goals have driven, and continue to drive, China's rapid renewable energy deployment. By 2030, the government aims to increase the share of non-fossil power generation to half of total power generation (NDRC 2017). In 2024, that share was 36 percent **(FIGURE 6.6)**.

China announced plans to continue increasing renewable energy deployment in its 14th Five-Year Plan (2025–2030). By 2025, it plans to increase wind capacity to between 400 and 450 GW and solar PV capacity to between 600 and 650 GW. By the end of 2024, China's total wind and solar PV installed capacity was 521 GW and 887 GW, respectively, surpassing the goals by 16 percent and 36 percent, one year in advance.

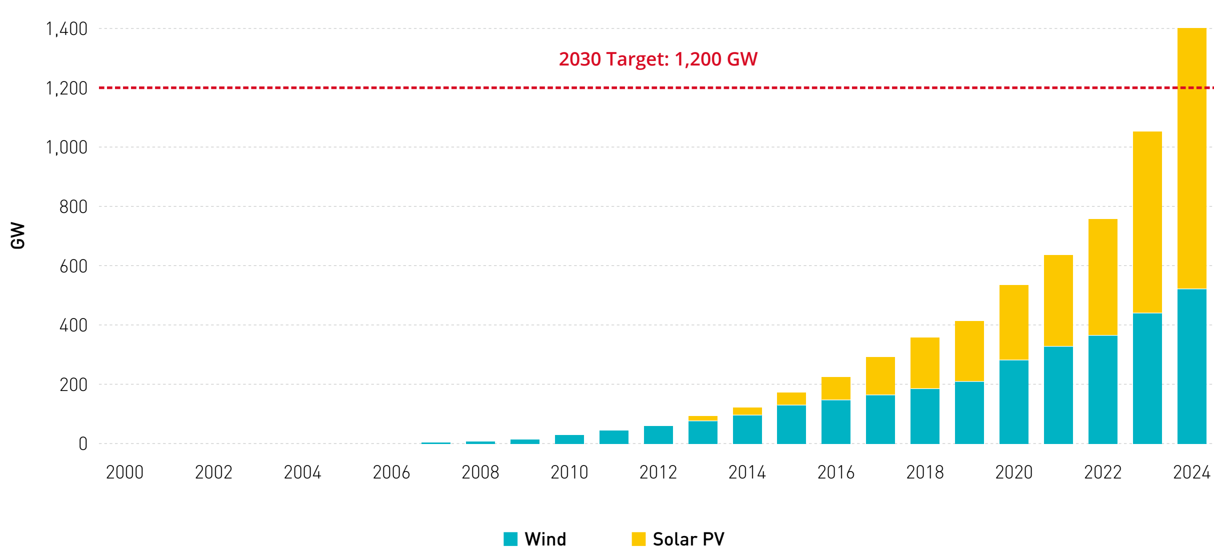
FIGURE 6.6 Share of nonfossil power generation in China, 2000–24



Source: *NBS 2024, China Electricity Council 2025.*

In an action plan to peak CO_2 emissions before 2030, China aimed to increase total installed capacity of solar and wind to 1,200 GW by 2030 (State Council 2021). By the end of 2024, China's total solar and wind capacity reached more than 1,400 GW, achieving the goal six years ahead of time (**FIGURE 6.7**).

FIGURE 6.7 Total solar and wind installed capacity in China, 2000–24



Source: *NBS 2024, China Electricity Council 2025.*

China is now developing its 15th Five-Year Plan (2026–30), which is expected to be released in March 2026. This plan will open a window for the implementation of power market reforms that support more renewable energy generation and provide market incentives to deliver system flexibility, through mechanisms such as effective price signals, improved dispatching practices, more market participation, and better, more optimized resource sharing nationwide (e.g., promote interprovincial trading).

Policies to accelerate renewable energy deployment in China

Despite China's rapid progress in building out renewable energy, further deployment may be constrained by the country's uneven geographic distribution distribution of renewable resources and the grid reliability risks posed by a high penetration of variable energy. Interregional transmission infrastructure and energy storage (grid-side and demand-side) can help to mitigate these issues, but their scale-up relies on important market reforms and enabling policies.

China's recent efforts to liberalize electricity markets mark a step toward better integration of renewable energy into the grid, but they are limited in two ways. First, electricity market reforms have largely focused on medium- and long-term power contracts that prioritize predictable outputs over variable renewable energy (Shen et al. 2024). The extension of additional liberalization measures to spot markets and ancillary service markets would create more opportunities for both renewable energy and energy storage to participate, as has been demonstrated by spot market pilots in provinces like Shanxi, Guangdong, Shandong, Inner Mongolia, and Gansu (Gao et al. 2024). Second, government-imposed price caps in the power market often disadvantage renewable energy and energy storage technologies, which rely on fluctuating prices to recoup their costs (Shen et al. 2024). Expanding market liberalization efforts and reevaluating price cap policies could accelerate the integration of these crucial technologies.

Furthermore, many decarbonization programs in China (e.g., green certificate trading, cap-and-trade, China Certified Emission Reduction, energy use permits) are siloed from electricity markets, lacking harmonized rules or oversight. Policies integrating the electricity market with these market programs can ensure that energy prices better reflect the cost of emitting and simplify compliance processes (Shen et al. 2024).

China's continued reliance on coal power is also hindering the deployment of renewable energy. While certain applications of coal power, like grid flexibility enhancement, can increase renewable energy integration in the short term, building new coal power plants could lead to technology lock-in (Shen et al. 2024), slowing uptake of alternative energy resources, including energy storage and demand-side resources. According to a 2021 study by Kahrl et al. (2021), for China to retire coal power by 2040 with no stranded assets, all existing coal power plants must be replaced with alternatives by the end of their financial life and all new electricity demand must be met with noncoal generation by the early 2020s. Policies that could effectively curb new coal power installations include enhanced carbon pricing, stricter air pollution regulations, and bans on new coal plants in specific regions. These strategies not only support the transition to renewable energy but also align with global sustainability targets.

Policies to help industrial firms access clean electricity

As mentioned earlier, solar and wind now make up 36 percent of China's total installed electricity generation capacity (China Electricity Council 2024). Despite the country's speedy progress on renewable energy deployment, industrial facilities continue to face major geographical, political, and economic barriers in accessing clean electricity. Policies that can help overcome those barriers are explored below.

Geographical distribution of renewable energy resources

Coastal provinces account for much of China's industrial activity but little of its renewable energy potential. According to studies by He and Kammen (2014), coastal provinces (i.e., Liaoning, Hebei, Tianjin, Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi, and Hainan) can collectively generate between 68 terawatt-hours (TWh) and 195 TWh of energy from onshore wind, 810 TWh from offshore wind, between 1234 TWh and 5244 TWh from central PV, and 140 TWh from distributed PV. Provinces in the Yangtze Delta, including industrial centers like Jiangsu, Shanghai, Zhejiang, and the inland province of Anhui, are even more resource-poor, with 7 to 23 TWh of annual onshore wind generation capacity and 45 TWh to 251 TWh of annual central PV generation capacity. On the whole, coastal provinces account for only 5-7 percent of China's total onshore wind potential and 8-15 percent of its central PV potential (He and Kammen 2014). Government support is critical for helping these industrial centers access renewable energy, including policies that increase offshore resources, expand interprovincial power trading, and promote onsite generation.

Offshore wind

As China's industrial activities are concentrated in coastal areas, offshore wind presents significant opportunities. At the end of 2023, China's offshore wind capacity was 37 GW (China Electricity Council 2024), just a fraction of its estimated potential of 469 GW of installed capacity and 810 TWh of annual generation, 347 TWh of which is situated in the Yangtze River Delta region (He and Kammen et al. 2014). Another study estimates that China's potential offshore wind capacity alone is 2.5 times the coastal region's average power demand, which includes industrial loads (Guo et al. 2023).

Policies to promote the expansion of offshore wind include a higher target for offshore wind deployment, coordinated planning for upgrades to ultra-high voltage transmission lines, and policies to support the development of energy storage (Guo et al. 2023).

Interprovincial power trading

Limitations on interprovincial power trading are another major barrier to renewable energy access in China, leading to low utilization of existing high-voltage transmission lines (Gao and Zhou 2022). In China, interprovincial power trading takes place mainly through the Beijing Power Exchange Center and the Guangzhou Power Exchange Center, although China's province-based electricity market reforms have fragmented the regulatory system and discouraged cross-border power-sharing among provinces (Ye et al. 2024). Another barrier is the high transmission tariffs that occur when transmission charges from different grid owners accumulate and become one large charge, also known as "rate pancaking" (Gao and Zhou 2022). China's government can help to surmount these barriers by standardizing fair access to the electricity market, which would allow more interprovincial trading and fairer allocations of transmission costs (Gao and Zhou 2022).

Siting new industrial facilities in renewable resource–rich regions

China's renewable energy resources are heavily concentrated in inland regions. To avoid the need for large-scale electricity transmission from those regions to coastal industrial centers, new industrial facilities can be sited in regions with more renewable resources. This strategy is in line with the Chinese Ministry of Industry and Information Technology's plan to move energy, carbon, and labor-intensive industrial activities to inland provinces (China Daily 2022a).

On-site renewable energy generation

Another option for industrial facilities to secure sufficient clean energy is on-site renewable energy generation (e.g., distributed solar PV on rooftops or unused land areas), though this strategy is likely to be most successful beyond the coastal areas where China's industrial firms currently reside. In China, the total technical potential of distributed solar PV on industrial, commercial, residential, and administrative land is estimated to be 380 GW of installed capacity and

440 TWh of annual generation, of which nonresidential land accounted for two-thirds (290 TWh) (Wang et al. 2021). On-site renewable energy, especially when coupled with energy storage, can help to phase out some captive fossil fuel plants, which have an estimated on-site thermal power generation capacity of 153 GW among all industrial firms in China (Sawe et al. 2024).

Yet on-site renewable energy is only a partial solution. The amount of renewable energy that Chinese industrial facilities can generate on-site is dwarfed by China's direct industrial electricity demand, which our model estimated to be 8539 TWh by 2050 after all intervention tiers are implemented. Moreover, the intermittency of renewable energy is not aligned with some industries' continuous operating needs, making energy storage systems critical.

Many policies can encourage industrial facilities to generate renewable energy on-site, such as mandates in building codes, streamlined permitting processes for installing building-integrated PV, low-interest loans, grants and tax rebates, and exempting distributed renewable energy systems from property tax assessments (C40 Cities Climate Leadership Group 2021).

In China, a recent policy on distributed solar PV management introduces major changes that could alter how large industrial and commercial distributed PV systems operate. The policy encourages these installations to primarily use all generated power on-site and to move away from grid feeding. Additionally, distributed PV projects are now exempt from electricity business licenses. These changes facilitate the creation of microgrids within industrial parks, allowing companies to sell electricity directly to neighboring facilities. This setup simplifies the local direct supply of clean electricity, potentially making point-to-point electricity supply a viable and attractive option for businesses in these areas.

Policies to increase consumption of clean electricity

In recent years, China has continually increased its use of clean electricity. In 2022, the country's consumption of non fossil energy sources—including hydroelectric, nuclear, wind, and solar power—accounted for 17.5 percent of its total energy consumption (NBS 2023).

Green certificates

Green electricity certificates (GECs) are a crucial mechanism to incentivize and verify renewable energy consumption by certifying proof of purchase and use of “green” power within various sectors. China introduced a voluntary GEC scheme in 2017 as an alternative to feed-in tariffs. However, only 220 million GECs were issued between 2017 and 2023. In 2023, the National Development and Reform Commission (NDRC) issued a directive that made GECs the exclusive proof of the environmental attributes of China’s renewable energy. The NDRC also expanded the scope of GEC issuance to include all types of renewable energy projects, such as wind, solar, biomass, geothermal, marine, and hydroelectric, swelling the supply of GECs. As a result, 4.734 billion GECs were issued in 2024 alone, but demand lagged and only 446 million were traded, representing just 9.4 percent of the year’s total. This discrepancy led to a plunging in prices, with the average GEC transaction price dropping below one yuan by year-end (Caijing Magazine 2025).

In response, the NDRC implemented a new policy in March 2025 to address the supply-demand mismatch of GECs. New measures promote both compulsory and voluntary green electricity consumption, targeting energy-intensive industries like steel, nonferrous metals, building materials, petrochemicals, chemicals, and data centers. These sectors must now meet specific quotas of green power consumption, verified through GECs.

This new policy also established a green power consumption accounting mechanism using GECs, strengthening their role in helping businesses develop green supply chains; report carbon footprints; and meet their environmental, social, and governance reporting obligations. Additional measures to boost green power consumption include barring renewable energy from the government’s dual energy control requirements (control of both total energy use and energy intensity) and incorporating GEC-traded electricity into the energy-saving performance evaluation system.

When implementing GECs, one must consider potential issues with pricing mechanisms and overall energy consumption dynamics. Differentiating pricing by region and certificate type, rather than imposing a uniform price, is critical. This approach recognizes the varying costs and environmental impacts across geographic areas and technologies. In doing so, it encourages fair market behavior and allows the market to better reflect the cost and value of green energy production.

A critical concern is the potential for GECs to increase overall energy consumption, known as the rebound effect. As the consumption of renewable energy rises, it could inadvertently raise the demand for electricity, including that generated from fossil fuels, as the mix within the grid is indistinguishable. Therefore, it is crucial to develop strategies that prevent environmental gains from being offset by higher overall energy consumption. This risk can be mitigated with the promotion of energy efficiency alongside clean electricity consumption while monitoring the grid energy mix with care.

Additionally, the pricing of GECs has a direct impact on consumer electricity costs, especially when their use is mandated. Transparent and considerate pricing strategies can manage the economic impact on consumers and ensure broad acceptance of clean energy initiatives.

Corporate green electricity procurement

In 2023, corporations around the world announced 46 GW of new solar and wind contracts, of which 9.7 GW are in the Asia-Pacific region (BloombergNEF 2024). Globally, corporations that have announced 100 percent clean energy targets are estimated to need a cumulative 105 GW of solar and wind capacity by 2030 (BloombergNEF 2024). One example is Apple, which in 2018 procured 1 GW of solar and wind projects across 14 provinces for its suppliers in the Chinese manufacturing sector (Apple Inc. 2024).

Facilitating corporate renewable energy procurement can help bring more renewable energy online and improve industrial facilities' access to it. In China, the absence of a direct point-to-point supply of clean electricity means companies, especially export-oriented enterprises, often rely on GECs as proof of renewable energy purchases. Yet these certificates, issued by the China Renewable Information Management Center, have struggled to gain recognition from international initiatives like RE100 due to concerns that environmental benefits are being double counted (RE100 2024).

To burnish the reputation of GECs for Chinese exporters and multinational corporations, the Chinese government has pursued measures to address the appearance of double-counting. One example is their exclusion of Scope 2 emissions (from purchased electricity) from major emitters from the national carbon trading market. They have also allowed shore wind and solar thermal project owners to either trade GECs or participate in China's voluntary carbon credit market to prevent overlapping benefits. These steps are intended to boost corporate demand for GECs and increase their market value.

Despite these efforts to align the green certificate market with international standards and eliminate the risk of double counting, challenges remain. For example, a power generation company could fulfill its carbon reduction obligations in the carbon market by investing in renewable energy while selling excess carbon allowances and GECs separately in the carbon and green certificate markets. Current policies have not yet fully addressed the complexities of double counting among these different mechanisms.

Conclusion

Industrial growth is key to unlocking economic development for the world's emerging economies, bringing better jobs and higher standards of living to billions of people. The East Asian region has grasped this reality and catapulted its growth by manufacturing a range of products, from the steel and cement that drive their industrialization to the electronics and clothes that consumers rely on around the world. However, the region has achieved this rapid growth by leaning into traditional manufacturing technologies and processes, which rely on fossil fuels. To ensure that the region's economic prosperity does not come at the expense of a healthy population and livable planet, policy makers and financing institutions must work fast to transition industrial energy use to clean sources. This industrial transition strategy will, if it succeeds, only enhance the region's economic competitiveness, create new jobs, and improve energy security.

