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China's Electrification Pathways: Findings from *the China Energy Outlook 2022*

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LIST OF ACRONYMS

BEV	battery electric vehicle
BF	Blast Furnace
BOF	basic oxygen furnace
CCUS	carbon capture, use, and storage
CNG	compressed natural gas
CO_2	carbon dioxide
DC	direct current
DHW	domestic hot water
DREAM	Demand Resources Energy Analysis Model
DRI	direct reduction of iron
EAF	electric arc furnaces
EVs	electric vehicles
FCEVs	hydrogen fuel-cell electric vehicles
GHG	greenhouse gas
GW	gigawatt
HDTs	heavy-duty trucks
IPCC	Intergovernmental Panel on Climate Change
LEAP	Low Emissions Analysis Platform
LNG	liquefied natural gas
LPG	liquified petroleum gas
NBS	National Bureau of Statistics of China
NEVs	new energy vehicles
PPCC	power plant coal consumption
PV	photovoltaic
TWh	terawatt-hours

1. Introduction

Electrification of the end-use sectors, along with the decarbonization of the power systems, can be a powerful strategy to achieve near-zero or net-zero carbon dioxide (CO_2) emissions by mid-century (Khanna et al., 2019; Khanna et al., 2021; Zhou and Mai, 2021). Increasing the adoption of electric end-use technologies not only replaces other fuels in end-use sectors but also can provide new services and other benefits, such as improved efficiency, reduced air pollution and water consumption, improved health and safety, improved productivity and product quality, as well as increased grid flexibility and efficiency (EPRI, 2018; Rightor et al., 2020).

Electrification, accompanied by a rapidly decarbonizing grid is a critical strategy for China to achieve its commitment of peaking CO_2 emissions before 2030 and reach carbon neutrality before 2060. A recent review and comparative assessment of ten scenario pathways for China toward a global 1.5°C compatible trajectory showed that non-fossil electricity provides the largest near-term opportunity to reduce CO_2 emissions, comparing to other potential strategies that replace fossil fuels (Khanna et al., 2021). The review showed that studies expected China's overall electrification rates reaching 40–70% by 2050.

Over the last four decades, China's electricity consumption has skyrocketed, increasing from 276 terawatt-hours (TWh) in 1980 to 7,521 TWh by 2020 (NBS, various years). The growth rate of electricity use reached to 12.5% per year on average during 2001–2010, outpacing the average 8% growth per year in the earlier two decades. The increase of electricity consumption slowed down in the last ten years, but still growing at 6% annually from 2010 to 2020. The growth of electricity use has been significantly higher than the increase of primary energy use in China, as shown on the left of Figure 1. China's overall electrification rate, measured as the share of electricity use in total energy consumption, has also increased from 7.1% in 1980 to about 28% by 2020 (NBS, various years), as shown on the right of Figure 1.

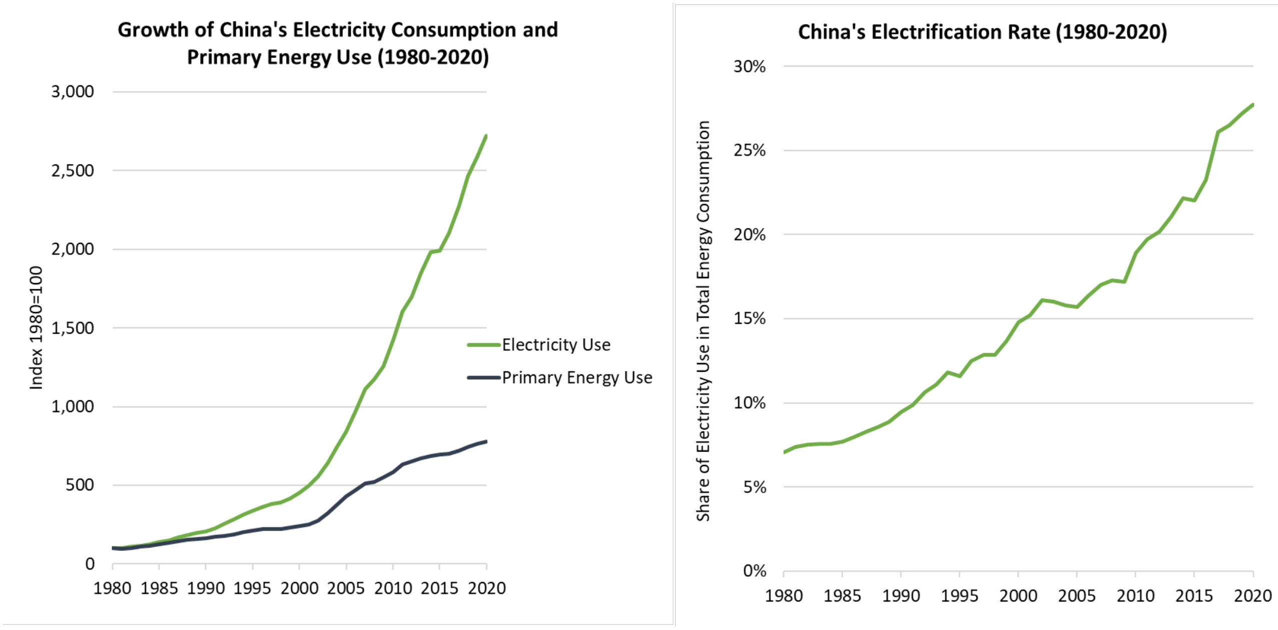

Figure 1. Growth of China's Electricity Consumption and Primary Energy Use (Left) and China's Electrification Rate (Right) during 1980–2020

Source: NBS, various years.

China's power sector has been decarbonizing at a faster rate than the overall Chinese economy, as shown in Figure 2. China's grid CO_2 emission factor decreased from 1.05 kgCO_2/kWh in 1980 to 0.75 kgCO_2/kWh by 2010, declining 1.1% per year on average. After 2010, China's power sector decarbonization accelerated, with grid CO_2 intensity decreasing at 2.7% per year from 2011 to 2020, reaching 0.57 kgCO_2/kWh (NBS, various years; IPCC, 2006). The decreasing rate of carbon intensity in the power sector has consistently outpaced the economy-wide carbon intensity, which only decreased 0.1% and 0.8% per year on average, during 1980–2010 and 2011–2020 periods, respectively.

China's power sector needs to be fully and rapidly decarbonized, in order to provide the necessary conditions for electrification of all end-use sectors and meet the significant demand of electricity consumption. Among the ten scenarios of China's mid-century decarbonization studies reviewed by Khanna et al. (2021), most studies expected solar and wind power generation to sharply increase from today's 9% in total electricity generation to 34–73% by 2050, while coal and/or natural gas power generation to be reduced from today's 68% to 7–35% of total generation by 2050 (Khanna et al., 2021).

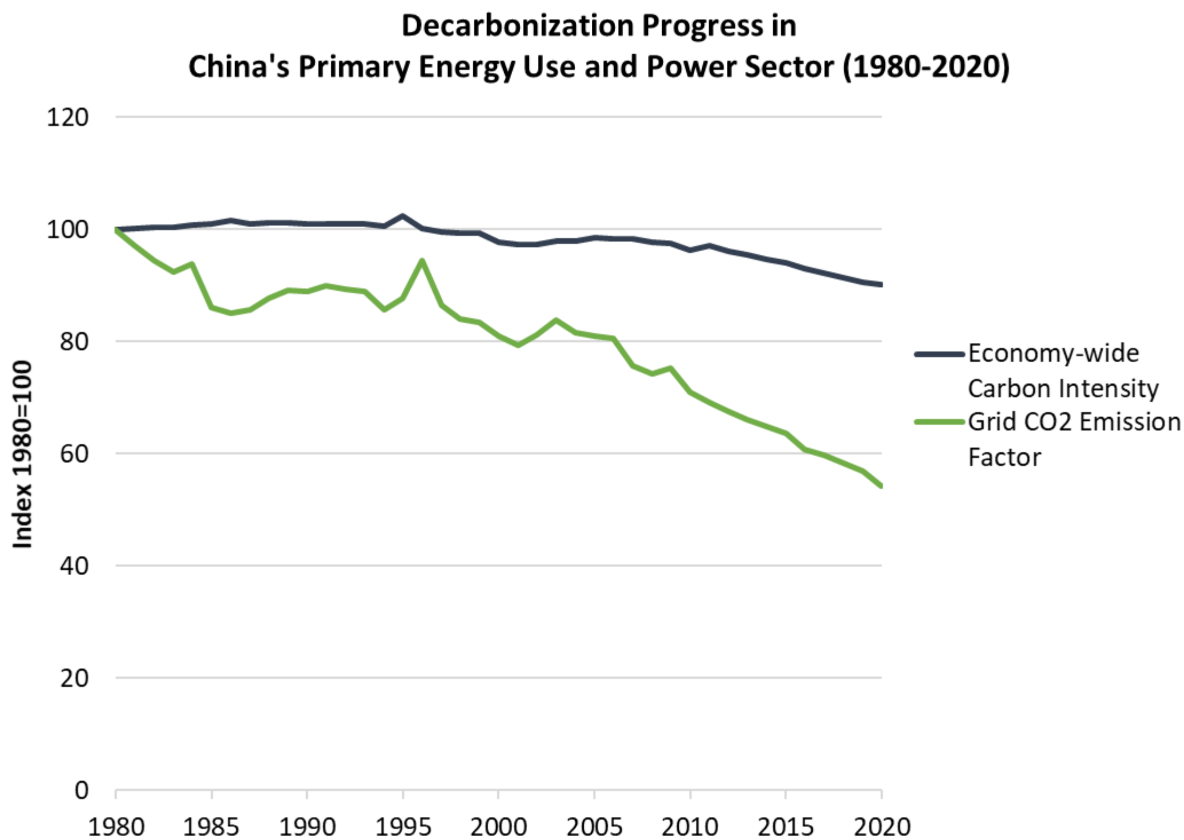

Figure 2. Decarbonization of China's Primary Energy Use and Electricity (1980-2020)

Sources: NBS, various years; IPCC, 2006.

Note: Energy data are from National Bureau of Statistics of China (NBS), using direct equivalent approach convert primary electricity to standardized energy units, which is consistent with the IPCC method. CO_2 emissions are calculated by using IPCC emissions factors.

This report focused on assessing China's electrification pathways through 2050. Since the analysis was conceptualized before China announced its carbon neutrality goal, the existing modeling framework only includes projections up to 2050. We first provided updates on recent electrification trends in China. We then gave an overview of our modeling approach and scenarios. After that, we summarized the key findings of electrification pathways in China's transport, buildings, and industry sectors. We discussed specific challenges to electrify each of the end-use sectors. Lastly, we concluded with the electrification potential results and implications for the power sector.

2. Recent Electrification Trends

China consumed 7,521 TWh of electricity in 2020, a 3.1% increase over 2019, with electricity use growing faster than China's total primary energy use in 2020. Electricity consumption increased 12% per year during 2000–2010, slowing to 6.7% per year on average between 2010 and 2020 (Figure 3).

Industry is the largest electricity-consuming sector, accounting for 68% of total final electricity consumption in 2019. The buildings sector, including residential, commercial, and public buildings, represented 28% of China's final electricity consumption in 2019. The transportation and agriculture sectors, both have seen rapid electricity consumption growth, and accounted for 2.4% and 1.9% of final electricity consumption in 2019, respectively.