This report identifies the best pathways to eliminate industrial greenhouse gas emissions in three emerging economies in the region: China, Indonesia, and Viet Nam. It focuses on manufacturing activities (not mining, drilling, agriculture, or construction) and covers a range of industrial decarbonization technologies, including energy and material efficiency; electrification; carbon capture, use, and storage (CCUS); green hydrogen; and clean chemical feedstocks. It groups those technologies into six tiers, from the highest priority approaches to the lowest (based on costs, practicality, and technological maturity). The aim is to help policy makers and investors sequence their support for industrial projects based on their chances of success.

An open-source model was created to estimate the impact of each technology tier on industrial energy use, energy-related emissions, and costs (capital and operating) in each country relative to a business-as-usual (BAU) scenario. It uses over 85 data sources—including government data and published analyses—to model six intervention tiers, representing policy-driven technology deployments that each build on the last and cumulatively eliminate 95–97 percent of the emissions from the industrial sector. The model outputs graphs showing the energy, emissions, and cost impacts of each tier in each country and for specific years between now and 2050.

According to the model, after all intervention tiers are implemented, China's industrial energy use is projected to be only 56 percent of its BAU industrial energy use, while Indonesia's is 54 percent and Viet Nam's is 62 percent. Although some clean industrial technologies increase energy use, efficiency interventions and some electrification measures are enough to substantially decrease net energy use in industry. At the same time, following all intervention tiers, industrial electricity demand is projected to be 86 percent higher than BAU levels in China, 46 percent in Indonesia, and 56 percent in Viet Nam. Industry will reach zero emissions only if the electricity that powers direct electrification and green hydrogen production comes from clean sources. Even after adopting the technologies in all six tiers in this analysis, if each country's power sector does not decarbonize beyond today's emissions intensity, 2050 industrial emissions will only be 30 percent lower than BAU levels in China, 32 percent lower in Indonesia, and 50 percent lower in Viet Nam. (Relative to 2022 levels, this is a reduction of 32 percent in China and increases of 18 percent in Indonesia and 5 percent in Viet Nam.)

Some industrial decarbonization interventions, like electrifying high temperature heat and deploying CCUS and green hydrogen in specific industries, will raise energy costs compared to BAU levels given the high price of electricity and the energy penalty of CCUS.[18] For every intervention except CCUS, energy costs play a far larger role than capital costs per unit of carbon abatement, meaning that policies that make cost-competitive clean energy more available are the best way to ensure the bankability of industrial decarbonization projects.

The report presents five case studies on efforts around the world to decarbonize heavy industries. It also offers key recommendations that should help policy makers and international financial institutions support the industrial transition to zero-carbon processes in China, Indonesia, and Viet Nam. These policies are critical not only for driving the deployment of technologies within each tier of the analysis, but also for bringing down the operating costs of industrial decarbonization and attracting investment from public and private institutions.

The report also includes an in-depth look at the technologies and policies to accelerate industrial electrification and power sector decarbonization in China, which could slash emissions from the world's largest and highest-emitting industrial sector. Finally, the report's appendices present several additional graphs from the model, as well as one detailed section on demand-side resources that industrial firms can provide to balance the electricity grid and another detailed section on business models and policy options that would scale up industrial heat pumps.

Our analysis shows that decarbonizing industry in the East Asian region is not only possible but also vital for the sustainable growth of the region's emerging economies. Delaying the transition risks locking in fossil fuel infrastructure, exposing industries and economies to risks as other countries transition away from fossil fuels. In contrast, ambitious support for clean industrial technologies can safeguard the future competitiveness of the region's industries. Moreover, success in the region would not just benefit the participating countries but also set a transformative precedent for emerging economies around the world.

[18] Savings from avoided payments under the \$50/tCO_2 carbon price used in the modeled scenario offset CCUS's increased energy costs. See the section on energy costs in Chapter 3.

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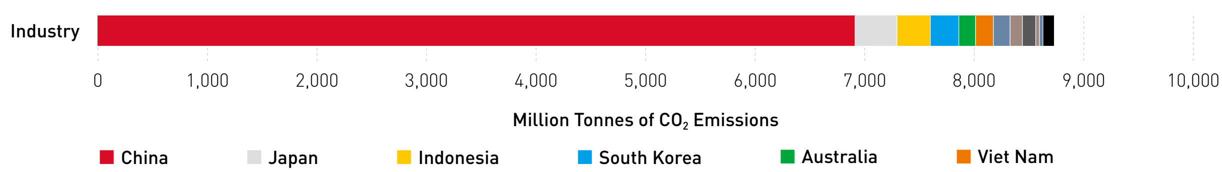
Appendix A.

Technical Appendix: Supplementary Figures

A.1 | Energy-related industrial emissions by country in the East Asia and Pacific region

FIGURE A.1 Energy-related industrial emissions in the East Asia Pacific Region by country in 2022



A.2 | Industrial energy use by subindustry

FIGURE A.2 Annual industrial energy use by subindustry and energy type in China in 2022

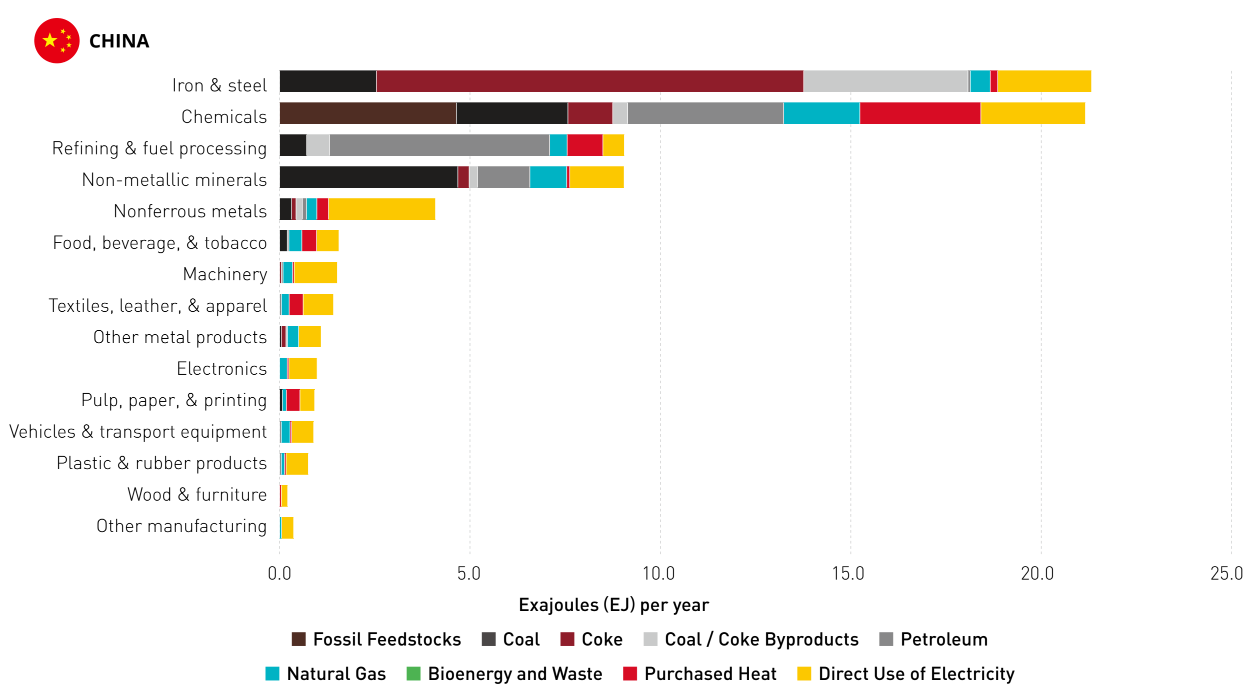


FIGURE A.3 Annual industrial energy use by subindustry and energy type in Indonesia in 2022

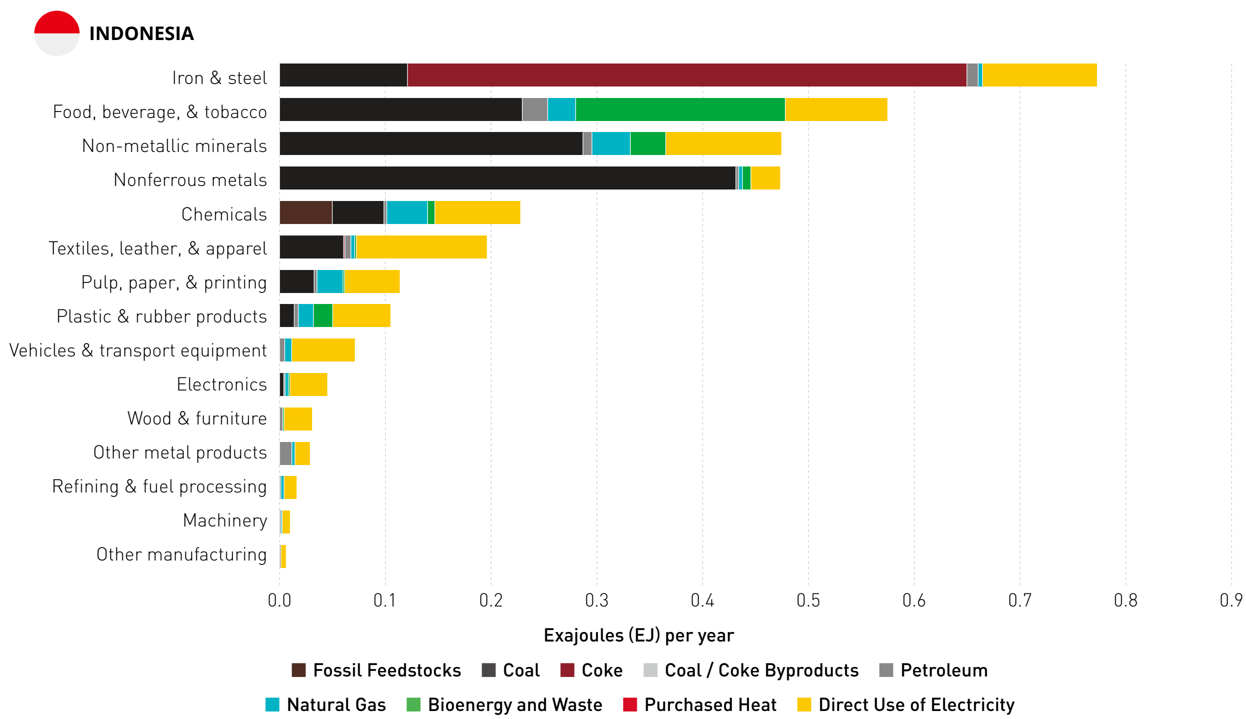
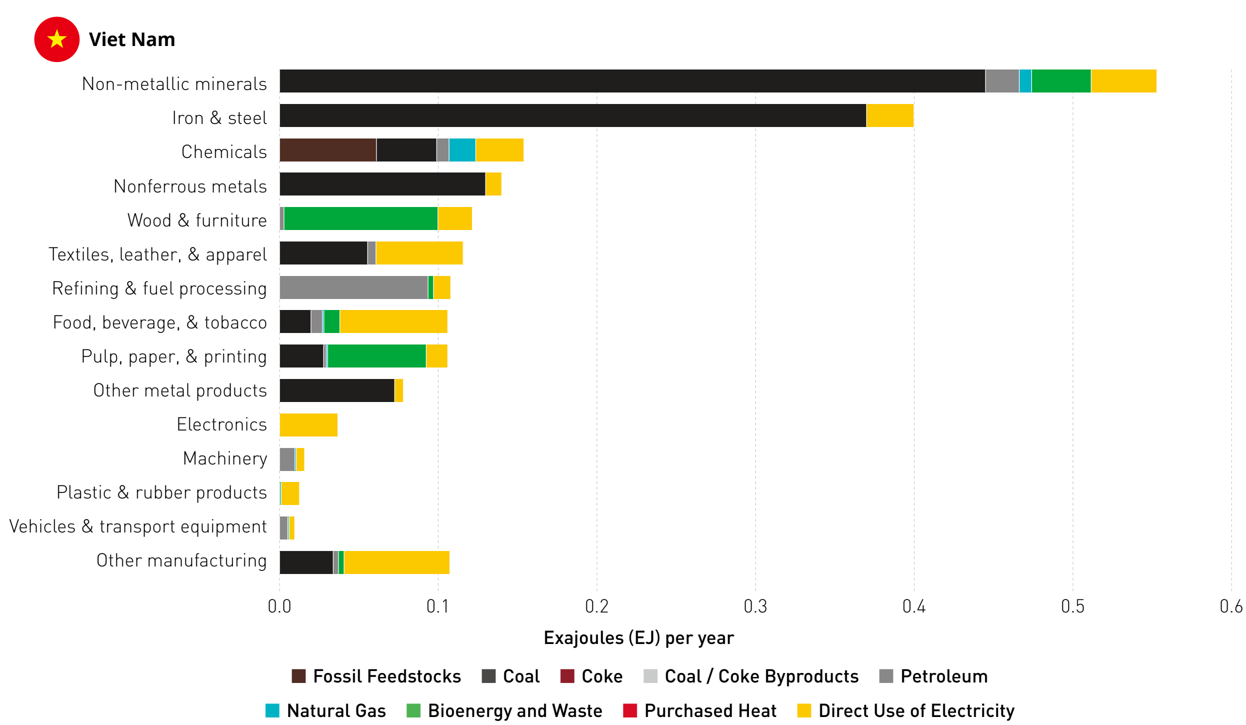


FIGURE A.4 Annual industrial energy use by subindustry and energy type in Viet Nam in 2022



A.3 | Change in demand by subindustry

FIGURE A.5 Anticipated natural changes in product demand and potential changes that could be achieved through material efficiency and product/building longevity policies in Indonesia in 2050 (relative to 2022)

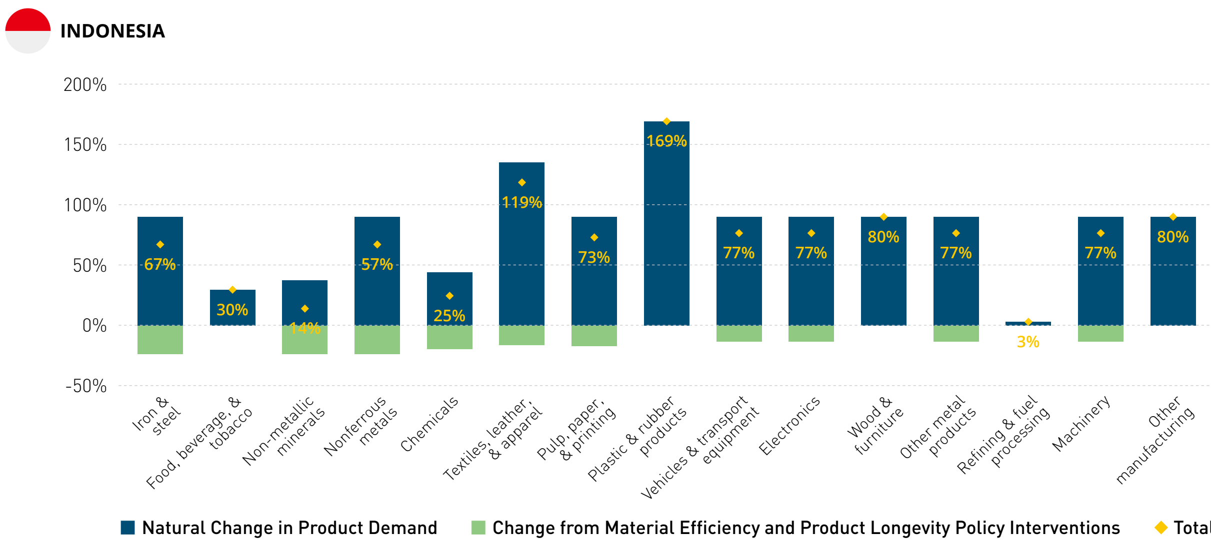
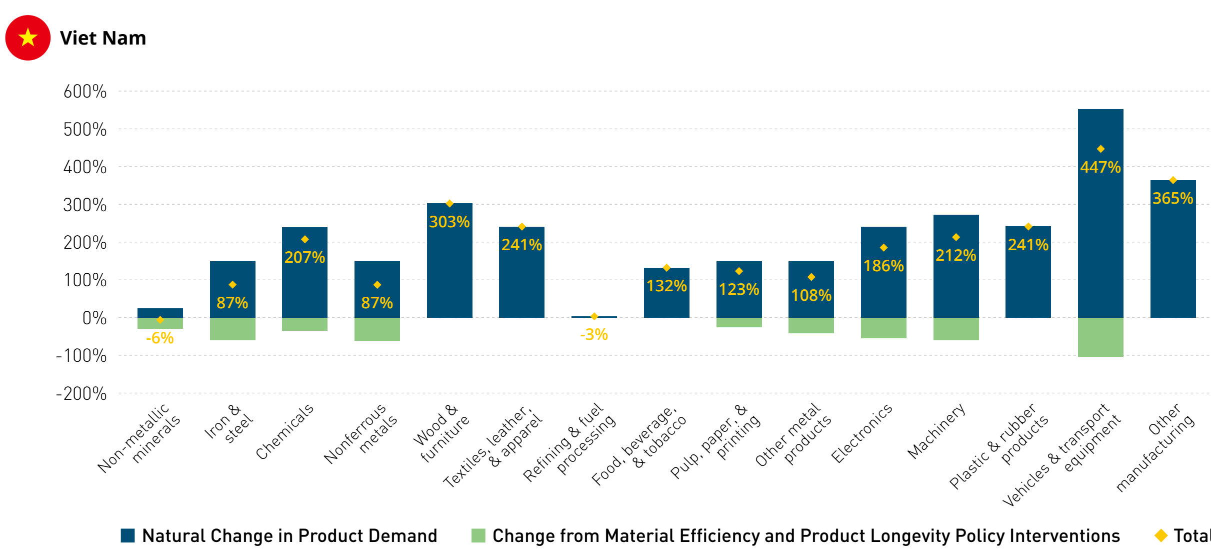


FIGURE A.6 Anticipated natural changes in product demand and potential changes that could be achieved through material efficiency and product/building longevity policies in Viet Nam in 2050 (relative to 2022)



A.4 | Absolute annual energy and annualized capital expenditures

FIGURE A.7 Absolute annual energy costs and annualized capital investment needs in China

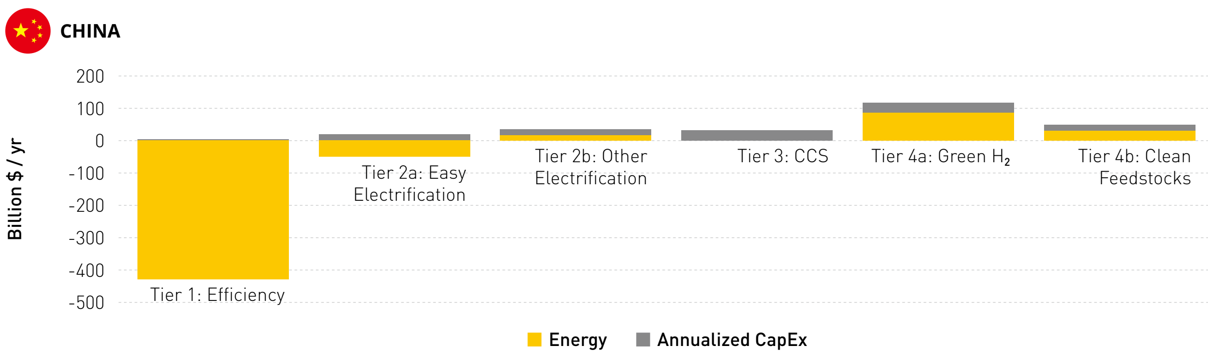


FIGURE A.8 Absolute annual energy costs and annualized capital investment needs in Indonesia

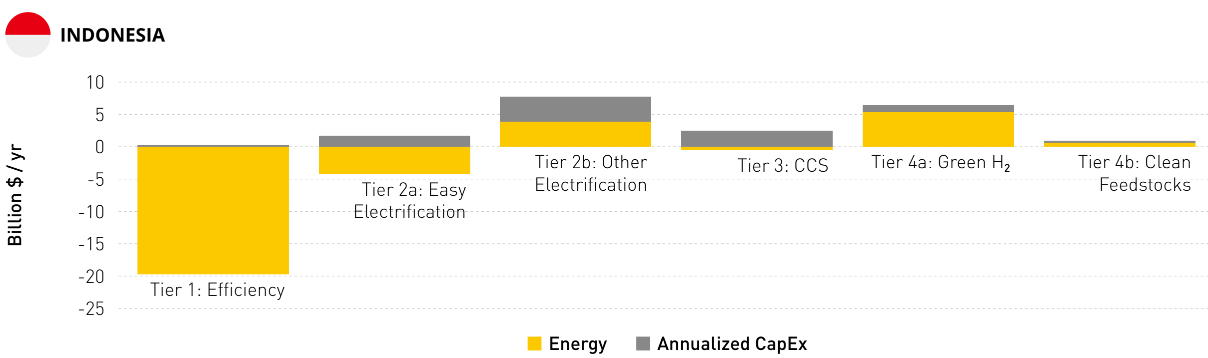
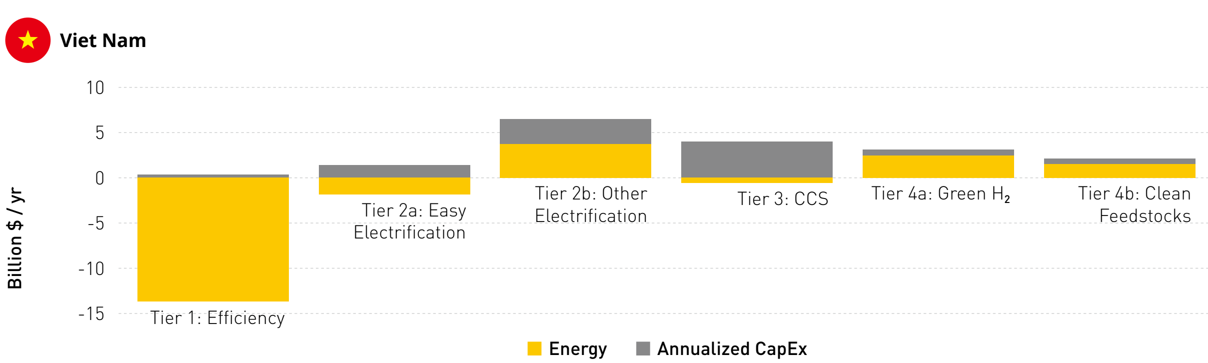


FIGURE A.9 Absolute annual energy costs and annualized capital investment needs in Viet Nam



A.5 | Composition of Tiers 1, 2a, and 2b

FIGURE A.10 Composition of energy use reductions from Tiers 1, 2a, and 2b in China

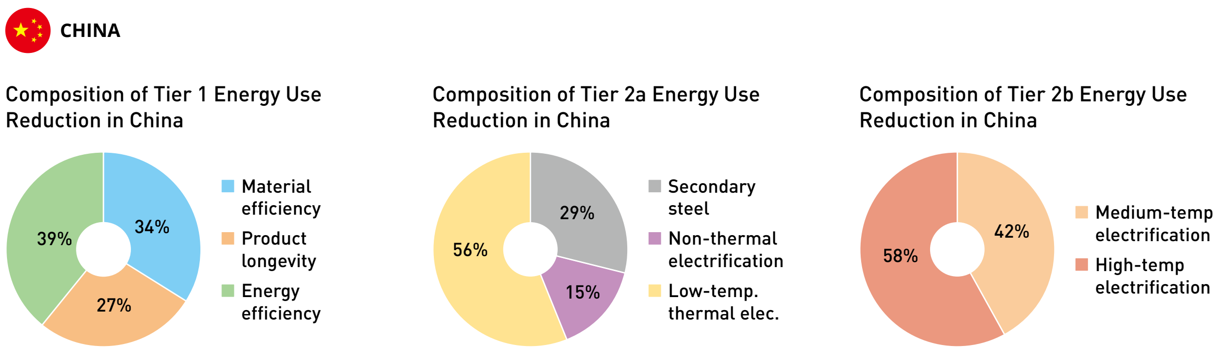


FIGURE A.11 Composition of energy use reductions from Tiers 1, 2a, and 2b in Indonesia

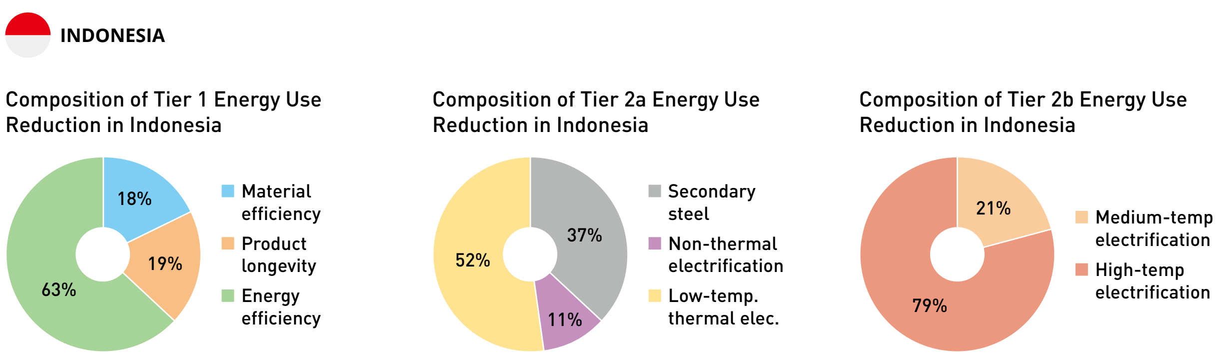
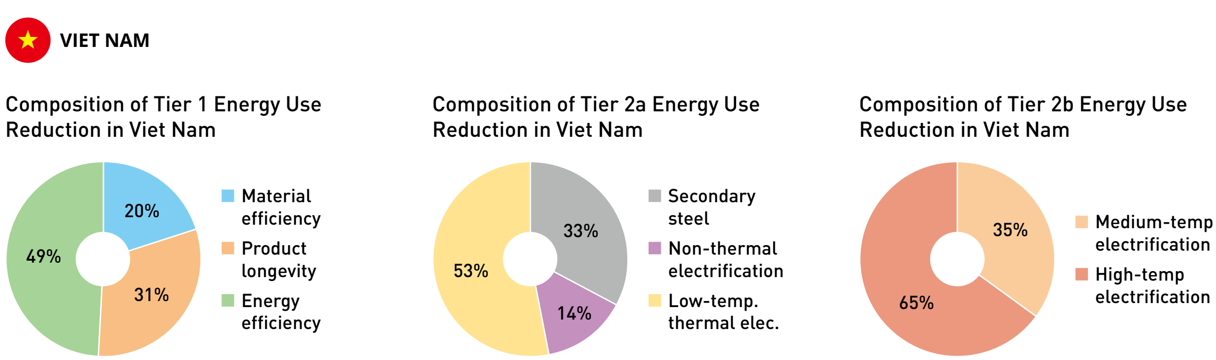
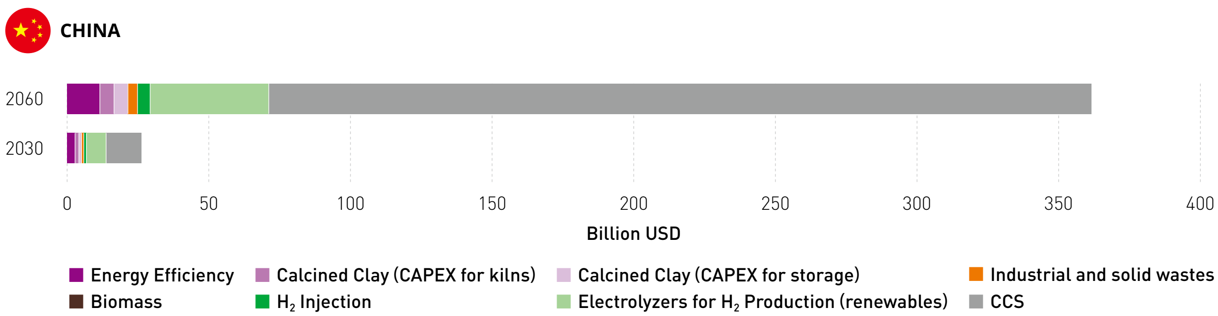


FIGURE A.12 Composition of energy use reductions from Tiers 1, 2a, and 2b in Viet Nam



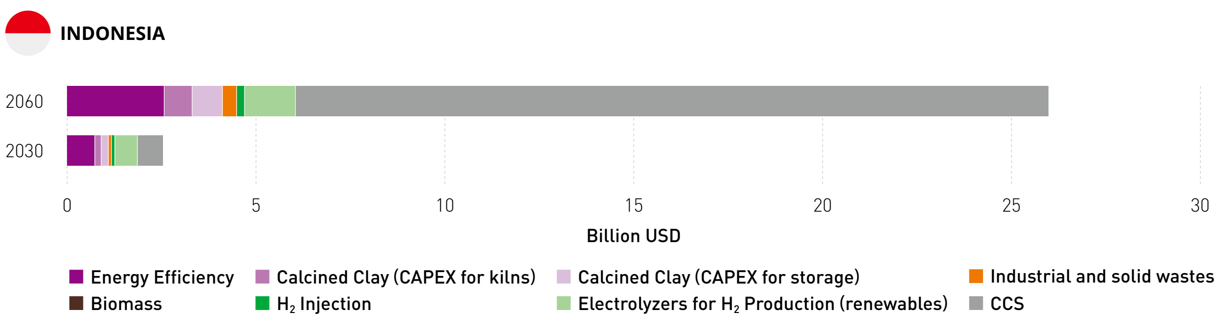
A.6 | Sectoral analysis: Cement

FIGURE A.13 Cumulative CAPEX investment needs for the cement industry in China



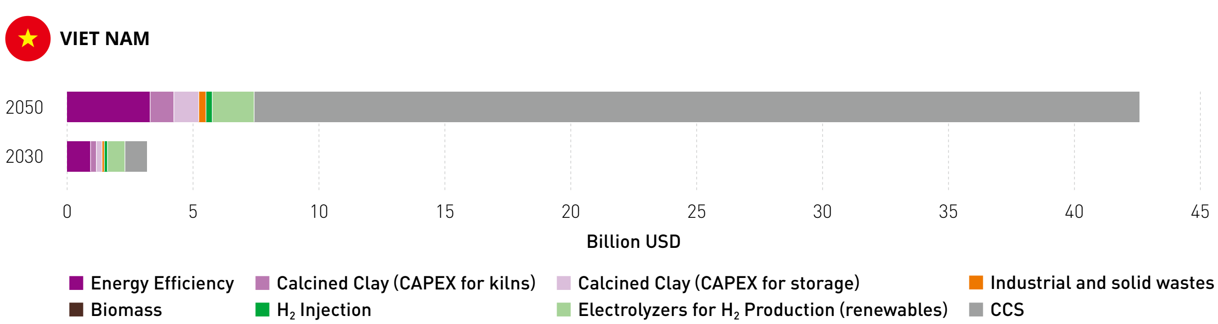
Note: The values shown here are lower than the CAPEX for the whole nonmetallic minerals sector.