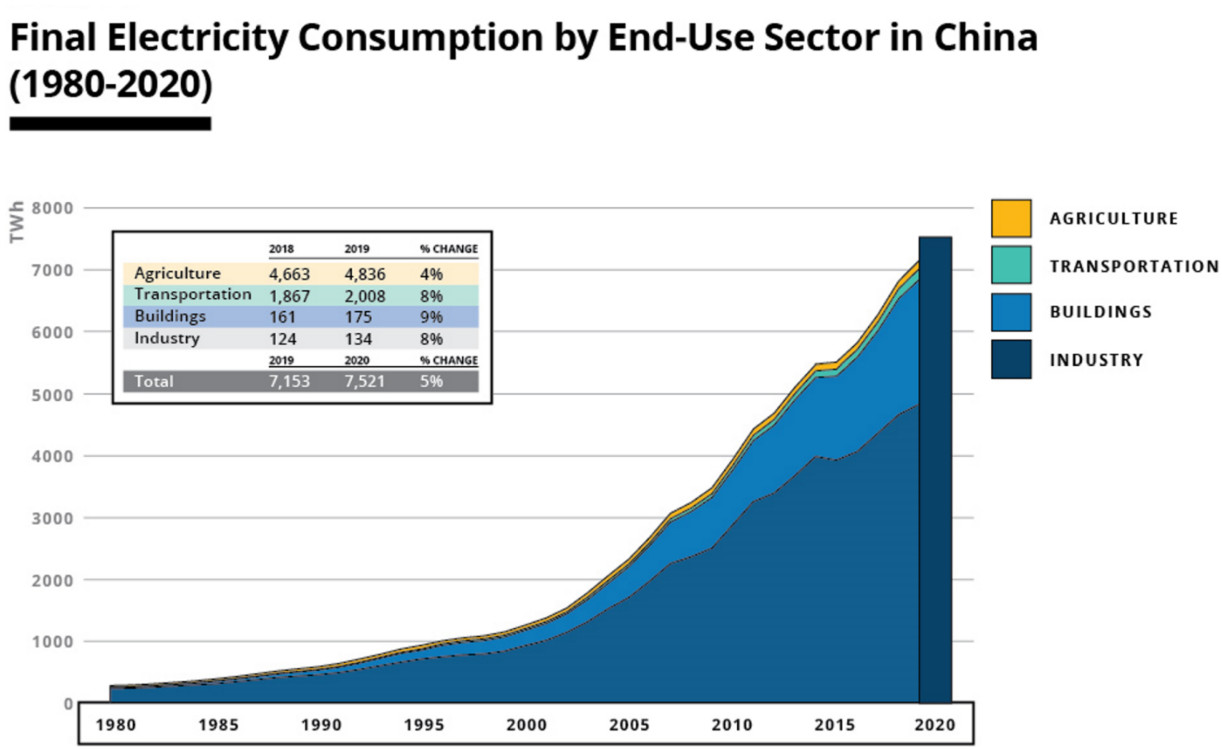

Figure 3. Final Electricity Consumption by End-Use Sector in China (1980–2020)

Sources: NBS, various years; CEC, 2021.

Note: Construction sector is included in the industrial sector.

China’s electricity generation is decarbonizing. In 2020, 32% of the total electricity produced was from non-fossil fuels (Figure 4). Hydro power generation and wind represented about 18% and 6% of the total production, respectively. Nuclear accounted for 5% of power generation, while solar contributed to another 3% (CEC, 2021). With a less carbon-intensive grid, electrification can play an important role in achieving China’s 2030 carbon peaking and 2060 carbon neutrality goals.

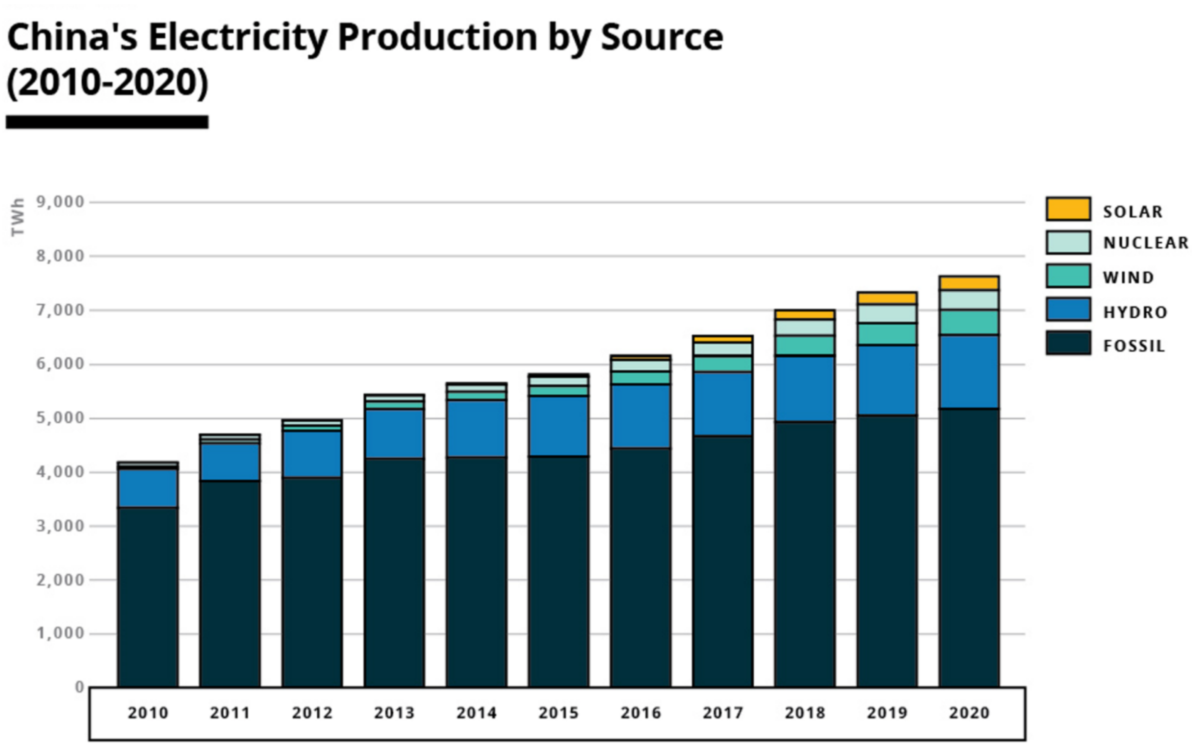

Figure 4. Electricity production by source in China (2010–2020)

Sources: NBS, various years; CEC, 2021.

Notes: 1) “Fossil” refers to electricity generation from fossil fuels, including coal, petroleum, and natural gas. 2) Does not include biomass.

At the end-use sectors, the share of electricity use in sectoral final energy use increased from 15% in 2000 to 27% in 2019 (Figure 5). The transportation sector had the lowest electrification rate in 2019, at about 5%. The buildings sector had the highest share of electricity use that year at about 38%. Industry’s electrification rate increased from 16% in 2000 to 28% in 2019.

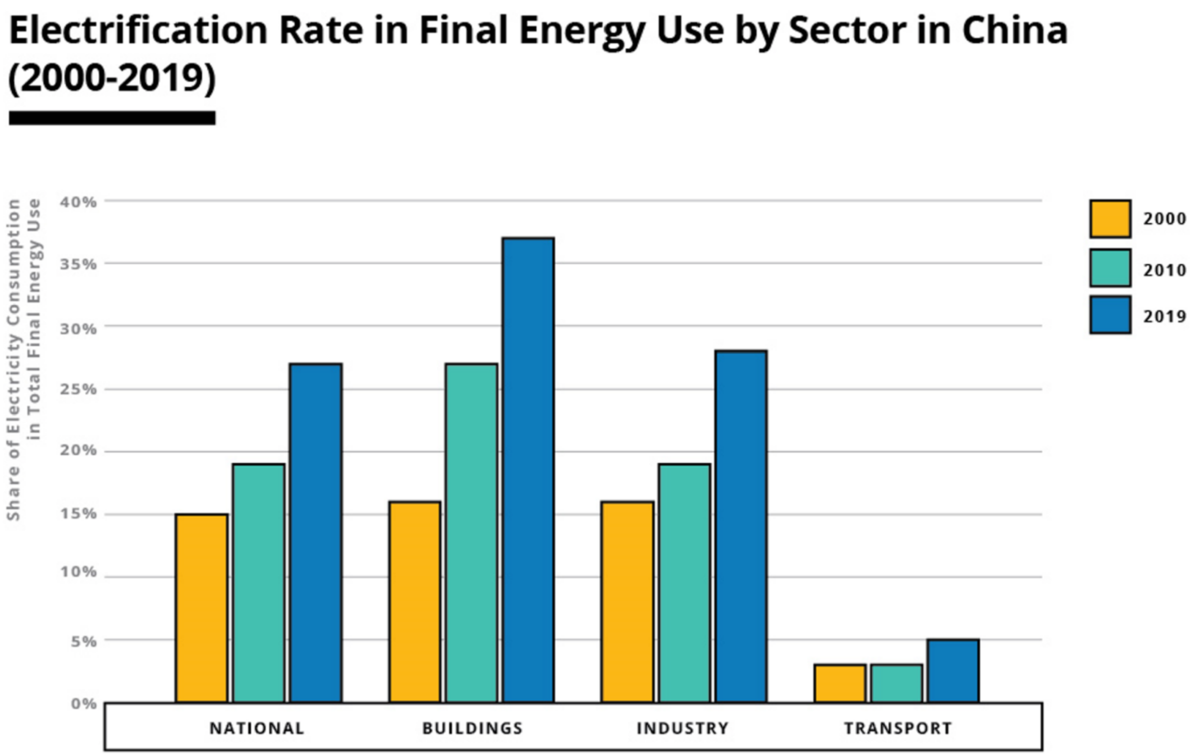

Figure 5. Electrification Rate in Final Energy Use by Sector in China (2000–2019)

Source: NBS, various years.

Notes: 1) Industry data also include construction; and 2) The results presented here are based on China's national statistics reporting methodology, where gasoline and some diesel use in buildings and industry sector were reported in those sectors instead of the transport sector. Using this methodology, the electrification rate of the transport sector was 5% in 2019. But if the use of gasoline and other oil products in buildings and industry sectors are allocated back to the transport sector, the electrification rate of the transport sector was about 2% in 2019.

3. Modeling Approach

The electrification pathway analysis, which is a part of the *China Energy Outlook 2022* (provide citation), uses Berkeley Lab's China 2050 Demand Resources Energy Analysis Model (DREAM) to develop bottom-up scenario projections of China's future energy and emissions. The China 2050 DREAM follows a bottom-up energy end-use accounting framework of China's energy and economic structure built using Stockholm Environment Institute's Low Emissions Analysis Platform (LEAP). Using the LEAP platform, the China 2050 DREAM framework employs both macroeconomic and non-linear, physical drivers to model integrated feedback within and across buildings, industry, transportation, and energy transformation (primary energy supply including electricity) sectors.

China 2050 DREAM differs from most other integrated assessment models in that uses non-linear, physical drivers such as population, demographics, and land area to drive the future growth of energy-consuming activities in buildings, industry and transport. In not relying solely on economic growth to drive future energy consumption, the use of these additional physical drivers helps capture potential saturation effects in energy equipment ownership and usage, living space and urban infrastructure, and fertilizer use that can contribute to plateauing of energy demand. This unique approach also captures important cross-sectoral linkages that may not be in other models, such as how slowdowns in new building and infrastructure construction can reduce domestic cement, steel and glass demand for construction. Lastly, the China 2050 DREAM incorporates decades of detailed Chinese energy-related statistics at sectoral and fuel-specific levels tracing back to 1980, and also characterizes the latest energy-consuming technologies in terms of energy efficiency and fuel mix for various end-uses. The current model only considers projections through the year 2050, as extensive data collection and model restructuring will be required to extend through 2060.

For calculating and reporting primary energy consumption, the China 2050 DREAM uses the direct equivalent approach (consistent with the Intergovernmental Panel on Climate Change, IPCC) as the default for converting primary electricity, rather than the power plant coal consumption (PPCC) method used in Chinese statistics (Lewis et al., 2015). For calculating energy-related carbon dioxide (CO_2) emissions, China-specific fuel energy and heat content are entered into the model and multiplied by the IPCC default CO_2 emissions factors for specific fossil fuels (IPCC, 2006).

This analysis constructed two main scenarios to represent two plausible future pathways for China's energy-related development through 2050:

> **Continuous Improvement Scenario**: This scenario assumes China will fully adopt the maximum feasible shares of today's commercially available, cost-effective energy efficiency and renewable energy supply by 2050. It considers all announced policy goals and targets, but also assumes that additional policies will be introduced to support the full adoption of today's commercially available and cost-effective technologies for a clean energy transition.
>
> **Deep Mitigation Scenario**: This scenario assumes China will fully develop and deploy deep decarbonization technologies, practices, and behavioral changes, including technologies that are currently in pilot or demonstration phases, to reduce greenhouse gas (GHG) emissions as much as technically feasible by 2050, without adopting carbon capture, use, and storage (CCUS) at a large scale. It not only includes multiple strategies to further accelerate energy efficiency improvement and renewable energy adoption, but also considers strategies for energy demand reductions, material efficiency improvement, technological upgrades (*including electrification* and other new, alternative fuels), and broader structural changes that impacts energy-related activities.