FIGURE A.14 Cumulative CAPEX investment needs for the cement industry in Indonesia



Note: The values shown here are lower than the CAPEX for the whole nonmetallic minerals sector.

FIGURE A.15 Cumulative CAPEX investment needs for the cement industry in Viet Nam



Note: The values shown here are lower than the CAPEX for the whole nonmetallic minerals sector.

A.7 | Sectoral analysis: Iron and Steel

FIGURE A.16 Cumulative CAPEX investment needs for the iron and steel industry in China

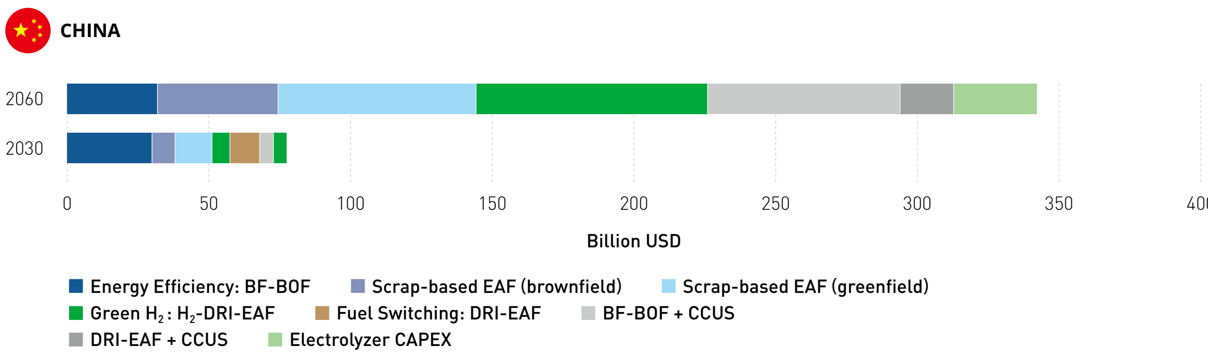


FIGURE A.17 Cumulative CAPEX investment needs for the iron and steel industry in Indonesia

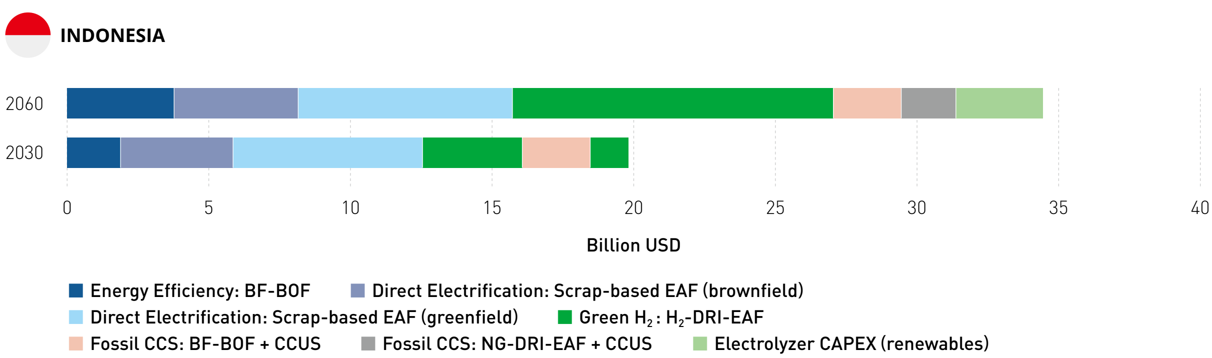
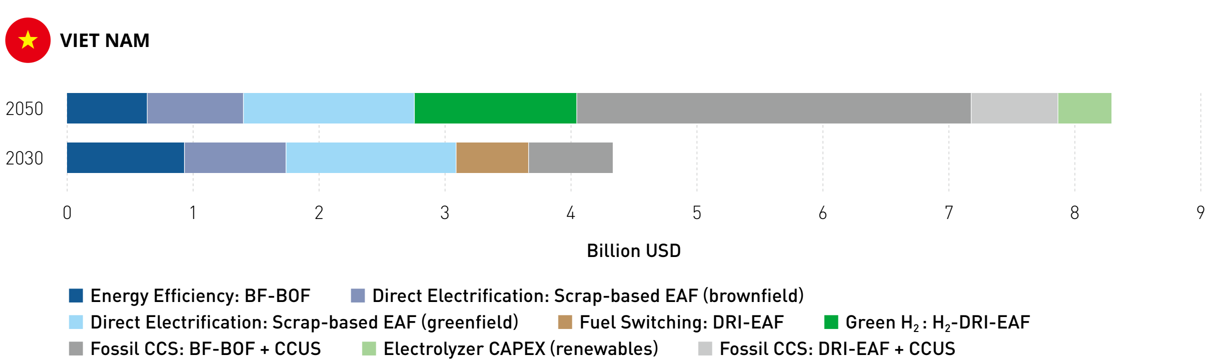


FIGURE A.18 Cumulative CAPEX investment needs for the iron and steel industry in Viet Nam



Appendix B.

Industrial Use of Demand-Side Resources

East Asian countries' economies and their associated electricity consumption are growing rapidly as decarbonization policies promote electrification and renewable power generation. Industrial demand comprises a substantial portion of East Asian electric consumption, making policies that support industrial decarbonization crucial to meet carbon reduction goals.

Flexibility, either from generation resources or from the demand side, will be crucial in meeting resource needs. For example, in addition to the need for increased investments in hydroelectricity and nuclear power, intermittent sources, both on the grid and off, will provide a growing share of electricity, especially in countries like Viet Nam. These variable resources place strain on the grid and require advanced measures to ensure reliable and affordable power.

This appendix examines the use of demand-side resources to help meet the need for flexible resources in a short period of time, with a particular focus on industrial decarbonization. Global experience has shown that it will be critical for East Asian countries to adopt policies and invest in resources, tools, and equipment that can take advantage of this inherent flexibility. It is an ideal time to take action, and the World Bank is well situated to support those efforts. Countries like Viet Nam are interested in modernizing their systems and industries. Fortunately, the dominant industries in East Asia are characterized by flexible industrial processes that can be incorporated into strategies and policies built around demand response or demand flexibility.

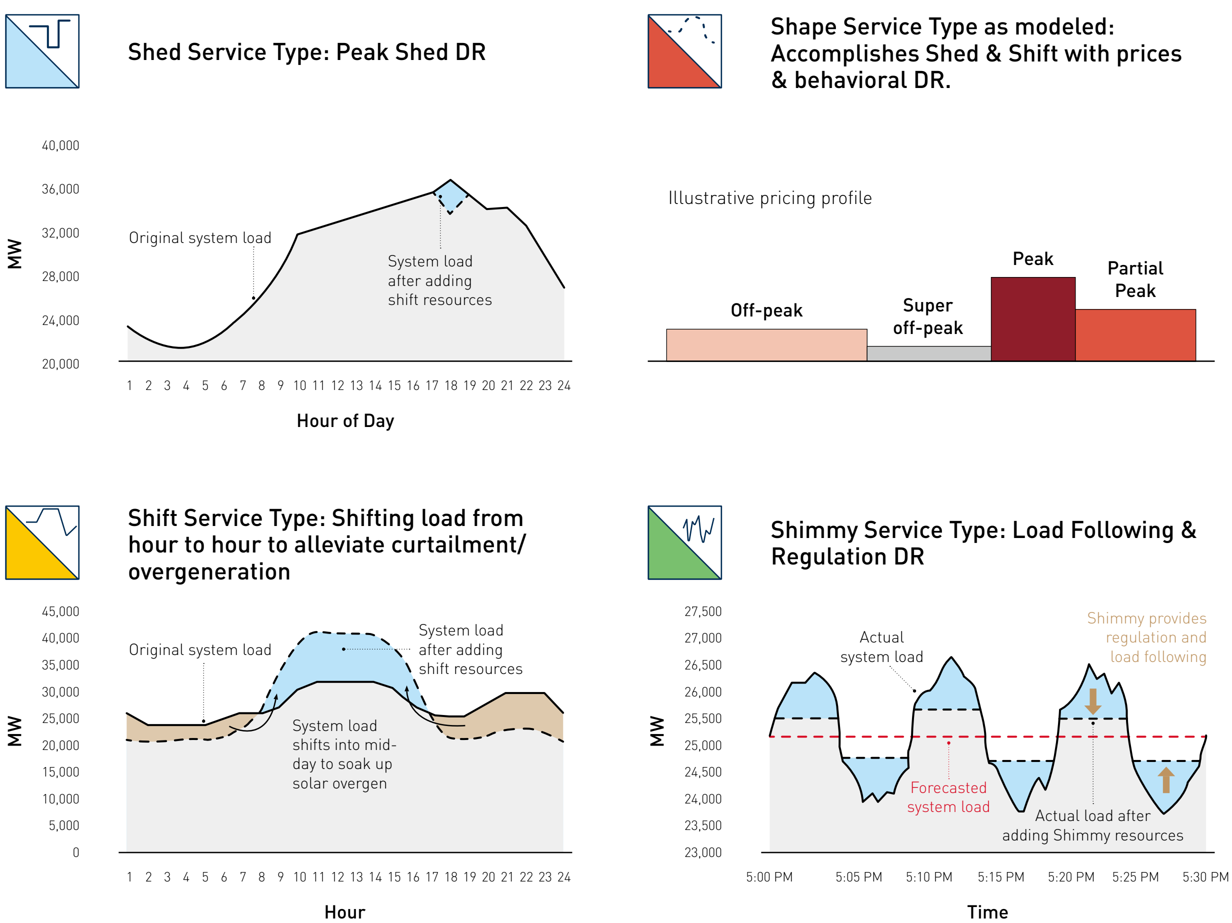
This appendix reviews demand-side resources that industrial firms can deploy, focusing on international experience and lessons learned. Finally, it will offer policy recommendations. As will be shown, demand-side resources can be deployed effectively on a large scale and can be incorporated in a holistic industrial decarbonization strategy in East Asia. The opportunities and challenges in applying these resources within Viet Nam are explored in detail as a case study.

B.1 | Demand-side resources and industrial decarbonization

Demand-side resources include a variety of technologies and actions that can adjust customer demand to lower or increase electric load to optimize electric system operations and lower carbon emissions. Demand-side resources include demand response schemes, distributed energy resources (DERs), demand flexibility, and the strategic use of storage technologies. When properly supported and maintained, demand-side resources can be used to reduce load and thereby reduce the need for new generating capacity and infrastructure (both transmission and distribution) or shift demand to help optimize electric system operation. These resources can be even more effective when combined through aggregations or virtual power plants (VPPs).

As shown in **FIGURE B.1**, the four main ways that demand-side resources can adjust load are by shedding, shaping, shifting, or shimmying load. Shedding refers to reductions in load through curtailment of processes or turning equipment off. Shaping involves the use of incentives like TOU rates to encourage adjustments or shifts in consumption patterns, ideally to off-peak periods. Shifting refers to the active shifting of load from hour to hour to alleviate system constraints. Loads can be shifted by rescheduling processes or the use of thermal or battery storage. Shimmying refers to quick up and down changes in load within short time intervals to provide ancillary services such as frequency control, typically created by digitized control systems.

FIGURE B.1 How demand-side resources can adjust load



The major types of demand-side resources are (1) demand response; (2) distributed energy resources; (3) demand flexibility; (4) energy storage; and (5) virtual power plants.

- **Demand response.** Demand response employs incentives and benefits for businesses and households to provide flexibility to the electricity system. Flexibility is provided by encouraging customers to voluntarily change their usual electricity consumption in reaction to price signals, or to specific requests that are adequately remunerated. In particular, demand response programs and techniques are typically designed to encourage customers to adjust consumption during times of system need or higher prices. TABLE B.1 lists several types of demand response across customer categories. Industrial demand response will be discussed in more detail in the next subsection.

TABLE B.1 Demand response types and applications

Sector	End-Use	Enabling Technology	Shed	Shift	Shimmy
Residential	Air Conditioning	Direct Load Control, Smart Thermostats	●	●	
	Electric Water Heating	Direct Load Control, Automated DR	●	●	●
	Pool Pumps	Direct Load Control	●	●	
Commercial	HVAC	Manual and Automated DR	●	●	●
	Data Centers		●	●	
	Lighting	Zonal and Luminaire Control	●		●
	Refrigeration (including warehouses)	Automated DR	●	●	●
Industrial	Wastewater treatment and pumping	Manual and Automated DR	●	●	●
	Processes and Large Facilities		●	●	
Agricultural	Pumping and Irrigation	Direct Load Control, Automated DR	●	●	
All	Electric Vehicles	Managed Charging, Vehicle to Grid	●	●	●
	Behind-the-Meter Batteries	Automated DR	●	●	●

- **Distributed energy resources.** DERs refer to generation sources that operate either "behind-the-meter" within a premise or on the distribution system, and when operated can adjust electric load. DERs can include solar photovoltaic (PV) systems, small hydroelectric facilities, electric vehicles, and small diesel, biogas, or natural gas-fired generators. This appendix will only examine non-carbon sources given country decarbonization goals.

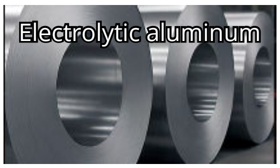
- **Demand flexibility.** Demand flexibility is a broad term that refers to the ability to change amount or timing of energy consumed to be responsive to grid needs. The capability of a customer or end-use to be flexible is dependent on the technology they use, and the nature of their specific end-use, work flow, and processes. Depending on the end-use and process, demand flexibility can be provided quickly (e.g., within seconds) or over longer timelines (e.g., over several hours or days).
- **Energy storage.** Like DERs, charging and discharging energy storage devices (primarily batteries, but could also include thermal storage and thermal batteries) behind-the-meter or on the distribution system can reduce demand for generation resources, shift load, and increase demand when needed.
- **Virtual power plants.** VPPs leverage the combined capabilities of the demand-side resources listed above to provide valuable support to the electrical grid. While VPPs share similarities with demand response or DER aggregations, VPPs typically incorporate enhanced use of modern technology, like instant communications, plus sophisticated forecasting, scheduling, and real-time operational adjustments.

B.2 | Industrial demand-side resources

Industrial firms and industrial processes have proven to be effective sources of demand-side response and resources. In many countries and markets, industry provides significant amounts of demand response and flexibility to support the electric system and lower overall electricity costs, while also being compensated for their actions. Moreover, many industrial processes can be shifted in time or have sufficient flexibility to respond quickly to price signals or system needs. Conversely, processes that require continuous production, such as plastic extrusion, would suffer if production were curtailed or stopped briefly, and are not good candidates. **FIGURE B.2**, based on recent work in China by the Rocky Mountain Institute, identifies seven industry segments that can provide demand response and flexibility.

As the figure shows, multiple industrial processes can serve as demand response resources. These processes can be shifted or curtailed within relatively short periods of time, without causing any negative effects on the production of industrial outputs. In addition to the processes included in the figure, two additional processes are generally identified as good demand response/flexibility candidates: mechanical pulp processing (pulp and paper), and chlor-alkali electrolysis (chemicals). The list of flexible industries includes many of the dominant industries in East Asia. For example, nonmetallic minerals (e.g., cement), iron and steel, textiles, and chemicals are four of Viet Nam's top five industries.