The analysis presented in this report focuses on the electrification strategies considered in the Deep Mitigation Scenario, and the remaining sectoral challenges in transport, buildings, and industry sectors for deep decarbonization by 2050, without adopting CCUS at a large scale.

4. Key Findings

In the Continuous Improvement Scenario, China's overall electrification rate increases from 22% in 2015 to 30% by 2030, and to 37% by 2050. The buildings sector achieves the highest electrification rate, reaching 57% by 2050. Industrial electrification improves at a pace similar to the national average, increasing from 23% in 2015 to 32% by 2030 and 38% by 2050. The transport sector, while increasing its electrification rate by five times, still has the lowest electrification rate among the key end-use sectors, reaching only 10% by 2050.

In the Deep Mitigation Scenario, the overall electrification reaches 60% by 2050, led by buildings at 88% of penetration, with significant deployment of commercialized electric technologies in the buildings sector. The industry electrification rate is accelerated, and reaches 36% by 2030 and 51% by 2050, due to a combination of process change, circular economy strategies, and adoption of electric technologies to electrify low to medium temperature heat. However, due to technological challenges to electrify some of the most energy-intensive and high temperature heat, the industry electrification rate remains below the national average. The transport sector electrification rate sees the most significant increase, reaching 39% by 2050, due to large-scale adoption of electric passenger vehicles and electric light and medium-duty trucks. Challenges remain for completely electrifying heavy-duty trucks, shipping, and aviation. Figure 6**Error! Reference source not found.** shows electrification rates by sector in the Continuous Improvement and Deep Mitigation Scenarios.

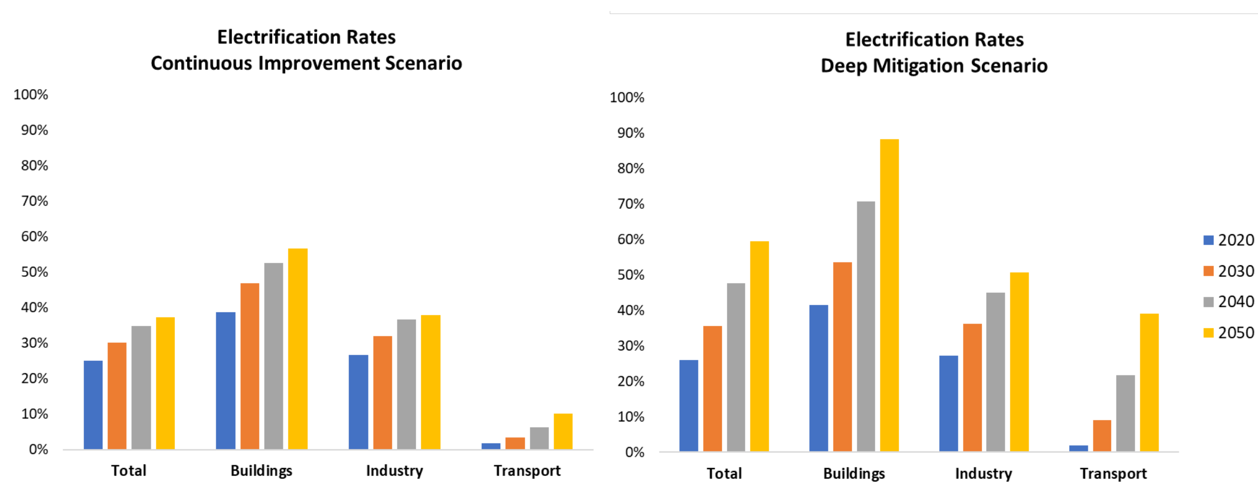

Figure 6. Electrification Rates by Sector in the Continuous Improvement and Deep Mitigation Scenarios

With higher adoption of electric technologies in the Deep Mitigation Scenario, we find that electricity demand will increase in all end-use sectors, compared to the Continuous Improvement Scenario. Transport electricity demand in the Deep Mitigation Scenario increases from 89 TWh in 2020 to 422 TWh by 2030 and 1,185 TWh by 2050, which is 96% higher than transport electricity use in the Continuous Improvement Scenario in 2050. The industrial sector electricity demand also increases from 4,440 TWh in 2020 to 5,643 TWh by 2030 and declines to 4,861 TWh, due to reduced industrial product demand and measures to improve material efficiency and recycling. Buildings electricity demand doubles from 2,310 TWh in 2020 to 4,693 TWh by 2050 in the Deep Mitigation Scenario, but is only 5% higher than the Continuous Improvement Scenario. Overall, we find that in the Deep Mitigation Scenario China's end-use electricity demand increases from 6,954 TWh in 2020 to 10,874 TWh by 2050, which is 17% higher than China's end-use electricity demand in the Continuous Improvement Scenario. Figure 7**Error! Reference source not found.** shows end-use electricity demand in China under the Continuous Improvement and Deep Mitigation Scenarios.

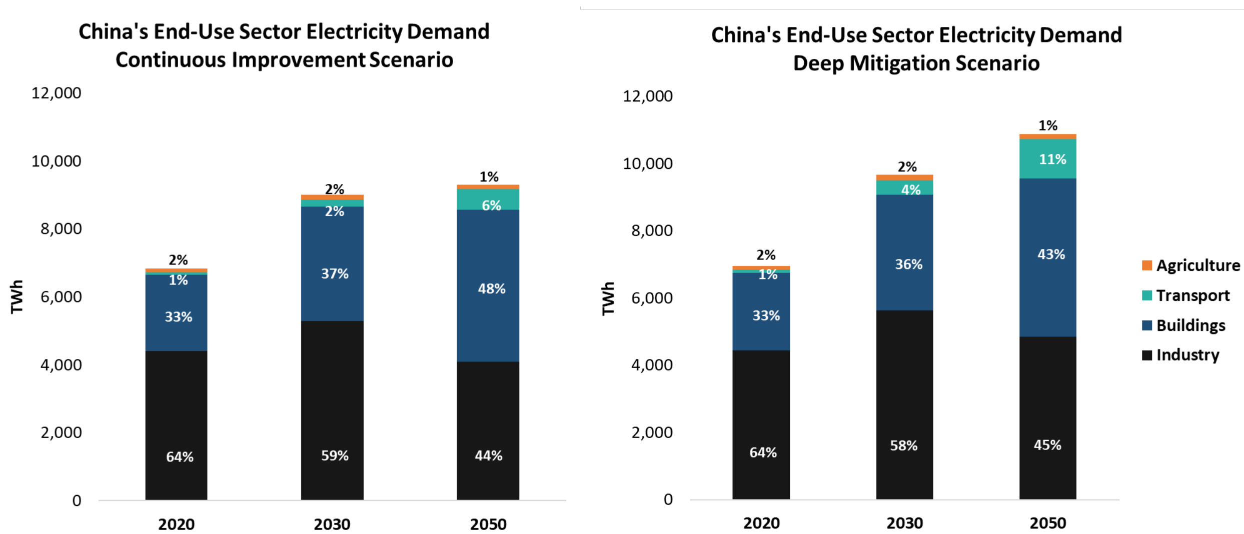

Figure 7. China's End-Use Electricity Demand in Continuous Improvement and Deep Mitigation Scenarios

5. Transport Sector Electrification Strategies and Challenges

5.1 Transport Electrification Status

Direct electricity use accounted for 5% of the final energy use in China's transportation sector in 2019, while petroleum products accounted for 80% (Figure 8), based on China's official figures. Direct use of coal in the transport sector dropped to 1% of total final energy use in 2019. Natural gas consumption, including liquefied natural gas (LNG) for heavy-duty trucks and compressed natural gas (CNG) for buses and taxis, increased to 11%.

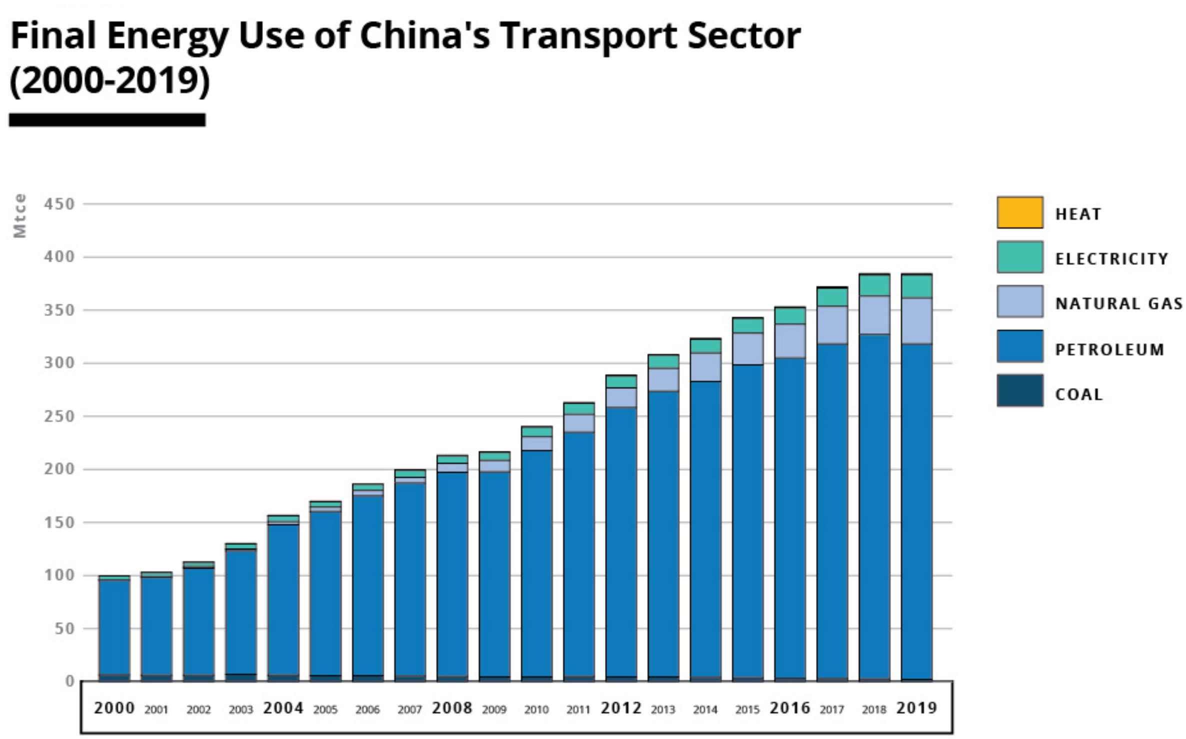

Figure 8. Final Energy Use of China's Transport Sector (2000–2019)

Source: NBS, various years.

Note: Electricity is converted to standard energy units using China's PPCC method.

However, China's official petroleum consumption accounting system understates the role of transportation from the demand-side perspective, as petroleum consumption is allocated to the end-use sector where petroleum products are consumed, rather than based on the purpose of the consumption. For example, in the official Chinese energy balance tables, the residential buildings sector also consumes "gasoline", even though this gasoline demand is from passenger transport. Adjusted figures of petroleum demand are presented in Figure 9, where all transport gasoline use in the buildings and industry sectors as well as jet fuel used in the public sector are adjusted back to transportation sector. Figure 9 also shows that about half of China's oil is used in the transport sector and the rest of the petroleum is consumed by other end-use sectors, such as for feedstocks and non-energy use, industry, buildings—e.g., using liquified petroleum gas (LPG) for cooking—and power and heat generation. Of the petroleum that is used for transportation purposes, about 48% is consumed as gasoline and 32% is diesel fuels. Passenger cars account for 89% of all gasoline use in China, or 17% of China's total oil use.

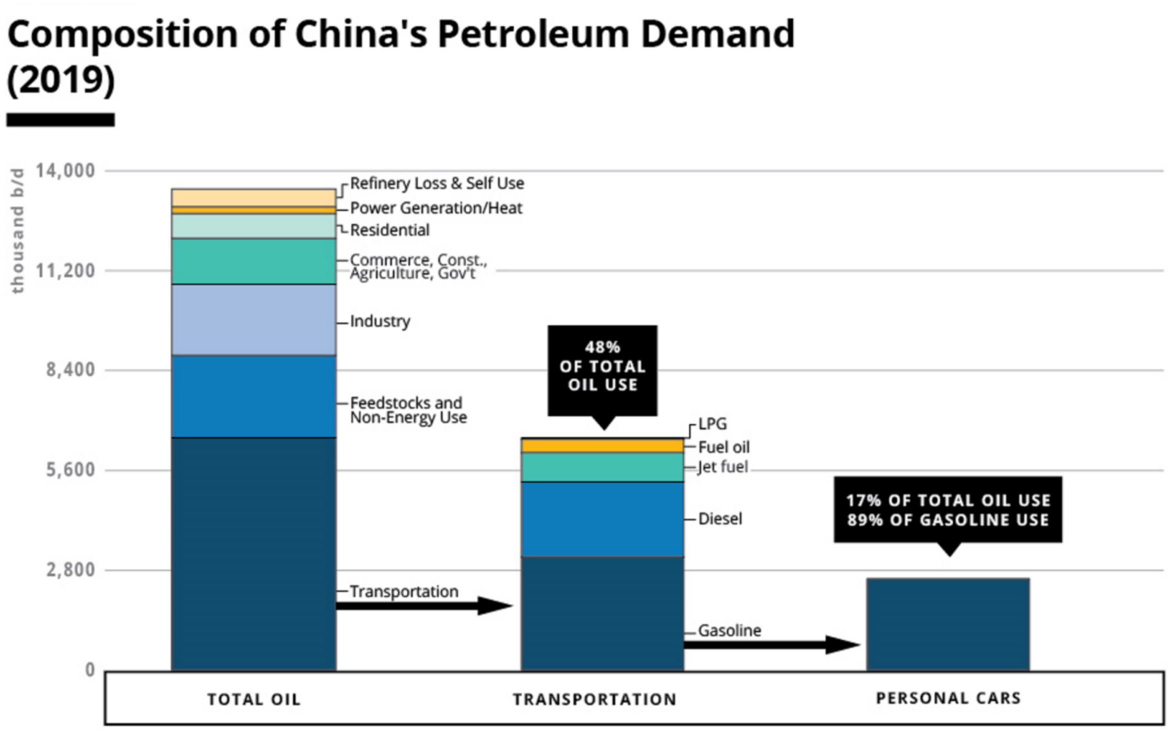

Figure 9. Composition of China's Petroleum Demand (2019)

Source: NBS, 2021.

Notes: 1) Petroleum demand in this figure has been adjusted from the official data by allocating all gasoline used for transportation in the buildings and industry sectors to the transport sector and allocating jet kerosene used in the public sector to the transport sector; 2) LPG: liquified petroleum gas.

From 2011 to 2020, China's sales of new energy vehicles (NEVs) increased from 6,189 units sold in 2011 to about 1.37 million units in 2020 (Xinhua, 2021). Of the 1.37 million NEVs sold in China, more than 1.1 million NEVs were battery electric vehicles (BEVs), representing 82% of the NEVs sales in China, as shown in Figure 10. Other types of NEVs include plug-in hybrid and fuel cell vehicles, selling 252,000 units in China in 2020. Globally, China alone accounted for 42% of global NEV sales. As shown in Figure 11, the market share of China's NEVs reached 5.4% in 2020, exceeding the global average of 4.2% (EV Volumes, 2021).

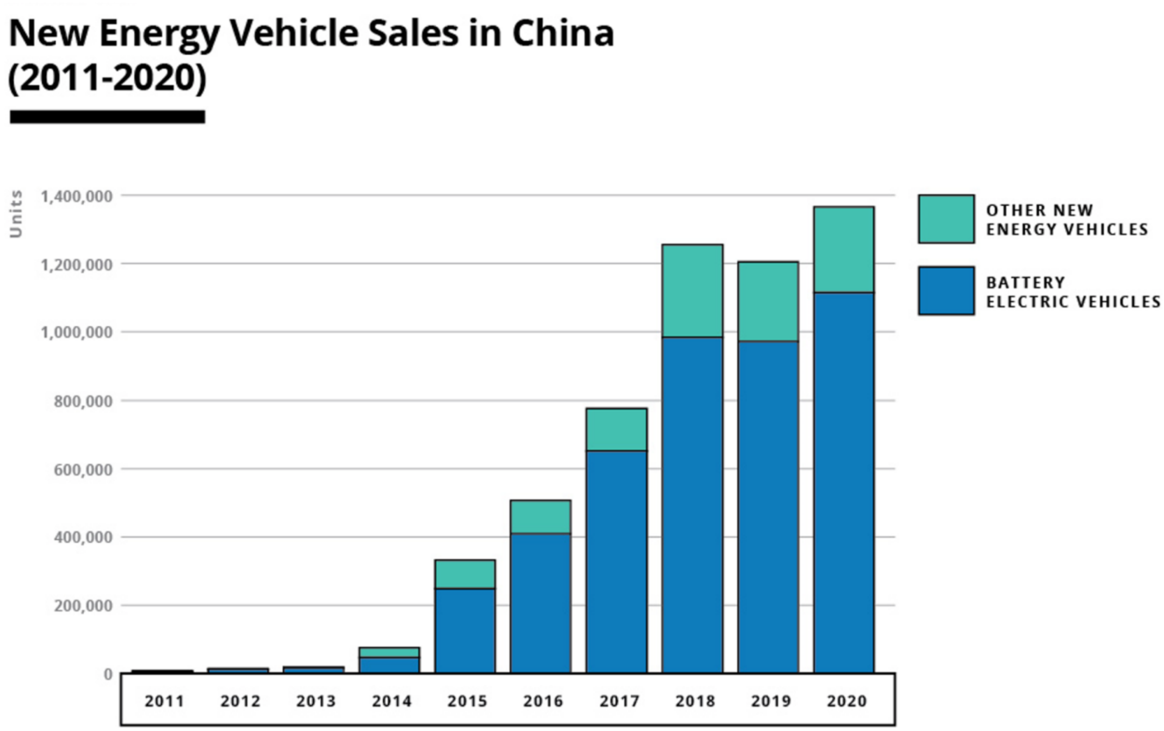

Figure 10. New Energy Vehicle Sales in China (2011–2020)

Sources: Zhou et al., 2020; Xinhua, 2021.

Note: "Other New Energy Vehicles" includes hybrid vehicles, fuel-cell electric vehicles, and hydrogen vehicles.

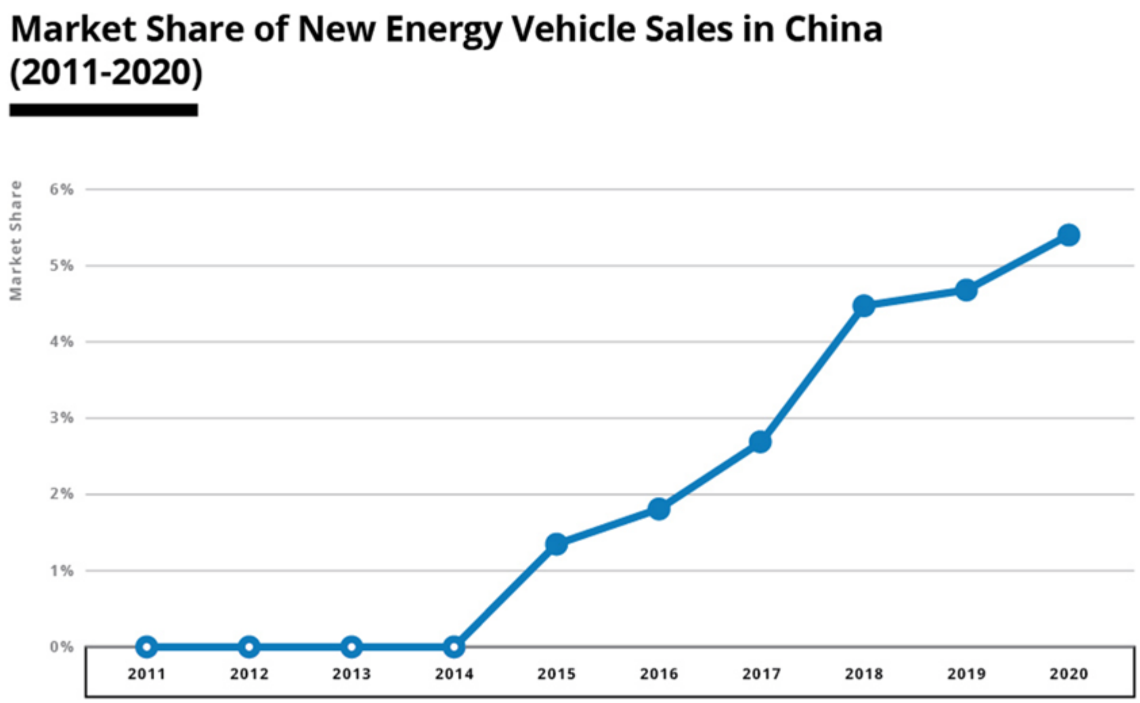

Figure 11. Market Share of New Energy Vehicle Sales in China (2011–2020)

Sources: Zhou et al., 2020; Xinhua, 2021.

The market share of NEVs in total truck sales decreased in recent years, dropped from 2.3% in 2018 to 0.9% in 2020, due to COVID-19 impacts, weaker economic growth, higher costs, and expected decline in subsidies.[1] Total sale of NEV trucks decreased from more than 85,000 units in 2018 to a little more than 42,000 units in 2020.

It is worth noting that heavy-duty vehicles are among the fastest growing segments in freight vehicle population in China. Based on the national standard on classifying heavy-duty vehicles, the National Bureau of Statistics of China (NBS) reported that China's heavy-duty vehicles increased about five times from about 1.5 million units in 2002 to more than 7 million units in 2018, growing at 10.3% per year (while light-duty vehicles are also growing at 10.3% per year).

By 2020, heavy-duty vehicles accounted for 28% of the total freight vehicle population, while light-duty vehicles accounted for 69%. The population of both medium-duty vehicle

[1] In April 2020, the Chinese government announced that subsidies for purchasing NEVs will be extended through the end of 2022. Between 2020 and 2022, NEV subsidies are being gradually reduced by 10%, 20%, and 30% from the previous year. Overall NEV subsidies in 2022 will be reduced by 30% from the 2021 level. Subsidies for specialty vehicles (e.g., city buses, city logistics delivery vehicles, post delivery vehicles, city sanitation vehicles) in 2022 will be reduced by 20% from the 2021 level (MOF, 2021). Subsidies will end on December 31, 2022.

and micro-duty vehicles decreased over the years, accounting for 3% of the total freight vehicle population in 2020.

Overall, the vehicle stock in China reached 281 million units as of 2020, with 4.92 million NEVs. The share of NEVs in the total vehicle stock has increased from 0.7% in 2017 to 1.8% in 2020. The vast majority of the NEV stock is battery electric vehicles, accounting for 81% in all NEVs by 2020.

In terms of charging infrastructure, China has a total of 1.681 million charging stations by 2020, including 807,000 public charging stations and 874,000 private charging stations. Compared to 2015, China's public and private charging stations have grown 14 and 109 times, respectively. Globally, China represents 60% of installed public charging stations (McKerracher, 2021).

5.2 Transport Electrification Strategies

In the Deep Mitigation Scenario, three key decarbonization strategies were considered for all modes of transportation: improving end-use efficiency, reducing or shifting activity to lower impact modes, and electrifying or switching to other cleaner fuels.

For electrification to be an effective decarbonization strategy for all energy demand sectors, rapid decarbonization of the power sector is essential. The power sector is fully decarbonized by 2045 in the Deep Mitigation Scenario (see Section 6 for power sector modeling assumptions and results).

In passenger road transport, China is already a global leader in hybrid, battery electric, and hydrogen fuel cell sales for light-duty passenger and buses, and we expect electrification of these segments to accelerate from 2020 through 2030 to account for 30-44% vehicle stock (see

Table 1 for details by segments). Through 2050, battery electric vehicle (BEV) technologies are expected to dominate compared to hydrogen fuel cell technologies, which play a much smaller role except for in heavy-duty buses. In the Deep Mitigation Scenario, all modes of passenger road transport reach 100% electrification by 2050 except heavy-duty buses where a very small share of compressed natural gas (CNG) remains in use for long-distance travel.

In freight road transport, electrification starts taking off after 2030 due to continued NEV technology development, reaching 100% for light-duty trucks and 90% stock for medium-duty trucks by 2050. For heavy-duty trucks, there is lower electrification potential, resulting in 50% battery electric, 25% fuel cell electric, and 25% liquified natural gas (LNG) shares of vehicle stock by 2050.