FIGURE B.2 Major industrial demand response and flexibility sources

Industry segments	Major flexibility sources/devices	Demand response temporal parameters: Lead time	Demand response temporal parameters: Response duration	Demand response temporal parameters: Recovery time[1]	Demand response potential (of total load)
 Electrolytic aluminum	Aluminum reduction cell, captive power plant	2h (aluminum reduction cell)	1–2h	2h (aluminum reduction cell)	20%
 Iron and steel (steelmaking)	Electric arc furnace, rolling line, captive power plant	Per shift (steel rolling); 10–30min (electric arc furnace)	0.5–1h	Per shift (steel rolling); 10–30min (electric arc furnace)	20%
 Ferroalloy	Submerged arc furnace, electric arc furnace, reduction furnace	1–2h	0.5–4h	1–2h	30%
 Cement	Rotary kiln, vertical kiln	1–2h	0.5–2h	1–2h	24%
 Textile	Loom, texturing machine	0.5–1h	0.5–4h	0.5–1h	35%
 Glass	Air compressor, annealing kiln, glass melting kiln, cold end glass cutting machine	0.5–2h	0.5–3h	0.5–2h	25%
 Equipment manufacturing	Melting furnace, heat treatment furnace, high frequency furnace	1–2h	0.5–3h	1–2h	20%

Timeline scale in each temporal cell: 0, min, 1h, 2h, 4h, 8h

Source: Authors reproduced based on State Grid Electric Power Research Institute, CEPRI, RMI.

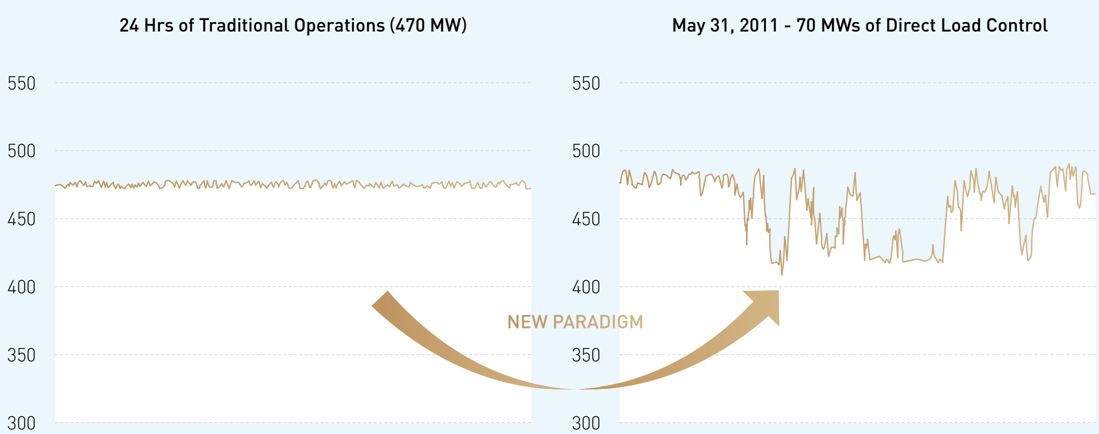
[1] Recovery time is defined as the return to normal operation from a certain demand response state, not from an interrupted state of operation.
h = hours

Processes that have thermal inertia or buffer capacity generally provide the greatest amount of flexibility, although this flexibility typically operates only in one direction. Due to technical requirements, several of these processes are suitable only for load reductions and not load shifting (e.g., electric arc furnaces and aluminum electrolysis), but others, like chlor-alkali electrolysis and mechanical refining of wood pulp, can be shifted.[2]

Past experience also provides examples of industrial processes that can rapidly adjust their processes to provide ancillary services like frequency regulation. **BOX B.1** describes the flexibility services that Alcoa's Warrick, Indiana plant successfully bid into the Midcontinent Independent System Operator's markets. With targeted investment in control equipment and communications devices, Alcoa Warrick has been able to provide extremely flexible demand response.

BOX B.1 Demand flexibility at the Alcoa Warrick Smelter

Alcoa's Warrick's aluminum smelter in the U.S. state of Indiana has bid demand response into the markets of the Midcontinent Independent System Operator markets for many years. The Warrick smelter was unique at the time for its ability to flexibly adjust the electric consumption in its potlines to provide about 70 MW (or about 13 percent of total plant load of 550 MW) of energy, spinning reserves, and regulation service to MISO as a Demand Response Resource (Type II). To exploit the demand response capabilities of the smelter, two primary systems were designed and installed to facilitate market participation: the power plant energy management system and the smelter potline load control system. In addition, metering, monitoring, communications, and control systems at the plant were modified to provide fast and accurate power consumption control.



Source: *Todd 2009.*

[2] M Ranaboldo, "A Comprehensive Overview of Industrial Demand Response Status in Europe," Renewable and Sustainable Energy Reviews 203 (October 2024).

Recent developments and cost reductions in storage technology have created new means of flexibility and demand reduction for industry. Storage devices can be paired with flexible industrial processes to flatten load profiles or to shift load off peak. For example, instead of adjusting industrial processes, strategic discharge of batteries could reduce demand during peak periods or times of system stress. This capability to shift load is particularly valuable to leverage variable resources like wind and solar. In addition, given their inherent ability to rapidly change operations and switch between discharging and charging, storage devices like batteries can provide ancillary services, such as frequency control.

Although load reduction and shifting are already possible to a significant degree from industrial processes and companies, the fulfillment of their potential lags globally, even in developed countries and regions like the United States and Europe. Industrial firms can and will adjust loads for short periods of time in response to system emergencies on the electric grid, and will adjust their consumption due to prices, but full exploitation of the potential for a flexible and dynamic industrial sector redeployment requires that the characteristics described below be maximized.

- **Full integration into business and production processes.** As long as demand response is considered as ancillary or a disruption to production processes, it will not be fully integrated into business operations. Flexibility in large-scale production represents a complex challenge for companies and must be accompanied by tools and measures to support strategic and operational decisions to accelerate implementation.
- **Investment in new technologies and processes and digitization of industrial processes.** Modern equipment is needed to increase demand flexibility. Computerized control systems, sensors, and automation, particular, increase demand flexibility and the ability to participate in implicit and explicit demand response programs. But, given the present costs of digital solutions, adoption has been slow.
- **Sufficient incentives or market opportunities for demand response actions.** Experience globally clearly indicates that industrial customers respond to incentives, such as opportunities for their demand reductions to be monetized in wholesale or retail markets.
- **The existence of aggregators to procure demand response and flexibility.** Where markets exist, the existence of aggregators who will procure demand response and flexibility from industrial processes and sell these products into markets is crucial. Unfortunately, experience in Europe has found that many aggregators only offer solutions that build on the current market design and do not participate in the new flexibility markets.[3]
- **Dynamic pricing.** Demand response actions and demand flexibility can be incentivized by dynamic pricing. The simplest form of dynamic pricing is time-of-use (TOU) rates, where electricity rates vary across set peak and off-peak periods. The purpose of these TOU rates is to provide price signals to encourage demand to shift to lower cost, off-peak periods. Increased response occurs when other, more dynamic, pricing forms, including critical peak

[3] M Ranaboldo, "A Comprehensive Overview of Industrial Demand Response Status in Europe," Renewable and Sustainable Energy Reviews 203 (October 2024).

pricing and real-time pricing, are in place.[4]

- **Flexibility markets.** Industrial demand flexibility can be further monetized through participation in flexibility markets. Multiple flexibility markets exist in Europe, with a large concentration of advanced flexibility operators in the United Kingdom. Starting in the mid-2010s, OFGEM originated the concept of local flexibility markets, where distribution network operators could procure services from flexible assets to solve local network issues. In 2023, network operators tendered a record 6.4 gigawatts (GW) of capacity in Great Britain's local flexibility markets, with 4 GW successfully contracted.[5]

B.3 | International experience with industrial demand-side resources

Industrial participation in demand response programs and in the provision of demand-side resources spans the globe, with most of the activity occurring in the developed world, particularly the United States and Europe, with additional activity in countries like Brazil, China, India, and Korea. But the topic is relevant to certain emerging economies as well. For that reason, this section closes with a case study on Viet Nam's experience.

United States

The United States has a rich history in utilizing all of the key demand-side resources and has developed and implemented many successful demand reduction and flexibility policies.

Demand response. Demand response provided by industrial firms and processes is a core component of U.S. demand response. Various forms of industrial demand response have existed for decades, such as interruptible rates, which provide large customers discounted rates in exchange for agreeing to reduce demand when directed (either through manual or automated demand response). Since the introduction of interruptible rates in the 1960s, utilities have implemented a wide variety of demand response programs, including voluntary reduction, emergency response,

4 Ahmad Faruqui, Sanem Sergici, and Cody Warner, "Arcturus 2.0 : A Meta-Analysis of Time-Varying Rates for Electricity," The Electricity Journal 30, no. 10 (December 2017): 64–72, https://doi.org/10.1016/j.tej.2017.11.003.

5 Elexon, "Market Facilitator for Distributed Flexibility," n.d., https://www.elexon.com/what-we-do/what-we-manage/market-facilitator-for-distributed-flexibility/.

and demand bidding programs. Recent programs introduced more flexibility and incorporated automation and aggregation. The creation and authorization of demand response in wholesale markets was also a major development. The development of these programs began in earnest in the late 1990s and early 2000s. A 2009 National Assessment of Demand Response Potential carried out by the Federal Energy Regulatory Commission estimated that 180 GW of demand reduction could be possible in the United States under aggressive policies.[6]

Demand response programs in the United States can be divided into implicit demand response driven by dynamic pricing and explicit demand response, where customers are offered incentives to reduce or adjust consumption when directed. Most large industrial customers in the United States operate on TOU rates by default, and, in some states (such as New Jersey), these customers are on real-time pricing by default. Unfortunately, estimates of the impact of these dynamic rates on consumption patterns are lacking. Explicit demand response programs include (1) programs conducted by retail electric utilities and (2) programs offered by wholesale grid operators, such as PJM in the eastern United States. FERC estimates that by the end of 2022, demand response programs offered by retail utilities to their customers had the potential to reduce demand by 30 GW.[7] Past surveys of these programs by FERC indicate that the majority of this potential from retail programs originated from industrial interruptible-rate programs.

A key attribute of demand response in the United States is the existence of wholesale programs and the creation of aggregators. FERC started approving demand response programs for regional transmission organizations (RTOs) and independent system operators (ISOs) in 1999. In 2009, it issued Order No. 719, which designated demand response aggregators as market participants in wholesale energy, capacity, and ancillary services markets.[8] By the end of 2023, wholesale demand response programs at RTOs and ISOs were estimated to reduce demand when directed by about 33 GW.[9] Furthermore, the primary sources of demand response in wholesale markets are large commercial and industrial emergency programs. Demand response resources are bid into RTO/ISO energy, capacity, and ancillary markets, but the total amount of cleared bids from energy and ancillary markets is small compared with the amount participating in capacity markets.[10]

Interestingly, a new customer type, cryptocurrency mining, has begun to participate in wholesale markets. Cryptocurrency mining has the capability to quickly pause the computation necessary

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6 Federal Energy Regulatory Commission, "A National Assessment of Demand Response Potential," June 2009, https://www.ferc.gov/sites/default/files/2020-05/06-09-demand-response_1.pdf.

7 FERC, 2024 Assessment of Demand Response and Advanced Metering, Staff Report, December 2024.

8 Federal Energy Regulatory Commission, "Wholesale Competition in Regions with Organized Electric Markets," 73 FR 64,100 Order No. 719 § (2008), https://www.govinfo.gov/content/pkg/FR-2008-03-07/pdf/E8-3984.pdf.

9 Federal Energy Regulatory Commission, "2024 Assessment of Demand Response and Advanced Metering" (FERC, December 2024), https://www.ferc.gov/sites/default/files/2024-11/Annual%20Assessment%20of%20Demand%20Response_1119_1400.pdf.

10 Monitoring Analytics, LLC, "2024 Annual State of the Market Report for PJM" 2 (March 13, 2025): 345.

to produce cryptocurrency products or shift the computing elsewhere. In particular, mines have directly provided demand response for the Electric Reliability Council of Texas.

While demand response has become more dynamic and responsive in recent years, particularly with residential and commercial customers and the entry of cryptocurrency miners, demand response from industrial customers (with the exception of Alcoa Warrick) largely requires prior notification and is largely focused on providing emergency response and participating in RTO/ISO capacity markets.

- **Distributed energy resources.** DERs are being deployed in the United States at a rapid pace, led by rooftop solar PV arrays, community solar facilities, and distributed storage. In addition, electric vehicles are starting to serve as generating resources or to support demand reduction.[11] Since many manufacturing facilities have large flat roofs, they provide a great location for solar installations. When there is available land within the facility, solar arrays can also be ground mounted. By pairing DERs with storage, industrial facilities can reduce their purchases from the electric grid, serve more of their needs from non-carbon sources, and thereby assist in their decarbonization goals.
- **Demand flexibility.** The value of demand flexibility is well recognized in the United States. Multiple analyses have identified their potential and value. For example, the Brattle Group's 2019 national assessment estimated that 200 GW of cost-effective demand flexibility potential could exist in the United States by 2030, or about 20 percent of total U.S. peak load.[12] In addition, states—including New York with its Grid of the Future proceeding[13]—are creating policies and regulatory structures to incentivize the use of flexible resources like demand response, electric vehicles, and batteries to provide services to retail and wholesale markets.

  As noted above, many industrial processes are inherently flexible, and some, like aluminum electrolysis, can provide rapid response. This flexibility may be a natural fit to balance variable renewable generation on site or procured off site. However, the potential for industrial facilities to provide demand response to retail and wholesale flexibility markets is still mostly untapped in the United States.
- **Electric storage.** Electric storage is growing rapidly in the United States. A March 2025 FERC State of the Markets report highlighted the massive deployments in grid-connected electric storage in several areas of the United States.[14] Distributed, behind-the-meter battery systems are projected to also grow quickly, with the National Renewable Energy Laboratory

[11] Brian Martucci, "US to Add 217 GW of Distributed Energy Resource Capacity through 2028, Wood Mackenzie Projects," Utility Dive (blog), July 3, 2024, https://www.utilitydive.com/news/wood-mackenzie-sees-217-gw-new-distributed-energy-resources-2028/720581/.

[12] Ryan Hledik et al., "The National Potential for Load Flexibility: Value and Market Potential Through 2030," https://brattlefiles.blob.core.windows.net/files/16639_national_potential_for_load_flexibility_-_final.pdf.

[13] New York Public Service Commission, "Proceeding on Motion of the Commission to Develop a Grid of the Future," Pub. L. No. Case 24-E-0165 (2024).

[14] Ashreeta Prasanna et al., "Storage Futures Study: Distributed Solar and Storage Outlook: Methodology and Scenarios" (National Renewable Energy Laboratory, 2021), https://www.nrel.gov/docs/fy21osti/79790.pdf.

projecting a potential of 116 GW in the United States by 2050.[15]

Batteries protect power customers from outages, enable them to avoid high peak prices (by charging their batteries during peak solar hours and discharging them later in the day) and, more broadly, offer arbitrage between low and high electricity prices.

- **Virtual power plants.** The use of VPPs to meet electric demand and decarbonization goals is rapidly gaining favor in the United States. Indeed, VPPs are essentially modern versions of demand response and DER aggregation, which have a long history in the country. Several states actively promote virtual power plants. Maryland's 2024 DRIVE Act, for example, requires Maryland utilities to deploy VPPs. The U.S. Department of Energy actively promotes VPPs with its VPP Commercial Lift-Off Reports. DOE estimates that 80 to 160 GW of VPPs could provide grid services in 2030.[16]

  The U.S. industrial sector has not been actively involved with VPPs. Given that the major distinction between demand response/DER aggregation and VPPs is the use of modern communications and sensing tools, the largest application of these developments thus far has been at the residential and small commercial customer level. Nevertheless, the same modern VPP tools can be used by individual industrial facilities or across a group of industrial companies. A good example of the potential of VPPs in industrial facilities is provided by Enel X, which partnered with Ardagh Group, a global packaging manufacturer, to deploy a virtual power plant across their North American facilities. This VPP aggregated Ardagh's on-site energy assets, including battery storage systems and flexible load sources, creating a central energy network. Through intelligent load shifting and participation in demand response programs, Ardagh reduced its energy costs by 10 percent while contributing to grid stability during peak periods.[17]

Europe

Demand-side resources are considered important resources in Europe and have been utilized for decades. The European Union has recognized their importance by revising its regulations and laws to accommodate demand response and flexibility actions (BOX B.2). The use of demand-side resources in the region is supported by the existence of markets, especially flexibility markets in the United Kingdom. Europe is facing the same flexibility pressures as East Asia, pressures created by the growth of intermittent solar and wind resources. Storage and demand-side flexibility are becoming essential for stabilizing markets and facilitating grid operation. Additional trends in Europe that are driving interest in demand flexibility are (1) the impact that natural gas prices and availability is having on peak prices and need for resources, and (2) a growing gap between midday solar oversupply and evening demand.