For rail, passenger rail is fully electrified by 2050 in the Deep Mitigation Scenario. For freight rail, fuel switching from diesel to electric results in 80% electrification by 2050. For passenger water and domestic freight shipping, natural gas is seen as a viable cleaner fuel for replacing fuel oil consumption but will require port refueling infrastructure, so it is expected to account for less than a third of total activity by 2050. For both shipping and aviation, while recognizing there are battery technologies being developed and prototyped, the Deep Mitigation Scenario does not include electric technologies as the main pathway to decarbonization, giving existing scaling limits and other challenges discussed below.

Table 1. Transport Sector Electrification Strategies and Assumptions in the Deep Mitigation Scenario

Electrification and Fuel Switching		
Passenger Transport		
Road	**Private Cars**	30% BEV, 1% FCEV of stock in 2030 95% BEV and 5% FCEV of stock in 2050
	Fleet Cars	37% BEV, 1% FCEV of stock in 2030 95% BEV and 5% FCEV of stock in 2050
	Taxis	43% BEV, 1% FCEV of stock in 2030 95% BEV and 5% FCEV of stock in 2050
	Intracity Buses	Heavy-duty buses: 30% BEV of stock in 2030 80% BEV, 15% FCEV, and 5% CNG in 2050 Light-duty buses: 65% BEV in 2030, 99% in 2050
Rail	**Intercity: High-speed**	/
	Other Intercity Rail	All electric by 2050
	Intracity: Subways and Light Rail	/
Water		Switch from fuel oil to 30% natural gas by 2050
Air		Improved blend with biojet: 50% share by 2050
Freight Transport		
Road	**Heavy-duty Trucks**	5% BEV and 20% LNG of stock by 2030 50% BEV, 25% FCEV, and 25% LNG of stock by 2050
	Medium-duty Trucks	5% BEV, 10% LNG, 5% diesel hybrid by 2030 80% BEV, 10% FCEV, and 10% LNG by 2050
	Light-duty Trucks	5% BEV, 10% LNG, 12% gasoline hybrid by 2030 100% BEV by 2050
Rail		Switch from diesel to 80% electric by 2050
Water	**Water: Domestic**	Switch from fuel oil to 20% natural gas by 2050
	Water: International	No LNG considered due to methane slip and overall GHG impact
Air		Improved blend with biojet: 50% share by 2050

Note: BEV is battery electric vehicle, FCEV is hydrogen fuel-cell electric vehicle, LNG is liquefied natural gas.

/ denotes not considered in scenario.

*Autonomous vehicles have mixed impact of increased activity by 11%, but decreased energy intensity by 19%.

5.3 Heavy-duty Road Freight Electrification Challenges

For road freight, there are multiple technical, economic, and institutional challenges to fully electrify heavy-duty trucks (HDTs). Although multiple battery electric HDT models are slated for commercial deployment with pilot production of fuel-cell HDTs also expected in 2022, there is still no widescale production or deployment. The physical requirements for HDTs are much more challenging to electrify, including heavier weight, longer travel distances, and operating times that require longer range and batteries with greater densities able to withstand more discharge cycles. For hydrogen fuel-cell HDTs that could provide longer ranges, there are additional safety challenges for hydrogen transmission and distribution networks and need for large-scale “green hydrogen” production to support full decarbonization. As a result of these expected technological limitations to NEVs for heavy-duty trucking, we expect LNG to remain as a cleaner, but not zero-carbon, alternative needed for long-distance trucking.

From an economics perspective, while rapidly declining battery costs suggest electric HDTs could achieve cost parity with conventional diesel HDTs by 2030, competing demand for batteries for grid storage and limited raw material supply chains may increase future cost uncertainties. Beyond technological and economic challenges, the current decentralized ownership and business model for heavy-duty freight and reliance on financing for new vehicle purchases in China also pose institutional challenges to electrification. In addition, there is a significant need for increasing the development and deployment of fast chargers and “megachargers” of greater than 1 MW capacity that are capable of meeting HDT charging needs to decarbonize significant segments of the HDT sector.

5.4 Aviation Electrification Challenges

There are electric prototypes for short-range aircraft such as those used for commute flights but these face near-term technological challenges due to the low energy density of batteries and long certification time needed for approving new aviation technologies. The Israeli-company Eviation is developing and testing a prototype 9-passenger aircraft with a 440 mile-range and has applied for certification for commercial operation starting in 2024 if approved (Lambert, 2021).

However, scale-up of deployment and commercial production is currently still limited by low battery energy density, which is still below 300 Wh/kg in today’s state-of-the-art batteries. For a twin-engine narrowbody aircraft to be electrified with a 600-mile range, much greater battery energy density of 800 Wh/kg is needed to balance the energy storage required and the weight it imposes on the aircraft. The current battery required to store the energy needed for a 600-mile trip would be nearly twice the maximum allowed take-off weight of the aircraft (Gray et al. 2021), compared to jet fuel that only accounts for 9% of maximum take-off weight.

5.5 Shipping Electrification Challenges

Battery-electric technologies for shipping are just in the testing stage. Currently, there are only two very small projects being tested globally. While we recognize the electric technologies could be technically feasible, these technologies are not considered to be viable in the near to medium term.

As a capital-intensive industry characterized by large, long-life assets and thin margins, the shipping industry faces multiple market and institutional barriers to adopting electrification measures without regulatory action. Given the industry's capital-intensiveness, loans provide 70% of the capital in the sector but investors currently lack motivation to invest in electrification measures such as alternative fuels that raise costs, after facing declining returns to shareholders of shipping companies in recent years (Shell & Deloitte, 2020). The global shipping industry also has a relatively decentralized ownership model that makes concerted change more difficult, with 80% of the global fleet owned by thousands of smaller ship owners (Shell & Deloitte, 2020). Charterers and shipping customers also do not want to incur additional costs out of competitiveness concerns, and multiple players in the industry value-chain and inflexible contracting models make the decarbonization responsibility less clear and more difficult to price.

5.6 Key Milestones for Electrification of the Transport Sector

Our analysis points to two main electrification milestones for the transport sector, as shown in Figure 12:

- Private car electrification increases from 3% in 2021 to 10% by 2030, and reaches 38% by 2050 under the Continuous Improvement Scenario. This electrification progress is accelerated under the Deep Mitigation Scenario, where electrified cars reach 30% of the car stock by 2030 and 100% by 2050.
- Heavy-duty truck electrification increases from 0.5% of the stock in 2021 to 5% by 2030, but then significantly increases to 75% by 2050 under the Deep Mitigation Scenario.

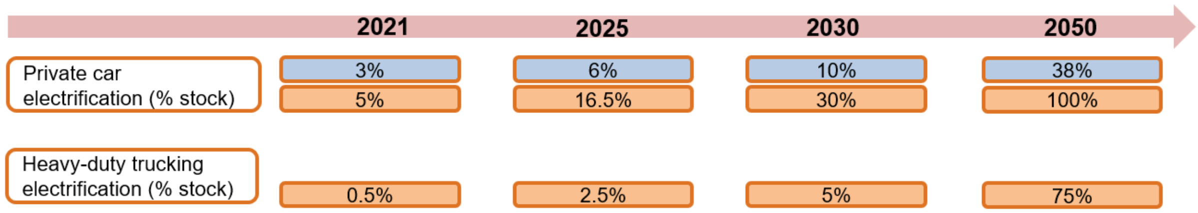

Figure 12. Key Electrification Milestones for the Transportation Sector

Note: blue boxes denote milestones for the Continuous Improvement Scenario and orange boxes denote milestones for the Deep Mitigation Scenario.

5.7 Energy Use and CO_2 Emissions of an Electrified Transport Sector

Under the Deep Mitigation Scenario, with a combination of demand reduction, energy efficiency improvement, and switching to cleaner fuels, the final energy demand of the transportation sector peaks by 2026 at about 604 Mtce, with electricity use accounts for 6% of total final energy use.[2] After that, final energy demand declines at a rate of 2% per year through 2050. By 2050, final energy demand drops to 372 Mtce, or 34% less than the level in 2020. Electricity accounts for 39% of total final energy demand in 2050, while fossil fuels (petroleum products and natural gas) account for 43% of the final energy demand in 2050, as shown in Figure 13.

For CO_2 emissions, transport sector won't peak until 2037 under the Continuous Improvement Scenario, emitting more than 1,527 $MtCO_2$. Emissions only decline slowly at a rate of 0.9% per year through 2050, reaching 1,354 $MtCO_2$ by 2050, or 11% above today's level. Under the Deep Mitigation Scenario, transport sector CO_2 emissions peak by 2026, and decline 5.8% per year through 2050. By 2050, transport sector CO_2 emissions drop to about 314 $MtCO_2$, or 74% below the 2020 level (Figure 14).

[2] This is calculated after adjustment of the current national statistical boundaries. The use of gasoline and some diesel products in the buildings and industry sector is allocated back to the transport sector.

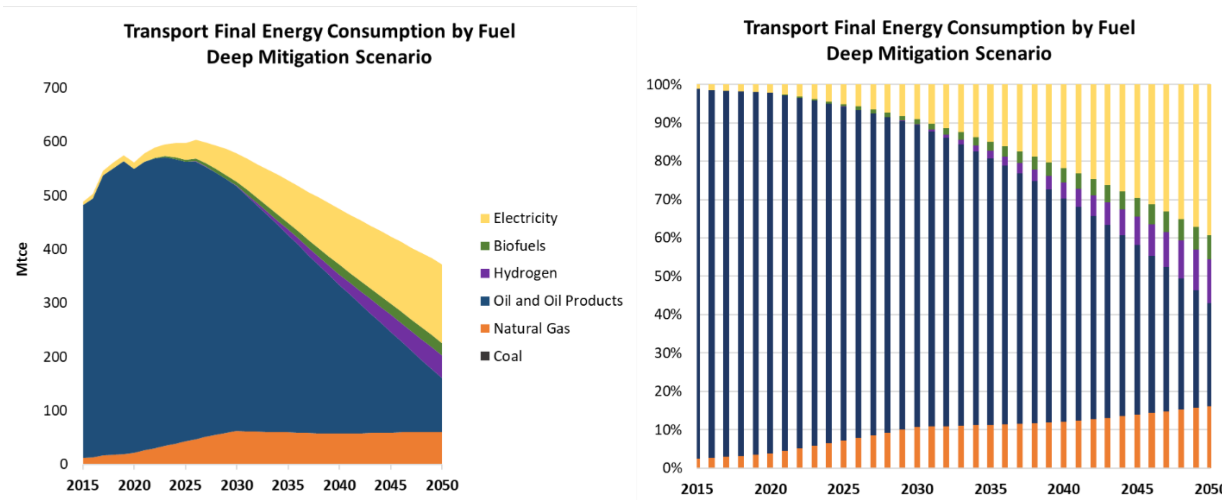

Figure 13. Transport Final Energy Consumption by Fuel (2015–2020) under the Deep Mitigation Scenario

The significant CO_2 emission reductions in the Deep Mitigation Scenario are due to switching to clean electricity as well as increasing the use of hydrogen and other lower-carbon fuels. The remaining CO_2 emissions in the transport sector by 2050 under the Deep Mitigation Scenario are due to electrification and decarbonization challenges in heavy-duty trucks, shipping, and aviation.