15 Prasanna et al.

16 U.S. Department of Energy, "Pathways to Commercial Liftoff: Virtual Power Plants," September 2023.

17 Sustainable Manufacturing Expo, "Benefits of Implementing Virtual Power Plants in Industrial Settings," n.d., https://www.sustainablemanufacturingexpo.com/en/articles/benefits-virtual-power-plants.html.

BOX B.2 Demand flexibility actions in the European Union

Over the last several years, the European Union (EU) adopted several reforms that should provide greater access to markets for demand-side resources and encourage greater demand flexibility.

The Clean Energy for All Europeans Package (2019) recognizes demand response and aggregators as market participants and requires EU Member States to enable independent aggregators to participate in all electricity markets without discrimination.

The Electricity Market Design Reform (2023–24) introduced reforms to enhance flexibility procurement at the distribution level, promote non-fossil flexibility (including demand response, VPPs, and storage), and permmit long-term contracts for flexibility and capacity.

The REPowerEU Plan aims to reduce gas dependency by scaling up clean flexibility through promotion of smart appliances, storage, electric vehicles, and digital energy services.

The Network Code on Demand Response, which is in development, is intended to harmonized rules across Member States for data access, baseline methodologies, and market participation criteria for demand response actors and aggregators.

Industrial customers are active in providing demand response to European utilities and markets. The set of industries involved is similar to that in the United States. It includes steel, cement, chemicals, and pulp and paper. The potential for industrial demand response in Europe is estimated to be about 15 to 30 percent of peak load.[18] Nevertheless, the ability and extent of industrial firm participation in demand response varies by country, with France providing the most opportunity, driven by its adoption of multiple market opportunities like capacity markets, and by its support for the creation of demand response products. For example, ArcelorMittal participates in the NEBEF (Mécanisme de Réduction de Consommation), which allows aggregators and consumers to offer load reductions into the energy market, independently of their supplier; the French Capacity Mechanism; and the primary reserve balancing markets. ArcelorMittal participates in these opportunities with the assistance of an aggregator, Restore, and through investments in digital infrastructure.

As in the United States, industrial firms deploy DERs, particularly solar PV, to reduce costs and meet decarbonization goals. It is estimated that a significant majority of the 263 GW of solar PV in Europe comes from smaller distributed facilities, but estimates of the quantity of solar at industrial sites are not readily available.[19]

18 Lennart Söder et al., "A Review of Demand Side Flexibility Potential in Northern Europe," Renewable and Sustainable Energy Reviews 91 (August 2018): 654–64, https://doi.org/10.1016/j.rser.2018.03.104.

19 SolarPower Europe, "EU Market Outlook for Solar Power 2023-2027," December 12, 2023, https://www.solarpowereurope.org/insights/outlooks/eu-market-outlook-for-solar-power-2023-2027.

As with other regions, battery energy storage deployments in Europe are increasing rapidly. It is estimated that 10.8 GW of batteries have been deployed in Europe, with industry comprising between 15 and 25 percent of that total.[20] Industries use batteries to reduce grid electricity usage during peak tariff periods, avoid capacity charges based on peak demand, charge batteries from on-site solar PV or wind for later use, support participation in energy markets, and provide backup and resilience.

European customers are long-time participants in VPPs, particularly industrial firms, and are becoming a cornerstone of Europe's energy transition. VPPs offer Europe a way to aggregate and control DERs like solar PV, wind turbines, batteries, and flexible loads. For example, in Germany, Next Kraftwerke launched one of the first commercial VPPs in the 2010s, aggregating biogas, wind, and industrial demand response. The use of VPPs is incentivized by highly variable electricity prices and the existence of flexibility markets. In addition, the creation of flexibility markets (noted above) indicates that European regulators have created conditions conducive to the development of VPPs. The European VPP market is projected to grow by close to 24 percent from 2024 to 2032, indicating significant expansion across all sectors, including industrial.[21]

Emerging market experience

Demand-side resources and demand response instruments have been widely deployed and tested in emerging markets. Leading the way are implicit, price-based programs, typically in limited pilots or to address short-term electric shortages.

Price-based demand response mechanisms such as TOU rates have been used in many countries; 40 percent of countries surveyed by the World Bank reported using them for their largest customers.[22] For example, Brazil has been using TOU rates for large and medium-sized customers for decades with significant benefits, achieving the initial objective of shifting loads to off-peak periods. TOU tariffs at the utility serving Minas Gerais have resulted in an estimated peak load reduction of 500 MW for high-voltage customers and 700 MW for medium-voltage (about 10 percent in total), for an estimated investment saving of $600 million, or about $6 billion if extrapolated to the entire country.[23]

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[20] Energy News, "The European Renewables Market Is Driving the Battery Storage Boom," February 6, 2025, https://energynews.oedigital.com/power-markets/2025/02/06/the-european-renewables-market-is-driving-the-battery-storage-boom.

[21] Triton Market Research, "Europe Virtual Power Plant Market 2024-2032," n.d., 2024–32, https://www.tritonmarketresearch.com/reports/europe-virtual-power-plant-market.

[22] World Bank Group, "Harnessing the Potential of Flexible Demand Response in Emerging Markets: Lessons Learned and International Best Practices," Energy Sector Management Assistance Program, November 28, 2024, 2025-05-23, https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099112724131541740.

[23] ESMAP 2024, p. 58.

Interruptible rates are not as widely used, except in South Africa, which has a negotiated pricing agreement with an aluminum smelter that provides two hours of interruptibility for an agreed maximum number of events per year.

Quantity-based, explicit demand response has been implemented with notable success in some markets. Interruptible contracts and load controls have been carried out in multiple countries, including Brazil, China, India, and South Africa. For example, India has implemented several pilots on load control. Tata Power in Mumbai implemented a load control program in 2012 to reduce load during peak shortages, transmission line tripping, and generator tripping, as well as when power purchase costs were high. The peak load for the utility was reduced from about 55 GW to 42 GW.[24]

The participation of demand-side resources in wholesale markets is less advanced in regions outside the United States and Europe. A primary reason for this low deployment is the lack of wholesale markets in many of these emerging countries. A notable exception is Brazil, which developed a demand-side bidding program in 2021. Participation was limited to large industrial companies (consuming more than 1 MW) or aggregators that could make offers a day or a week ahead to shift load from peak to nonpeak periods (typically for a four-hour reduction). If accepted for dispatch, qualified bids would be remunerated based on estimated load reduction (actual vs. deemed or baseline consumption). An estimated 3 GW of demand response was produced. The program lasted three months, from September through November 2021, but was no longer needed after the probability of loss of load returned to normal levels.[25]

A focus on Viet Nam's demand-side resources

Through a series of governmental decisions starting in 2006, the use of demand-side resources in Viet Nam has been carefully examined and phased in gradually. By the mid-2010s, the Vietnamese electric utility EVN had begun to roll out more comprehensive demand response programs, targeting industrial and commercial customers. The approval, in 2018, of the National Program on Demand Side Management for the period 2018–2020 (Decision No. 279/QD-TTg) was the next step in EVN's efforts to apply demand response strategies to optimize electricity consumption and ensure grid stability. The objectives of this decision are to:

- Uniformly apply engineering, technological, and socioeconomic solutions to the implementation of demand-side management programs
- Implement the national demand-side management program in line with trends in the energy sector and national electricity development planning, thereby ensuring the

[24] ESMAP 2024, p. 21.

[25] World Bank Group, "Harnessing the Potential of Flexible Demand Response in Emerging Markets: Lessons Learned and International Best Practices."

optimization of social resources, efficiency, and benefits for consumers and electric utilities in the chain from power generation, transmission, distribution, sale, and use

- Reduce the peak load capacity of the national electric system as well as regional electric systems in order to reduce the need for investment capital for construction and expansion of the electric system, ease power price pressure, and contribute to sustainable development and reasonable energy resource management
- Raise awareness of users and the society at large about effective use and demand side management, gradually transforming traditional users into smart users.

Currently, Viet Nam is implementing a voluntary demand response program, where large customers participate in a spirit of cooperation and volunteerism. In return for participating, these customers receive benefits: (1) early notification of the restoration of power supply after an outage; (2) inclusion on the list of priority customers; and (3) exemption from certain maintenance and customer care responsibilities. Since 2023, more than 11,000 customers have joined the demand response program, with approximately 4,000 in the North region, 2,000 in the Central region, and 6,500 in the South. Some 3,500 are customers of EVN Hanoi; 1,700 of EVN Ho Chi Minh.[26] EVN claims that adjusting production schedules has helped companies reduce their total electricity consumption by 25-30 percent, and time-of-use (TOU) rates have saved nearly 15 percent on electricity bills.[27]

The further expansion of demand response programs in Viet Nam is stymied by economic and regulatory challenges, primarily the absence of clear incentive mechanisms. Current legal and regulatory frameworks lack explicit provisions for financial incentives to encourage consumer participation in demand response programs, making it difficult to attract and motivate consumers to further adjust their electricity usage patterns. The Ministry of Finance has been considering changing this framework for several years, but no changes have been forthcoming.

In addition, TOU rates have been in place since 2014, encouraging off-peak consumption. While these rates promote shifting of load from peak to off-peak periods, the difference between peak and off-peak rates has been insufficient to induce sizable shifts in reductions in peak consumption. Additionally, as the power system evolves, the definition of peak hours needs to be more dynamic in order to increase the efficiency of the TOU mechanism.

[26] Communications with Ahn Hoang Le, World Bank, March 20, 2025.

[27] "Why is Vietnam stuck in power shortages, and how are they dealing with them?" Reccessary, June 4, 2024, www.reccessary.com/en/news/vn-market/why-is-vietnam-stuck-in-power-shortages-and-how-are-they-dealing-with-them.

B.4 | Policy recommendations and possible financing opportunities

The policy recommendations in this section focus on how industrial customers can use demand-side resources to support industry decarbonization. Global experience with the adoption of demand-side resources, particularly at industrial facilities, indicates that several conditions are necessary. First, to make lasting changes, the economics of demand-side actions must be substantial to compensate for possible costs or loss of revenue stemming from changes in production. Adequate incentives, clear price signals, or subsidization of demand-side efforts will be required. Second, steady policy and regulatory support of technologies, programs, and markets for demand-side resources is essential to create urgency and stimulate interest on the part of industry and other enablers, such as aggregators. “Market design and other regulatory barriers can restrict the participation of demand-response providers that would otherwise be cost-effective,” reports the World Bank Group in a major 2024 report.[28] Third, if possible, markets for the output of industrial demand-side action like demand response or grid injection from on-site batteries should be developed. Many countries have feed-in tariffs or net energy metering policies, but more direct participation in markets is needed. Fourth, since industrial use of demand-side resources will entail changes in processes, investment in modern, digital production management systems may be required to achieve significant impact. Fifth, industrial companies tend to be conservative in their operations. Getting past this inertia will require extensive effort.

As noted earlier, countries in East Asia have a particularly great need flexibility and flexible resources. To take the example of Viet Nam, where the current focus of the country’s electric policy is non-carbon generation sources (such as hydroelectricity and nuclear power) and the build-out of transmission infrastructure, intermittent sources will represent major sources of generation in the future, both on the grid and off.

To address the need for flexibility and new resources, the focus of the recommendations that follow is the adoption of policies and investments in resources, tools, and equipment to exploit and regulate the flexibility inherent in East Asian industry.

Recommended: Technical support

Technical support to promote or incentivize the adoption of demand-side resources can be provided to policy makers and regulators or directly to industrial firms or their associations. Potential technical support includes the following.

[28] World Bank Group, “Harnessing the Potential of Flexible Demand Response in Emerging Markets: Lessons Learned and International Best Practices.”

- **Technical materials.** Technical materials or consulting assistance can be made available to regulators, policy makers, or company managers to ensure that they have the latest information on demand-side resources and policy options appropriate for their country. A vast amount of information and expertise is available; technical assistance helps ensure that information is provided effectively.
- **Targeted research support.** Targeted research support will likely be needed to assist in the development or support of policies and regulations. Grid modernization, demand flexibility, and the use of demand-side resources are challenging to deploy within existing regulatory structures, even in the developed world. To craft the policies, regulations, and institutions needed to make rules to support demand-side resources effectively, governmental and regulatory entities may benefit from research support.
- **Direct technical assistance.** Technical assistance in engineering, information technology, and other areas could be provided directly to industrial facilities or their agents. International experience has shown that, except for large multinational corporations, the expertise needed to reduce or shift energy consumption is in short supply (as is interest in acquiring that expertise). Nevertheless, with targeted technical assistance geared toward specific industries or industry needs, investment and participation in demand-side programs and markets may become possible. In particular, a comprehensive data strategy for industrial flexibility could be created to develop data models, algorithms, process models, and workflows, and to provide solutions that are either industry agnostic or offer a high degree of adaptability for industries that fall into certain categories.[29]

Recommended: Policy and regulatory support

International experience indicates that the deployment and implementation of demand-side resource policy is a necessary precursor for resource deployment. While climate policy goals in East Asian countries may not focus specifically on demand-side resources, the overall policy goals of decarbonization and grid modernization support the use of demand-side resources. To promote demand response and demand flexibility, country-level demand-side policies should be considered and developed.

- **Development of open wholesale markets.** Benefits from the deployment of demand-side resources are maximized when there are open wholesale markets that can provide additional monetization and support. Without competitive wholesale markets, the ability to monetize flexibility products. Real-time spot markets operated by electric utilities are beneficial, but they typically do not allow for the participation of demand-side resources. Development of wholesale markets, especially in countries dominated by a single incumbent utility, is difficult and time-consuming, but support for their development should be given high priority.

[29] Ranaboldo, "A Comprehensive Overview of Industrial Demand Response Status in Europe."

- **Development and implementation of incentivse-based demand response and flexibility products.** International experience shows that demand response programs and flexibility markets that compensate industry for curtailing or shifting consumption generate the most participation and innovation. Support for the development of these programs would be provided to decision-makers and regulators. Discounted interruptible rates, heavily used in the United States, should be promoted as a first step toward incentives-based programs. By requiring demand reductions when directed, these rates will help ensure that demand reductions will occur during periods of system stress. Furthermore, since they do not directly involve payments or direct incentives, these rates should be easier to adopt.
- **Dynamic pricing support.** Technical and regulatory support for the creation of dynamic pricing tariffs, such as critical peak pricing and real-time pricing, will be crucial in the development of demand flexibility. While TOU rates incentivize load shifting, their static nature and lack of focus on the highest peak periods reduces their value and incentive potential. Alternatively, policy support could be provided to increase the differential between peak and off -peak TOU prices. For example, the peak/off-peak ratios in Viet Nam are around three. International experience has shown that ratios of four or higher may be necessary to induce change in consumption.
- **Support for the adoption of cost-benefit analysis.** The experience in other countries is that demand-side resources can be cost-effective with operational optimization. The adoption of cost-benefit analysis in East Asian countries to support policy making and regulatory decisions should be encouraged through technical support and the provision of tools and analysis.
- **Support for grid codes and standards.** Support for the development and deployment of grid codes and standards that recognize the existence of demand-side resources and measure their role is important. Model codes and standards include agreements on renewable energy, trading rules, measurement, uniform carbon accounting, and clear rules for VPP output, as well as for measurement and verification of load reductions.

Recommended: Financial support

Ultimately, and in keeping with the focus of the World Bank, financial investments may be required to assist industrial decarbonization by supporting demand-side resources. Potential financial support options include the following

- **Direct loans.** Direct loans to industrial facilities or companies could be offered to help finance key demand-side resources. This form of financial support should match country policy. For example, Viet Nam has called for international climate financing of renewables and demand-side resources. Areas to support could include (1) batteries and control systems; (2) on-site installation of solar PV; and (3) digitization or automation of industrial processes.
- **Direct loans to support purchase of carbon credits or renewable energy certificates.** Another means to support demand-side resource deployment could be financial support

or loans for the purchase of carbon credits or renewable energy certificates.

- **Funding for green banks or revolving funds.** The World Bank could provide seed money or funding for country-level or industry-specific green banks or revolving funds. Industrial firms could access these funds to finance their demand-side resource investments.
- **Financial support for market entry.** Loans could be offered to support entry of demand response vendors, aggregators and other companies into East Asian countries and markets.

TABLE B.2 A comparative analysis of demand response, demand flexibility, and virtual power plants

Aspect	Demand response	Demand flexibility	Virtual power plants
Core function	Produces load adjustments, like peak shaving during high demand periods and valley filling during low periods, effectively stabilizing the grid or enhancing the utilization of renewable energy.	Manages load adjustments at an individual level, optimizing energy use in response to varying conditions and price signals.	Coordinates a network of distributed energy resources (DERs) and demand response resources to function as a single, flexible unit, optimizing grid operations and market participation for economic and operational benefit.
Resource scope	Focuses on adjustable loads that can respond to grid signals and directives.	Utilizes a range of controllable resources, including loads, storage, and DERs at an individual or localized level.	Manages a diverse mix of resources, integrating them to function cohesively as a single operational unit for enhanced grid stability and market engagement.
Time scale	Typically operates over minutes to hours to address immediate grid needs.	Engages in automated or quick adjustments to adapt to real-time and forecasted energy conditions.	Manages energy resources on various time scales, from real-time adjustments for frequency regulation to strategic participation in energy, capacity, and ancillary services markets.
Control method	Combines direct control by grid operators with user-enabled adjustments based on utility signals.	Generally uses automated systems and user-configured settings to optimize energy usage, enhancing both efficiency and grid responsiveness.	Employs advanced control, communication, and coordination systems to orchestrate a wide range of DER operations, ensuring optimal integration and responsiveness.
Business model	Involves compensation mechanisms based on time-based tariffs and incentive-based payments for specific grid-support activities.	May utilize innovative business models like flexibility contracts or trading system services to leverage the ability to modulate energy use and production effectively.	Participates actively in energy, ancillary, and capacity markets, using aggregated resource capabilities to generate revenue and provide grid support under varying conditions.
Summary	Generally used for quick grid relief during peak times, emergencies, and periods of high prices; typically managed both by grid commands and some user participation.	A proactive system that continuously adapts to grid conditions at an individual or local level, providing enhanced grid stability and efficiency through intelligent management of customer load, generation, and storage resources.	A sophisticated and dynamic integration of diverse energy resources managed through complex systems that function as a single flexible unit, optimizing both operational performance and economic returns through strategic market participation.

Appendix C.

Policy Recommendations for Electrification of Industrial Heating: Focus on Heat Pumps and Financing Mechanisms

C.1 | Innovative business models

At present, industrial heat pump manufacturers typically follow a traditional business model of direct sales of equipment to users. Given the high capital costs of steam-generating heat pumps, many heat pump manufacturers have sought and benefitted from government grants, an important source of funding to incentivize early adoption. In addition, heat pump manufacturers may offer discounted pricing or shared-risk agreements to incentivize customers. Another financing option under this business model is to provide a leasing-style structure where customers finance equipment directly from the heat pump manufacturer, allowing them to spread the upfront capital expenditure over a series of manageable payments. Market growth under this traditional business model relies on demonstrating technical viability, leveraging existing government incentives, and attracting heat pump adoption through education and engagement.

Heat pump manufacturers are increasingly exploring business models that include service contracts and maintenance agreements, such as the heat-as-a-service (HaaS) model. The Energy Service Company (ESCO) model has been a successful approach for improving energy efficiency in industrial facilities by enabling businesses to adopt new technologies without significant upfront investment. Under this model, ESCOs finance, install, and maintain energy-saving equipment, with clients repaying the investment through shared energy savings. This approach reduces financial risk for facility owners and accelerates the adoption of efficiency measures.[1] The heat-as-a-service model builds on this concept, with the heat pump manufacturer providing the equipment and handling engineering, design, installation, and ongoing operations and maintenance, ensuring the system's performance over its lifetime. The industrial customer avoids significant upfront capital expenditure and instead pays for the heat delivered at a predictable price, benefiting from reduced operating costs and the improved energy efficiency of heat pumps. By shifting heat production from a capital-intensive investment to a managed service, this model lowers financial barriers for companies seeking to decarbonize their thermal energy needs. This model has seen success in the building sector, where cooling (and heating) demand are relatively more stable and predictable than the industrial sector, within programs like the Cooling-as-a-Service Initiative targeting adoption in developing countries.[2,3]

Heat pump manufacturers may partner with EPC firms to manage project integration and deployment while collaborating with financial institutions and investors to capitalize their projects.[4]

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1 Daniel Galis, "Heat-as-a-Service in Action: Insights from Early Renewable Heat Projects," WBSCD (blog), July 1, 2024, https://www.wbcsd.org/news/heat-as-a-service-in-action-insights-from-early-renewable-heat-projects/#.

2 Energy Transitions Commission, "Reaching Net-Zero Carbon Emissions from Harder-to-Abate Sectors by Mid-Century - Sectoral Focus: Building Heating," August 2020, https://www.energy-transitions.org/wp-content/uploads/2020/08/200729-ETC-Paper-Building-Heating-FINAL.pdf.

3 Sustainable Energy for All, "Cooling as a Service: A Disruptive Business Model for Sustainable Cooling," 2020, https://www.seforall.org/news/cooling-as-a-service-a-disruptive-business-model-for-sustainable-cooling.

4 Ankur Dass et al., "Shares Exploring Three Business Models for Industrial Heat Pump Manufacturers," RMI (blog), January 31, 2025, https://rmi.org/exploring-three-business-models-for-industrial-heat-pump-manufacturers.

Success under the heat-as-a-service business model will depend on standardizing heat pump solutions, expanding manufacturing scale and sales volumes, and ensuring a smooth customer experience.

An emerging feature of the heat-as-a-service model is the inclusion of electricity procurement and electrical infrastructure management as part of the service. In this variation, the heat pump provider assumes responsibility not only for the equipment, installation, and maintenance but also for securing the necessary electricity supply and building supporting infrastructure. This may involve establishing a dedicated mini-substation that operates independently from the customer's existing electricity demand and rates. By creating a separate electricity feed, providers can actively manage energy procurement, often securing more favorable electricity rates through negotiations with utilities or by leveraging real-time pricing models in markets where this is feasible. This approach can be particularly advantageous for industrial facilities with significant power demands, especially in cases where the existing grid infrastructure requires upgrades to accommodate the additional load. Additionally, this model offers flexible siting opportunities, allowing heat pumps to be installed at a distance from the main facility, providing adaptability for complex industrial layouts. Finally, this model could be leveraged to encourage procurement of renewable electricity, such as power purchase agreements, which are essential to rapid decarbonization via electrification.

Another possibility for scaling up this business model for industry is applications of electrified heating in industrial parks. Industrial parks could offer bundled services for heating, taking advantage of economies of scale and the ability to use waste heat across facilities. In China, steam for industrial process heating is often provided for multiple facilities from a centralized source. While the heating source is typically coal-fired boilers, the existing steam distribution infrastructure and payment models could be leveraged to transition to electrified heating technologies.

Based on this assessment of heat pump business models and case studies, we put forward several policy recommendations to scale up heat pump adoption through innovative business models.

1. **Encourage Partnerships with Stable and Experienced Energy Service Companies (ESCOs)**
   Policymakers should incentivize partnerships between industrial heat users and stable, experienced ESCOs that can implement HaaS models based on demonstrated financial stability, technical expertise, and reliability. For example, governments can provide certification programs or accreditation for ESCOs to build trust and support long-term partnerships. Policymakers should also encourage standardized HaaS contract templates that offer stable, predictable heat prices over extended periods, similar to power purchase agreements.

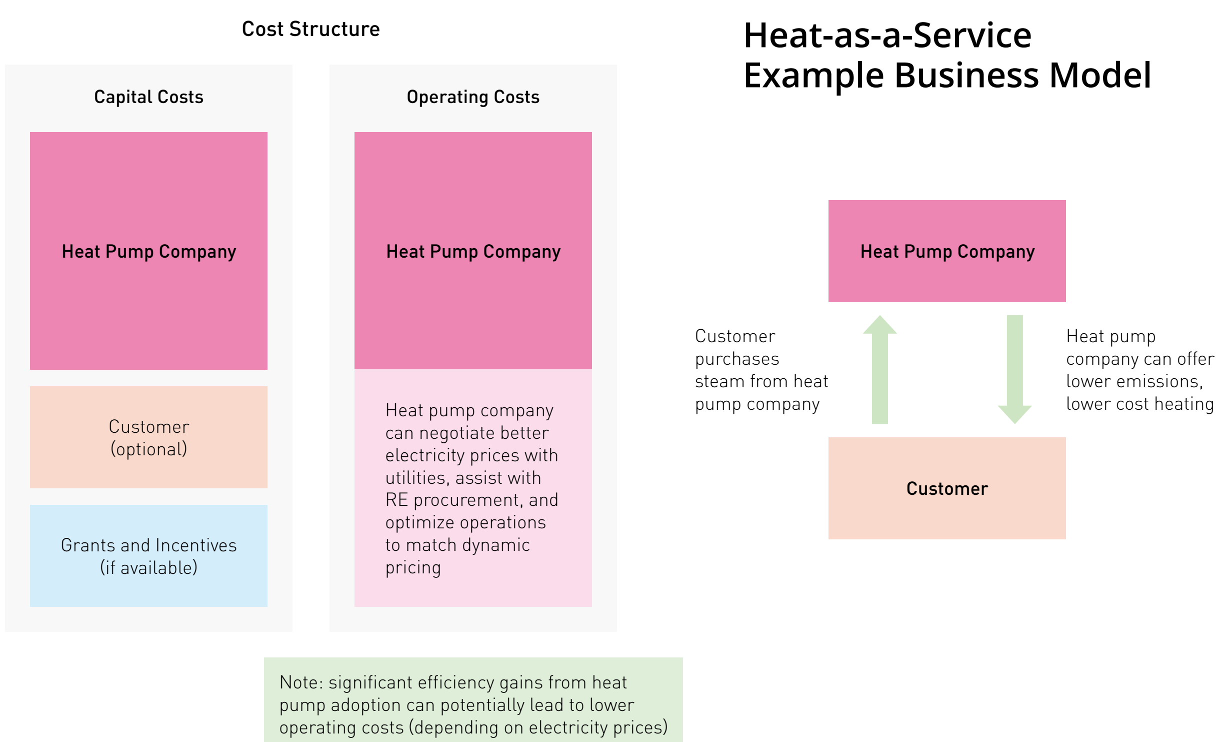
2. **Encourage Haas Providers to Support Renewable Energy Procurement**
   Policymakers should incentivize HaaS providers to support renewable electricity procurement as part of their service model, building on HaaS models that include electricity procurement and infrastructure services. Additionally, regulatory frameworks should allow

HaaS providers to negotiate with utilities to secure favorable electricity rates for electrified facilities. Furthermore, policymakers can facilitate partnerships between HaaS providers, utilities, and industrial energy users by promoting collaborative pilot programs that demonstrate the financial and environmental benefits of integrated heat pump and renewable energy solutions.

3. **Facilitate Collaborative Funding Models that Pair HaaS with Public Subsidies**
   Policymakers should encourage potential HaaS providers to proactively pursue public support for HaaS projects as part of their service model. This approach can maximize the impact of government funding by ensuring projects are financially viable and reduce risks for industrial adopters.

4. **Promote Pilot Programs and Knowledge Sharing**
   To build trust in HaaS models, policymakers should support pilot programs that demonstrate the economic and operational benefits of HaaS agreements. Additionally, governments should facilitate platforms for sharing best practices, case studies, and lessons learned to encourage broader adoption of the HaaS model across industries.

FIGURE C.1 Overview of how HaaS business models can provide heat services and structure support for both capital and operating costs



Case study: Heat-as-a-service model to scale up industrial heat pump adoption

Several case studies of heat-as-a-service models offer lessons for future projects. The Heineken Seville brewery project implemented a HaaS model to finance and operate a solar thermal power plant. Under this model, Engie, acting as an ESCO, funded the initial €20 million investment, secured a €13.4 million government subsidy, and retains ownership of the plant throughout the 20-year contract period. At the end of the contract term in 2043, ownership of the solar thermal plant will transfer to Heineken.[5] The Felleskjøpet steam-generating heat pump project at an animal feed manufacturing facility in Norway follows a HaaS business model with a unique ownership structure. ESCO Aneo Industry and agricultural cooperative Felleskjøpet co-lease the ammonia heat pump system from heat pump manufacturer GEA. As part of the agreement, Aneo faces penalties if the system underperforms, incentivizing optimal operation.[6]

C.2 | Reducing capital cost

Capital costs are the major barrier for heat pumps, relative to other electrification technologies like electric boilers or process-specific equipment like electric dryers. Although industrial heat pumps build on mature technologies, capital costs can still be lowered by technological innovation. One promising avenue for cost reduction is the development of scalable, modular heat pump designs that prioritize standardization over custom-built systems (as is currently the norm). By mass-producing standardized components, manufacturers can achieve economies of scale, as many steam-generating heat pump manufacturers today still operate at relatively small scales. Innovations in key system components, particularly compressors, refrigerants, and heat exchangers, also play a significant role in reducing costs and improving efficiency. Since compressors account for up to 40 percent of total heat pump costs and consume 90 percent of the system's energy, improving their design can dramatically enhance system performance. For example, advanced centrifugal turbocompressors with magnetic bearing systems eliminate contacting parts, reducing maintenance requirements while achieving higher temperature lifts with fewer stages. New refrigerants are also emerging as a solution to improve heat pump performance and reduce costs. Solid-state refrigerants and innovative chemical loops offer higher efficiency while lowering environmental impact and refrigerant costs, which can account for up to 15 percent of total system expenses.[7]

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5 Heineken, "Utilize Solar Thermal HaaS to Cut Industrial Emissions," TheClimateDrive (blog), June 13, 2024, https://www.theclimatedrive.org/action-library/utilize-solar-thermal-to-cut-industrial-heat-emissions.

6 Dass et al.

7 Selene Law, "Industrial Heat Pumps Ready to Scale Up," CleanTech Group (blog), January 14, 2025, https://www.cleantech.com/industrial-heat-pumps-ready-to-scale-up/.