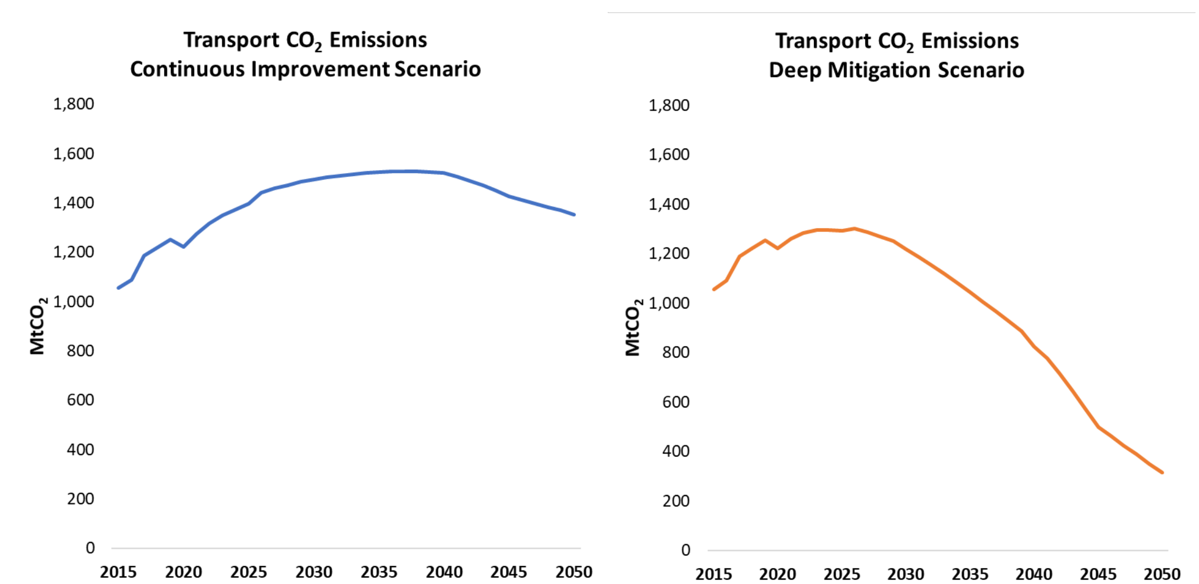

Figure 14. Transport Sector CO_2 Emissions in Continuous Improvement and Deep Mitigation Scenarios

6. Buildings Sector Electrification Strategies and Challenges

6.1 Buildings Electrification Status

Total energy and electricity consumption in China's buildings sector have been increasing significantly for decades. By 2020, total building operational energy use accounted for about 21% of China's total primary energy consumption (NBS, 2021a). From 2000 to 2020, primary energy consumption in China's buildings sector almost quadrupled and electricity use increased more than 800% (NBS, various years).

Electricity penetration in total building energy use has been increasing steadily since 2001 as the use of electrically-powered devices—such as appliances and air conditioners—has grown. Figure 15 shows the evolution of buildings sector final energy use and the electrification rate from 2000 to 2020 (NBS, various years). Electricity was a main energy carrier in public buildings and commercial buildings during this period. Electrification rate of the buildings sector grew from 16% in 2000 to about 28% in 2020 (NBS, various years). However, natural gas, coal, LPG, and other oil products are also used for space heating, water heating, and cooking.

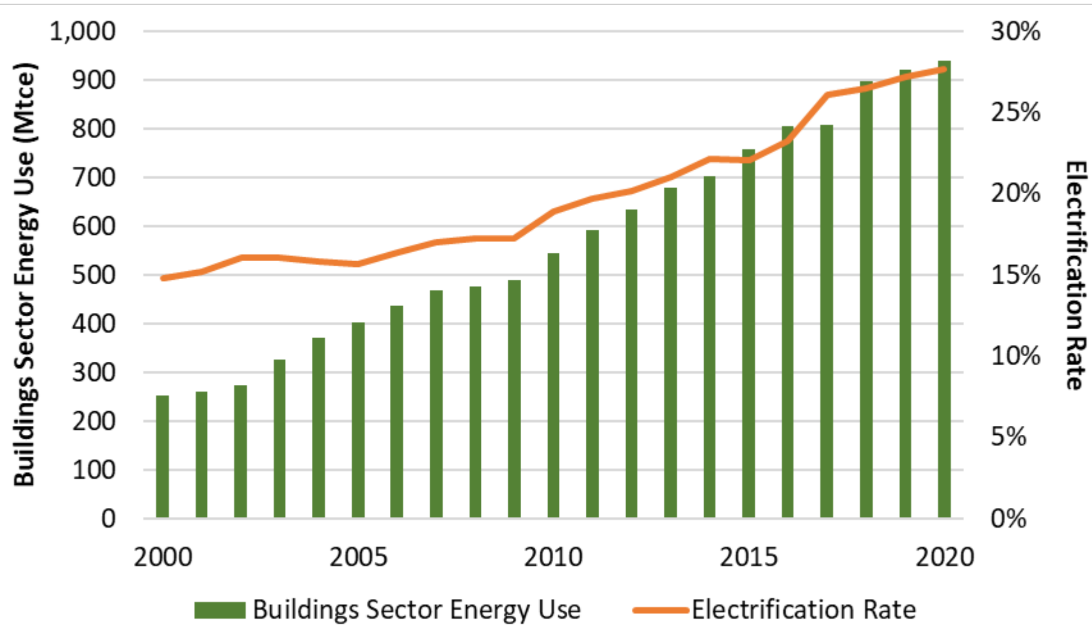

Figure 15. China's buildings sector commercial energy consumption (2000–2020)

Source: NBS, various years.

Both past trends and the current status indicate significant potential for building electrification. For example, space heating energy use in regions of China with centralized district heating networks are dominated by coal and natural gas currently. Electricity only represents a small share of the total energy consumption, leaving a huge potential for electrification. In addition, large amounts of biomass are still used for heating and cooking, especially in rural areas. Such traditional use of biomass will likely be replaced by electricity over time, driving electrification rates to higher levels.

Technological improvement plays an essential role in the process of electrification, and electric technologies for buildings have experienced rapid development during the past decades. As of now, technically, almost 100% of energy use in the building sectors, including both residential and commercial buildings, can be electrified. The three major fields for electrification are space heating, water heating, and cooking, for which direct fuel combustion constitutes a substantial market share. Electric technologies for these end uses are not only commercially-available but also provide an equivalent level of service. Such electric technologies include heat pumps for space heating and cooling, electric water heaters, electric stoves, and more.

6.2 Buildings Electrification Strategies

The Deep Mitigation Scenario assessed three main strategies to decarbonize building operation energy, including improving energy efficiency, switching to electricity-using end-uses, and using renewable energy.

Fuel switching and electrification can be the key pathways for decarbonizing space heating, water heating, and cooking. Electrifying heating, especially in North China, requires replacing coal-based district heating systems with efficient heat pumps. In rural areas, coal use for space heating will be completely phased out and replaced by electric heating (e.g., heat pumps). By 2050, heat pump water heaters and electric cooking stoves achieve 70% and 100% penetration, respectively.

Net zero energy buildings require both efficiency improvements and renewable energy adoption. Building integrated PV is assumed to be implemented in buildings in both rural and urban areas. Direct Current (DC) power distribution systems in buildings can integrate PV, battery storage, and DC loads and better utilize distributed renewable energy.

Other renewable energy technologies, such as solar thermal and ground-source heat pumps are also adopted in the Deep Mitigation Scenario. To further decarbonize the buildings sector, building-to-grid integration allows renewable energy from the power grid to be consumed by bundling end use technologies.

6.3 Selection of Electrification Technologies

Space heating accounts for about 25% of China's buildings sector energy use (BERC, 2021). Unlike the U.S. buildings sector, where heating is mainly provided by distributed technologies such as boilers in individual buildings, buildings in China, especially in the northern climate zones, are heated by centralized city-scale district heating systems. Chinese district heating systems are often fueled by natural gas and coal. Electrifying the district heating systems in China is a key component of decarbonizing China's buildings sector. As China is using different types of district heating systems with a mix of fuel sources and heat sources, district heating electrification will focus on community, campus, and building block scale, where district heating systems use coal or natural gas. For large city scale district heating systems that utilize steam, the focus is to switch from coal or natural gas-based steam to waste heat from power plants or industrial facilities.

Heat pumps are a promising electric heating technology to replace coal and natural gas-based heating in China. Generally speaking, heat pumps are much more energy efficient than electric resistance technologies. Recent advances in technologies also enable air-source heat pumps to operate at lower temperatures (US DOE, n.d.). For example, cold-climate heat pumps now perform even in outdoor temperatures well below freezing (Alpine, n.d.; Rheem, n.d.). Electric heat pumps for space heating and cooling enjoy increasing market shares in the United States in the past few years (US EIA, 2017a). Also, advanced technologies such as ground-source heat pumps can further boost heat pump efficiency, even when operated in a cold outdoor environment. It is widely believed that heat pump technologies will become the dominant space heating technology in the future.

Domestic hot water (DHW) accounts for about 15% of the residential building energy use in China (Zhou et al., 2019). The existing DHW systems primarily consume natural gas. In small towns and rural areas, LPG- and coal-based DHW systems are still commonly used. In urban households, electric resistant heating devices are becoming more common. While their capital costs are lower, electric resistance technologies are much less energy efficient than heat pumps, and thus more expensive to operate (US EIA, 2017b). Using a heat pump water heater can greatly boost DHW system efficiency compared to resistant electric water heaters.

Electric resistance stoves and electric induction stoves are two major kinds of electric stoves that can be installed in all kinds of buildings. Electric induction cookstoves generally have slightly higher capital costs compared to their gas counterparts, while electric resistance cookstoves are similar in capital cost to their gas alternatives. According to a recently published report on California (E3, 2019), electric stoves, both electric resistance and induction, have moderately higher operation costs compared to gas stoves (up to $80 per year). However, electric resistance stoves could serve as a lower-cost option than gas stoves in new buildings since installing electric resistance stoves in new construction can avoid the cost of connecting gas lines to the kitchen. The development of electric cooking technologies also will need to accommodate Chinese cooking techniques. Chinese cooking features high temperature cooking associated with oil stir-frying. Such cooking techniques also require using round-bottom pans so there is a large cooking pan surface to stir food.

Rooftop photovoltaic (PV) systems make use of solar energy to generate electricity. The electricity is then used to satisfy the building's local energy consumption. As penetration levels of solar PV systems increase over time, the potential for overproduction of solar power has increased (Mills and Wiser, 2015). This problem applies to other renewables as well. Increased level of electrification—expanding the demand of electricity in end-uses—can potentially make better use of these resources. Also, the addition of rooftop PV to electric storage offers a great value by providing resilience that enables buildings to operate during critical events.

6.4 Electrification Challenges in Buildings

A Berkley Lab research team conducted surveys with the buildings sector stakeholders in both US and China, including high-level decision makers in U.S. technology companies and the Chinese experts from government agencies, a design institute, utilities, technology companies, professional associations, and research institutes (Feng et al., 2021).

Survey results suggest that lack of end-user awareness and lack of government/utility policies and incentives are the two leading barriers to building electrification in China (Figure 16). Requirements for technology installation and transformer/substation capacity updates, high technology costs, and low fuel prices (e.g., coal and natural gas) also play significant roles.

The high cost of electricity and the lack of technology availability, though mentioned less frequently than the others, constitute notable barriers to building electrification. Chinese experts in the survey emphasized the importance of high electricity costs (rural electricity costs in particular), consumer energy preferences, and market mechanisms as leading barriers, and suggested revising relevant standards and updating transformer/substation capacity.

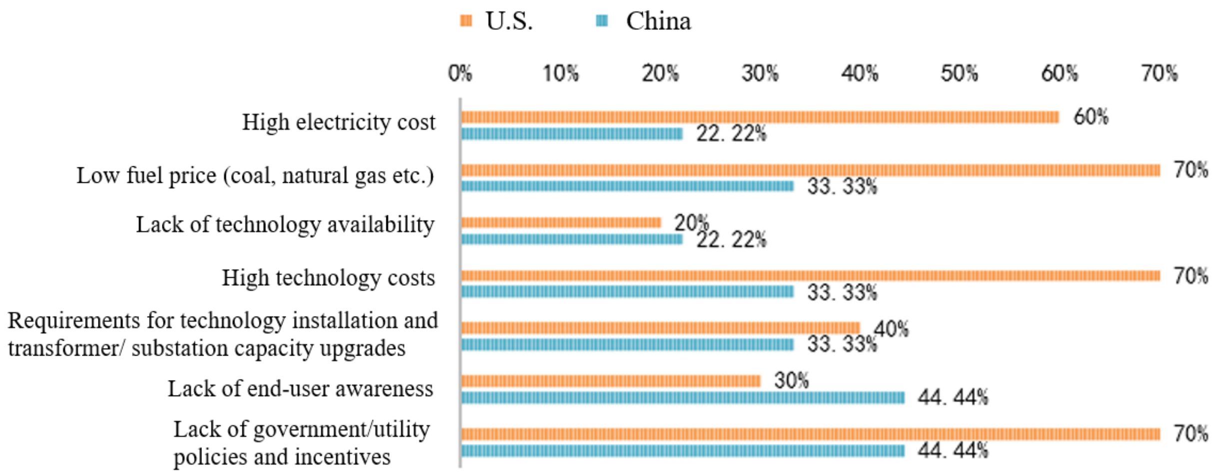

Figure 16. Questionnaire results on the major barriers to building electrification

Source: Feng et al., 2021.