Direct R&D support for these innovations will be important, and scaling up heat pump manufacturing across different geographies can provide additional economic benefits to the domestic economy (currently, steam-generating heat pump manufacturers are still small-scale, and concentrated in the United States, Europe, and Japan). The U.S. offers an example of government support spurring manufacturing capability for heat pumps in the 48C manufacturing tax credit, expanded through the Inflation Reduction Act. This incentive allowed eligible companies to receive tax credits covering up to 30 percent of qualified investments, helping reduce capital costs and support manufacturing growth. Skyven is an example company which leveraged the 48C tax credit to expand its production of steam-generating heat pump systems.[8]

Given the need to innovate steam-generating heat pump designs and lower capital costs, we put forward several policy recommendations, with a focus on financial mechanisms:

1. Expand Financial Support for Heat Pumps

Given the significant upfront costs associated with heat pump installations, policymakers should prioritize expanding capital and operational incentives to improve financial viability and lower manufacturing costs.

Expanding public funding options, such as government grants and investment tax credits, is a critical tool for lowering heat pump capital costs. Programs like the 48C tax credit in the United States have proven successful in supporting manufacturers investing in clean energy projects, including heat pumps. Policymakers should design incentives that are accessible to small and medium-sized businesses to ensure equitable access to funding. Alongside direct financial incentives, policymakers should invest in research and development to support innovative heat pump designs that improve efficiency, lower material costs, and simplify system integration.

Philanthropic organizations can play a valuable role in funding initial demonstration projects that prove the technical and financial viability of heat pump installations. Policymakers can encourage public-private partnerships that combine philanthropic capital with government incentives to scale up successful pilot projects.

2. Increase Available Financing for Heat Pumps

Overcoming the upfront cost barriers of heat pumps will require a diverse set of financing mechanisms that address various barriers to investment. The following financing approaches can help mitigate the financial risks associated with large-scale heat pump installations:

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[8] Chris Barnhill, "DOE Announces $145 Million for Skyven Technologies to Decarbonize Industrial Steam," Skyven Technologies, March 25, 2024, https://skyven.co/news/doe-oced-145-million-funding/.

- **Traditional Lending:** Policymakers should encourage local and international banks to offer low-interest loans or concessional financing to industrial facilities adopting heat pump technology as well as equipment manufacturers seeking to expand production of steam-generating heat pumps. Loan guarantees provided by governments can de-risk these investments, making lenders more willing to offer favorable terms. Development banks can play a key role in financing heat pump adoption in emerging markets, where access to affordable capital is often limited.
- **Sustainability-Linked Financing:** Policymakers can promote sustainability-linked financing tools such as green bonds, which provide capital for specialized projects at competitive interest rates based on e.g. meeting decarbonization milestones. Specialized lending and investment funds dedicated to decarbonization technologies should be expanded to target sectors like food processing, chemicals, and textiles — industries with heating profiles suitable for steam-generating heat pump adoption.
- **Private Sector Investment:** Encouraging venture capital (VC) and private equity (PE) firms to invest in heat pump innovation and manufacturing can help scale the industry faster. These investment models are particularly useful for supporting emerging companies developing novel heat pump designs.
- **Co-Investment from Downstream Brands:** In sectors with strong consumer demand for low-carbon products (such as apparel, textiles, and food processing), policymakers can encourage downstream brands to co-invest in heat pump projects within their supply chains. Corporate guarantees can help small and medium-sized industrial facilities secure favorable financing terms
- **Development Bank Financing:** Development banks can play a central role in financing large-scale industrial heat pump projects, especially in regions where access to capital is limited. Targeted financing programs can provide concessional loans or blended finance structures that combine public and private funding to de-risk investments. Development banks can also provide technical assistance to ensure project success, further encouraging adoption. Recognizing that concessional financing is limited, development banks could create a pooled fund that also blends government and bank financing to offer more attractive and accessible financing to potential adopters.

C.3 | Reducing installation cost

Installation costs are often an underappreciated barrier to heat pump adoption and can be significantly higher than the cost of the heat pump equipment itself. In some cases, installation expenses are three to five times the cost of the heat pump unit, adding substantial financial burden to potential adopters. Moreover, installation timelines are lengthy, often taking one to two years from equipment order to full commissioning. These costs are driven by several factors, including complex retrofitting needs, site-specific engineering, and integration with existing industrial systems. Heat pumps that require extensive custom design, new piping infrastructure, or upgraded electrical capacity can further increase costs.

Innovative heat pump designs and strategic installation approaches offer promising pathways to reduce installation expenses. Supporting the development of heat pumps with standardized, modular designs can simplify the installation process and significantly reduce costs. Plug-and-play configurations reduce the need for custom integration by allowing heat pump units to be pre-assembled, factory-tested, and delivered in a ready-to-install state. This approach minimizes on-site engineering work, shortens installation timelines, and lowers labor costs.

Industrial facilities with multiple production lines can reduce upfront installation costs by implementing phased installation strategies. This approach involves installing heat pumps incrementally — one or two production lines at a time — rather than attempting a full-scale conversion all at once. Phased installations allow businesses to spread capital expenses over time, which is particularly useful for smaller manufacturers or companies with limited cash flow. Additionally, incremental adoption reduces disruptions to production, making it easier for facilities to maintain operations throughout the installation process.

Given these avenues for reducing installation costs, we put forward the following policy recommendations:

1. **Incentivize Plug-and-Play Designs and Phased Installation**
   Research and development initiatives can support more modular, standardized heat pump systems. Providing grants or tax incentives for companies that develop and commercialize plug-and-play configurations and/or phased installations can accelerate innovation and reduce installation costs.

2. **Streamline Permitting and Regulatory Processes**
   Lengthy permitting procedures often extend installation timelines and increase costs. Policymakers should establish clear guidelines and fast-track permitting processes for heat pump installations, particularly for facilities also seeking to procure renewable energy to pair with heat pumps.

3. **Provide Technical Assistance for Industrial Facilities**
   Policymakers should fund technical support programs that help industrial sites assess optimal installation strategies and identify low-cost integration solutions. This could include training for contractors and engineers to build expertise in modular heat pump systems, since third-party EPCs are often involved in heat pump installation.

Appendix D.

Scenario Input Data and Assumptions

An overview of the modeling approach and key assumptions is detailed in Chapter 2: Methodology. This appendix provides additional detail on specific settings employed in the modeling. The following table contains a large selection of inputs to the model (including data and assumptions). Outputs from the model are covered in Chapter 3: Modeling Results.

The Excel-based computer model used in this study has been released open source, accompanying this report. For more detail on input data (including citations to its 89 data sources and where those sources are used in the calculations), please see the model.

D.1 | Selected input data and assumptions by country

	CHINA	INDONESIA	VIET NAM
Share of primary steel production replaced by increased secondary steel production (percent)			
Iron & steel	60	70	60
Share of nonelectrified non-feedstock energy use handled via CCS (percent)			
Nonmetallic minerals	67	78	83
Iron & steel	65	33	83
Nonferrous metals	100	100	100
Share of nonelectrified non-feedstock energy use handled via green H_2 (percent)			
Refining & fuel processing	100	100	100
Chemicals	100	100	100
Nonmetallic minerals	33	22	17
Iron & steel	35	67	17
Share of chemical feedstocks provided by energy source (percent)			
bioenergy	30	30	30
green hydrogen	40	40	40
blue hydrogen	30	30	30

	CHINA	INDONESIA	VIET NAM
2022 electricity generation share by electricity source (percent)			
Coal	61.18	61.56	39.59
Petroleum	0.81	1.83	0.02
Natural Gas	3.11	17.00	11.15
Nuclear	4.72	0.00	0.00
Hydro	14.67	8.18	35.86
Bioenergy	2.06	6.18	0.14
Wind	8.62	0.11	3.34
Solar	4.83	0.13	9.63
Other renewables	0.00	5.00	0.26
BAU electricity demand projection for nonindustrial sectors (TWh)			
2022	4,414	218	115
2025	5,048	285	136
2030	5,683	399	180
2035	6,318	512	235
2040	6,952	625	301
2045	7,587	738	366
2050	8,222	851	440
Carbon pricing (US$/tonne CO_2)			
BAU (constant through 2050)	$13.37	$0.00	$0.00
Decarbonization scenario (linear phase-in through 2050)	$50.00	$50.00	$50.00
Energy prices, 2022 actual (US$ billion/PJ)			
Coal	0.003	0.003	0.003
Coke	0.003	0.003	0.003
Coal/Coke Byproducts	0.003	0.003	0.003
Petroleum	0.015	0.015	0.008
Natural Gas	0.013	0.013	0.009
Bioenergy and Waste	0.003	0.003	0.007
Purchased Heat	0.017	0.017	0.003
Electricity	0.027	0.027	0.020

	CHINA	INDONESIA	Viet Nam
Energy prices, 2050 forecast (billion US$/PJ)			
Coal	0.004	0.004	0.004
Coke	0.004	0.004	0.004
Coal/Coke Byproducts	0.004	0.004	0.004
Petroleum	0.019	0.019	0.010
Natural Gas	0.017	0.017	0.011
Bioenergy and Waste	0.004	0.004	0.007
Purchased Heat	0.020	0.020	0.004
Electricity	0.029	0.029	0.026
Anticipated natural percentage change in demand through 2050			
Food, beverage, & tobacco	0	30	132
Textiles, leather, & apparel	0	135	241
Wood & furniture	0	90	303
Pulp, paper, & printing	0	90	148
Refining & fuel processing	3	3	3
Chemicals	45	45	241
Plastic & rubber products	97	169	241
Nonmetallic minerals	-29	37	24
Iron & steel	-21	90	148
Nonferrous metals	15	90	148
Machinery	-21	90	272
Vehicles & transport equipment	-21	90	551
Electronics	-21	90	241
Other metal products	-21	90	148
Other manufacturing	0	90	365

	CHINA	INDONESIA	Viet Nam
Material efficiency potential			
Pulp, paper, & printing	5	9	10
Chemicals	24	14	10
Nonmetallic minerals	22	11	10
Iron & steel	13	6	10
Nonferrous metals	13	6	10
Energy efficiency potential (percent)			
Food, beverage, & tobacco	6.0	8.0	10.5
Textiles, leather, & apparel	30.0	32.0	15.0
Wood & furniture	13.0	14.0	15.0
Pulp, paper, & printing	15.0	21.0	19.0
Refining & fuel processing	10.0	13.0	16.0
Chemicals	20.0	19.4	16.0
Plastic & rubber products	2.0	7.0	11.9
Nonmetallic minerals	15.0	15.7	18.0
Iron & steel	19.0	24.0	13.0
Nonferrous metals	10.0	10.0	10.0
Machinery	9.0	7.0	5.0
Vehicles & transport equipment	6.0	4.0	2.0
Electronics	16.0	11.0	7.0
Other metal products	18.0	15.0	13.0
Other manufacturing	7.0	5.0	3.0
Clean H_2 energy cost in 2050 (US$/kg H_2)			
High improvement (default)	$1.80	$3.50	$2.17
Low improvement	$2.50	$5.10	$4.00
Present day	$3.90	$11.11	$8.33
Discount rate (percent)			
For capital equipment	7	7	7

D.2 | China non-feedstock industrial energy use in 2022 (PJ)

CHINA

	Coal and Coke	Petroleum	Natural Gas	Bioenergy & Waste	Purchased Heat	Electricity
Food, beverage, & tobacco	226	21	351	0	396	570
Textiles, leather, & apparel	37	14	228	0	354	786
Wood & furniture	2	7	23	0	9	160
Pulp, paper, & printing	85	17	88	0	359	376
Refining & fuel processing	1,311	5,794	454	0	929	576
Chemicals	4,488	4,092	1,976	0	3,192	2,751
Plastic & rubber products	41	21	73	0	44	579
Nonmetallic minerals	5,199	1,392	952	0	64	1,448
Iron & steel	18,094	38	536	0	184	2,471
Nonferrous metals	605	106	279	0	309	2,803
Machinery	64	44	254	0	39	1,142
Vehicles & transport equipment	15	27	242	0	29	570
Electronics	7	15	193	0	35	750
Other metal products	215	18	265	0	8	594
Other manufacturing	2	8	50	0	3	314

D.3 | Indonesia non-feedstock industrial energy use in 2022 (PJ)

INDONESIA

	Coal and Coke	Petroleum	Natural Gas	Bioenergy & Waste	Purchased Heat	Electricity
Food, beverage, & tobacco	230	24	26	197	0	97
Textiles, leather, & apparel	62	7	3	1	0	124
Wood & furniture	1	3	0	0	0	27
Pulp, paper, & printing	33	2	25	1	0	52
Refining & fuel processing	0	1	4	0	0	12
Chemicals	49	3	38	7	0	81
Plastic & rubber products	14	4	14	18	0	55
Nonmetallic minerals	287	9	36	34	0	109
Iron & steel	649	12	3	0	0	108
Nonferrous metals	431	3	3	8	0	28
Machinery	0	2	1	0	0	8
Vehicles & transport equipment	0	5	7	0	0	60
Electronics	4	1	3	1	0	36
Other metal products	0	12	2	0	0	15
Other manufacturing	0	1	0	0	0	5

D.4 | Viet Nam non-feedstock industrial energy use in 2022 (PJ)

VIET NAM

	Coal and Coke	Petroleum	Natural Gas	Bioenergy & Waste	Purchased Heat	Electricity
Food, beverage, & tobacco	20	8	1	10	0	68
Textiles, leather, & apparel	56	5	0	0	0	55
Wood & furniture	0	2	0	97	0	22
Pulp, paper, & printing	28	2	0	62	0	13
Refining & fuel processing	0	94	0	3	0	11
Chemicals	38	8	17	0	0	30
Plastic & rubber products	0	0	1	0	0	12
Nonmetallic minerals	445	21	8	38	0	41
Iron & steel	370	0	0	0	0	30
Nonferrous metals	130	0	0	0	0	10
Machinery	0	10	1	0	0	5
Vehicles & transport equipment	0	5	1	0	0	3
Electronics	0	0	0	0	0	37
Other metal products	72	0	0	0	0	6
Other manufacturing	33	3	0	3	0	64

List of Abbreviations

BAU	business-as-usual
BF-BOF	blast furnace-basic oxygen furnace
CapEx	capital expenditure
CBAM	Carbon Border Adjustment Mechanism
CCS	carbon capture and storage
CCUS	carbon capture, utilization and storage
CH_4	methane
CO_2	carbon dioxide
CO_{2e}	carbon dioxide equivalent
DERs	distributed energy resources
DR	demand response
DRI	direct reduced of iron
DSM	demand side management
EAF	electric arc furnaces
EJ	exajoules
EMDEs	emerging markets and development economies
EOR	enhanced oil recovery
ERCOT	Electric Reliability Council of Texas
ESCO	energy service company
ETS	emissions trading system
FERC	Federal Energy Regulatory Commission
FITs	feed-in-tariffs
GDP	gross domestic product
GECs	green electricity certificates
GEOA	Green Energy Open Access of India
GHG	greenhouse gas
GPP	green public procurement
GW	gigawatt
H_2	hydrogen
HaaS	heat-as-a-service
HYBRIT	hydrogen breakthrough ironmaking technology
IFIs	international financial institutions
ISOs	Independent System Operators
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
MISO	Midcontinent Independent System Operator
MRV	monitoring, reporting, and verification
Mt	million tonnes
MW	megawatt
MWh	megawatt-hour
MWhth	megawatt-hour of thermal
N_2O	nitrous oxide
NDCs	Nationally Determined Contributions
NDRC	National Development and Reform Commission of the People's Republic of China
NOx	nitrogen oxides
PJ	petajoules
PV	photovoltaic
R&D	research and development
RD&D	research, development and demonstration
RE	renewable energy
RECs	Renewable Energy Certificates
RTOs	Regional Transmission Organizations
SCC	Social Cost of Carbon
SMEs	small and medium enterprises
SPC	Shadow Price of Carbon
STEM	science, technology, engineering, and mathematics
TOU	time-of-use
TVET	technical and vocational education and training
TWh	terawatt-hour
U.S. DOE	U.S. Department of Energy
VPP	virtual power plants

Let today's actions create tomorrow's abundance.

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ESMAP Energy Sector Management Assistance Program