The survey also indicated that electrification challenges are different in China compared to the barriers in the U.S., which include low fuel prices, high technology costs, lack of government/utility policies and incentives, and high electricity costs. Lack of technology availability, requirements for technology installation and transformer/substation capacity upgrades, and lack of end-user awareness are smaller challenges in the U.S. buildings sector electrification.

The questionnaire also asked respondents what are the barriers to transitioning from coal to electricity in rural heating in China. The results show that technology cost, energy costs, and lack of long-term supporting policies on technology installation are the major barriers (Figure 17). In addition, the coal to electricity transition in rural heating would be more applicable to new construction, since retrofits would be very expensive without significant subsidies and incentives.

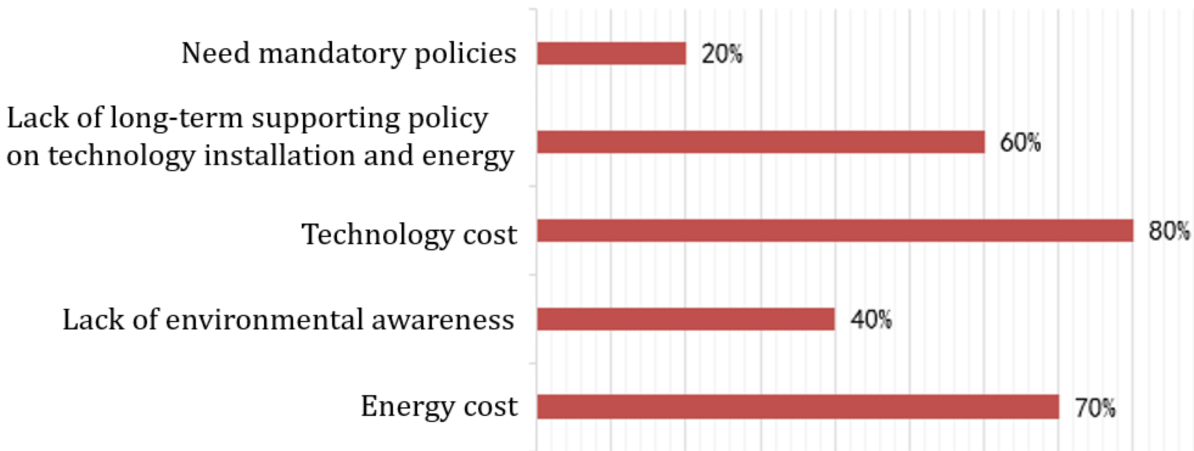

Figure 17. Questionnaire results on barriers to electrifying rural heating in China

Source: Feng et al., 2021.

6.5 Key Milestones for Electrification of the Buildings Sector

Figure 18 shows key milestones in China's buildings sector. A key direct electrification indicator is the adoption of electric technologies for space heating. Under the Continuous Improvement Scenario, the rate of adoption increases from 7% in 2021 to 11% by 2030 and only 19% by 2050. The Deep Mitigation Scenario accelerates the uptake of electric technologies for space heating, increasing the penetration level from the current 7% to 20% by 2030 and further to 45% by 2050.

Figure 18 also highlights other indirect electrification milestones, including improved energy efficiency in heating and cooling, increased development of net-zero energy buildings, and higher adoption of distributed renewable energy in buildings. Specifically, the share of net-zero energy buildings in total building stock will be increased from today's 2% to 24% by 2030 and 60% by 2050 in the Deep Mitigation Scenario. Distributed renewable energy penetration will also be improved from today's 4% to 8% by 2030 and 25% by 2050.

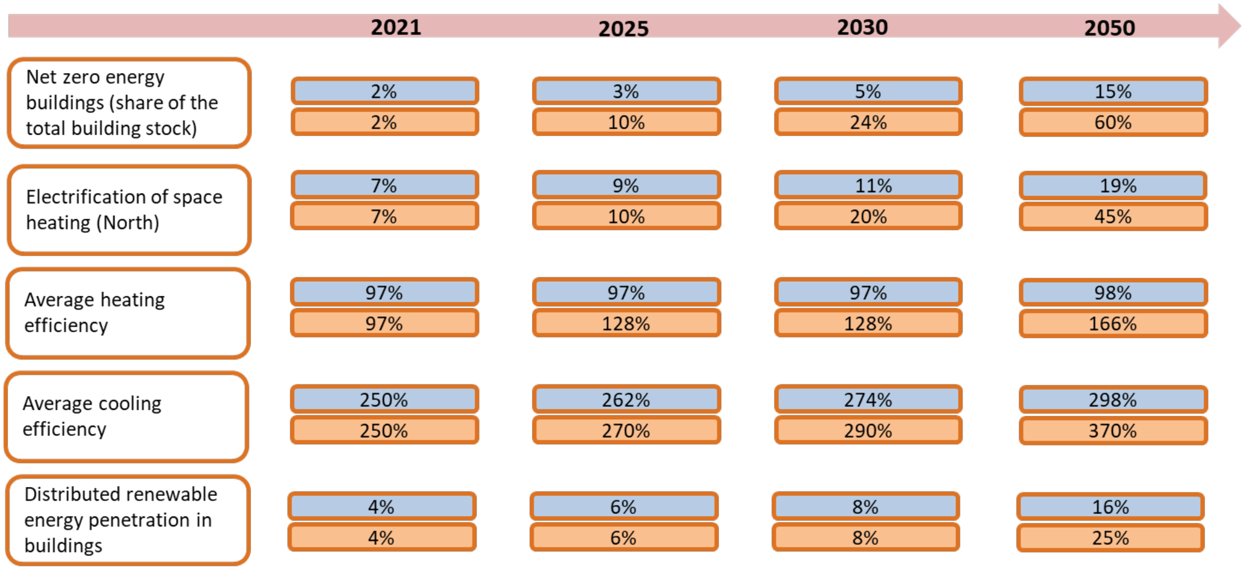

Figure 18. Key Electrification Milestones of the Buildings Sector

Note: blue boxes denote milestones for the Continuous Improvement Scenario and orange boxes denote milestones for the Deep Mitigation Scenario.

6.6 Energy Use and CO_2 Emissions of an Electrified Buildings Sector

In the Deep Mitigation Scenario, buildings sector final energy demand peaks by 2029, reaching more than 790 Mtce, or 16% above 2020's level. Final energy demand gradually declines after 2030, reaching 653 Mtce by 2050, or 4% below 2020's level, shown in Figure 19.

Among the end-uses, energy use of appliances and equipment sees the largest rise, increasing 151% by 2050. The contribution of appliances and equipment energy demand also increases from 10% in 2020 to 27% by 2050. Heating, the largest energy needs in buildings today, will decrease in both final energy use and its contribution in the Deep Mitigation Scenario. Heating energy demand will decline from 273 Mtce in 2020 (40% of total final energy demand in buildings) to 133 Mtce by 2050 (20%). In addition, cooking energy demand will decrease 17% from 132 Mtce in 2020 to 110 Mtce in 2050, but the contribution of cooking energy demand in total final buildings energy use is stable, at around 17% by 2050.

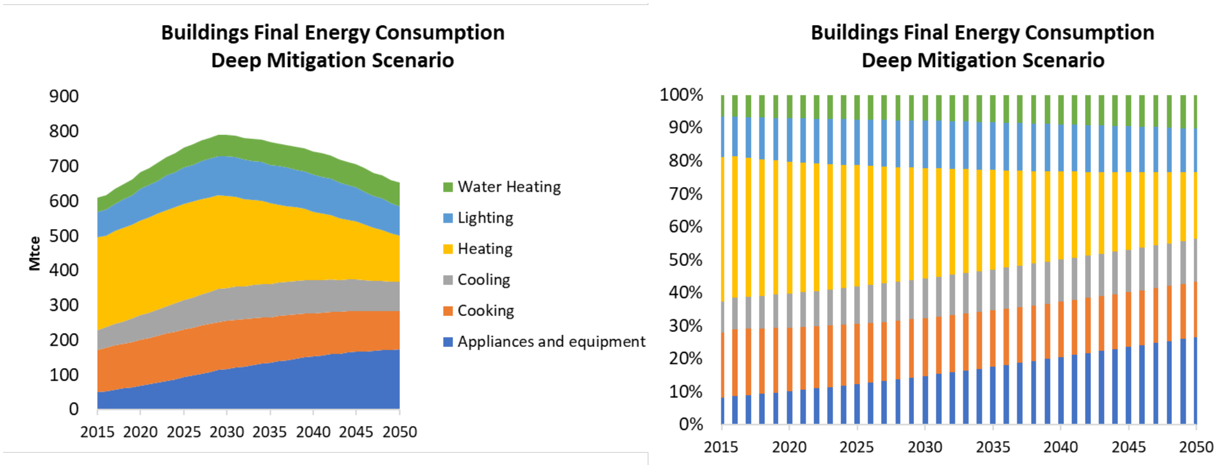

Figure 19. Buildings Sector Final Energy Consumption by End-Use (2015–2020) under the Deep Mitigation Scenario

Buildings CO_2 emissions have significantly different results across the two scenarios. In the Continuous Improvement Scenario, buildings CO_2 emissions plateau between 2020 and 2030, and decline quickly after 2030. The buildings sector will not be completely decarbonized in this scenario, but will still be emitting about 500 $MtCO_2$ by 2050 (Figure 20).

In the Deep Mitigation Scenario, buildings CO_2 emissions can be almost fully decarbonized. Emissions peak by the early 2020s and decline sharply after 2030, due to accelerated adoption and use of a number of technologies, including electric and renewable technologies, aggressive improvement in energy efficiency of heating and cooling, and large-scale adoption of net-zero energy buildings.

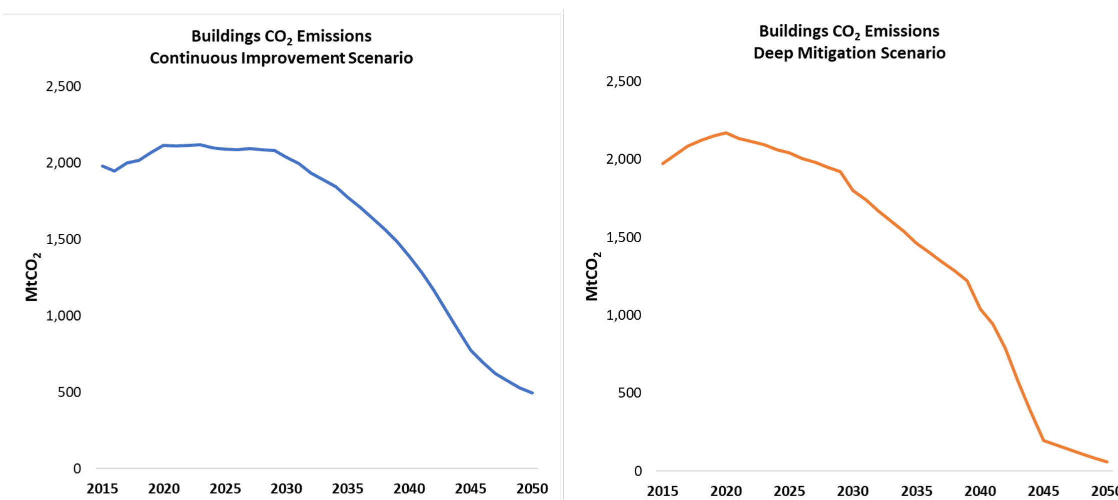

Figure 20. Buildings Sector CO_2 Emissions in Continuous Improvement and Deep Mitigation Scenarios

7. Industry Sector Electrification Strategies and Challenges

7.1 Industry Electrification Status

China's primary energy use is dominated by the industrial sector[3], which accounted for 65% of all primary energy use in 2020 (NBS, 2021a). Within industry, the manufacturing sector accounted for 92% of total industrial final energy demand in 2019 (NBS, 2021a). Mining activities and production and supply of water and gas represented the other 8% in 2019 (NBS, 2021a).

Manufacturing traditionally relied on coal as its energy input. Contribution from coal and coal-based products reached the highest in 1985, accounting for 75% of total manufacturing energy demand. The share of coal and coal products has declined in the recent years. In 2018 coal and coal products were still the largest energy input at 48% of the final manufacturing energy use. But the share of direct use of coal, i.e., using coal as a fuel for combustion, sharply declined from 47% in 1980 to 19% in 2018. The decline of direct coal use was most significant in the last few years due to China's increasingly stringent air pollution control policies. However, the share of coke and coke products (mainly for the iron and steel industry) increased from 14% in 1980 to 28% in 2018.

Over the years, electricity demand in the manufacturing sector grew sharply, increasing from consuming 298 TWh in 1985 to 4,577 TWh by 2018, or 14.5 times increase. At the same time, the share of electricity use in China's manufacturing final energy use also increased from 9% in 1985 to 22% by 2018 (Figure 21). While electricity plays a smaller role in meeting China's industrial energy demand, compared to coal or other fuels, China's industry consumes a significant amount of electricity due to the production volume and

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[3] According to China's latest standard on *Industrial Classification for National Economic Activities (GB/T 4754-2017)* and the latest energy balance tables in *China Energy Statistical Yearbook*, "industry" includes: mining, manufacturing, and production and supply of electricity, gas, and water. The manufacturing sector includes 31 subsectors, ranging from energy-intensive to less energy-consuming industries (AQSIQ and SAC, 2017). Also, in China's classification, "construction" is grouped with "industry" as "secondary industry". Energy supply sectors, such as petroleum refining and coking are also included in "manufacturing", according to the energy balance tables in the *China Energy Statistical Yearbook* (NBS, 2021a).

scale of the Chinese industries. Industry sector dominated China's electricity consumption in the past, representing more than 80% of final electricity consumption in the 1980s. By 2019, industry remains the largest electricity-consuming end-use sector in China, accounting for about 68% of final electricity use (NBS, 2021a).

Compared to other countries, China's industrial sector has slightly lower shares of electricity use and relies more heavily on fossil fuels. About 22% of China's final industrial energy use was electricity in 2018, while the share in other selected countries ranged from 24% (United States), 25% (Japan), and 34% (Germany) (IEA, 2021; NBS, 2021b). While the share of coal use in China declined to 48% in 2018, the share of coal use in India, Japan, Germany, and United States was 46%, 18%, 10%, and 6%, respectively (Figure 22).

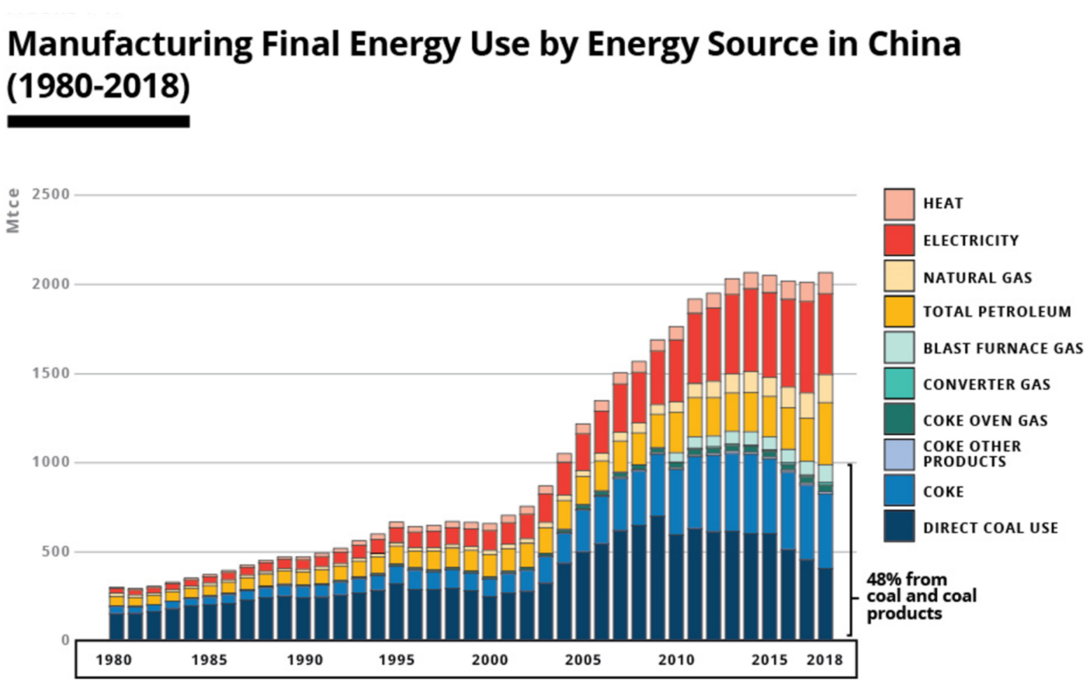

Figure 21. Manufacturing Final Energy Use by Energy Source in China (1980–2018)

Source: NBS, various years.

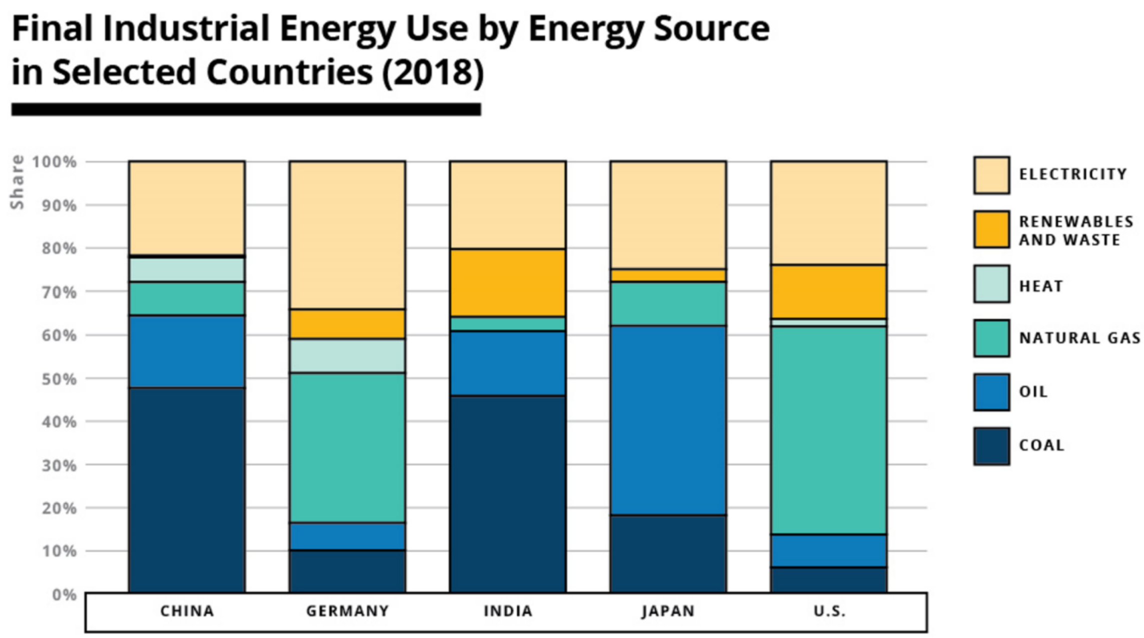

Figure 22. Final Industrial Energy Use by Source in Selected Countries (2018)

Sources: IEA, 2021; NBS, 2021b.

Notes: 1) China energy data are from NBS (2021b); energy data for other countries are from IEA (2021); 2) both data sets include non-energy use; 3) IEA (2021) defines "Renewables and waste" to include on-site "hydro, geothermal, solar, wind, and tide/wave/ocean energy and the use of these energy forms for electricity and heat generation, as well as solid biofuels, liquid biofuels, biogases; industrial waste and municipal waste"; 4) "Electricity" refers to electricity purchased from the grid, which was generated via a mixture of renewable and non-renewable sources.

7.2 Industry Electrification Strategies

Modeled industrial subsectors

We conducted process-level energy modeling for eight industrial subsectors, including alumina and aluminum, ammonia, cement, copper, ethylene, glass, pulp and paper, and steel. Future demand of these industrial commodities is based on physical drivers, i.e., population growth and peaking, urbanization and employment, and personal wealth and consumption, which in turn drives the demand for commercial and residential floor space, appliance and equipment ownership, infrastructure (roads, railways, and other urban infrastructure systems), consumer products and vehicles, and fertilizers.

In addition, we modeled other manufacturing subsectors such as food, beverage, and tobacco, textiles, chemical fibers, timber and furniture manufacturing, printing and publishing, medicine, rubber and plastics, metal products, machinery, transport equipment, and electronics. Future demand of these manufacturing subsectors is estimated based on economic drivers, such as industrial value-added.

Selection of electric technologies

Electrification is considered a key decarbonization pathways in industry, along with improving energy efficiency, adopting material efficiency and circular economy strategies, and using other alternative, low/zero-carbon fuels. The measures and technologies considered in the industry modeling are either already commercially available (whether being widely adopted or not) or emerging, i.e., in the piloting and demonstration stages. Technologies and measures that are in the early stage of research and development, such as plasma heating for cement making and iron ore electrolysis, are not considered.

Table 2 provides a summary of industry-specific key technology assumptions used in the Continuous Improvement Scenario and the Deep Mitigation Scenario. In the following sections, we discuss electrification strategies and challenges in the most energy-intensive manufacturing sectors, including the steel, cement, and chemical sectors.

Table 2. Key Industries Electrification Strategies and Assumptions

Cement	
Continuous Improvement	Waste Heat to Power Generation adopted in all rotary kilns. Did not consider electric technologies to electrify clinker production.
Deep Mitigation	Waste Heat to Power Generation adopted in all rotary kilns. Did not consider electric technologies to electrify clinker production.
Steel	
Continuous Improvement	Waste heat/pressure utilization is adopted in BF-BOF route, reaching 100% by 2030.
	Steel production from scrap-based EAF process increases to 20% by 2030 and 40% by 2050. Electricity accounts for 95% of total energy use in scrap-based EAF.
	Steel production from DRI – EAF steelmaking increases to 3% by 2030 and 5% by 2050.
Deep Mitigation	Waste heat/pressure utilization is adopted in BF-BOF route, reaching 100% by 2030.
	Steel production from scrap-based EAF process increases to 20% by 2030 and 50% by 2050. Electricity accounts for 100% of total energy use in scrap-based EAF.
	Steel production from DRI – EAF steelmaking increases to 5% by 2030 and 15% by 2050.
Alumina	
Continuous Improvement	Electricity use increases slowly, accounting for 40% of energy use by 2050 in the Bayer Process.
Deep Mitigation	The share of electricity increases to 70% by 2050 in the Bayer process.
Aluminum	
Continuous Improvement	Secondary aluminum production increases from 20% in 2020 to 58% by 2050.
Deep Mitigation	Secondary aluminum production increases from 20% in 2020 to 75% by 2050.
Copper	
Continuous Improvement	Electricity use accounts for 45% of total energy inputs by 2050 in primary copper production.
	Electricity use accounts for 84% of total energy inputs by 2050 in secondary copper production.
Deep Mitigation	Electricity use accounts for 80% of total energy inputs by 2050 in primary copper production.
	Electricity use accounts for 100% of total energy inputs by 2050 in secondary copper production.
Glass	
Continuous Improvement	
Flat glass	Did not consider electric technologies to electrify flat glass production.
Container glass	Slightly increased use of electricity to 8% by 2050.
Deep Mitigation	
Flat glass	Increase use of electricity through 2050, considering technologies such as electric furnaces.
Container glass	Electricity use increases to 30% by 2050, considering technologies such as electric furnaces.
Pulp and Paper	
Continuous Improvement	Electricity use increases to 50% by 2050 in paper making based on imported pulp.
Deep Mitigation	Electricity use increases to 60% by 2050 in paper making based on imported pulp.

Note: BF: blast furnace; BOF: basic oxygen furnace; EAF: electric arc furnace; DRI: direct reduction of iron.

7.3 Steel Sector Electrification and Challenges

Currently, primary steelmaking heavily relies on coal and coal products (coke). Coke is used a reducing agent to convert iron ore into iron. Coal is also combusted during this process to provide the very high process temperature (1,100°C–1,500° C) needed for the reaction. This primary steelmaking process utilizes blast furnaces (BFs) for ironmaking and basic oxygen furnaces (BOFs) for steelmaking. The coke-making process, coal-burning for process heating, and the chemical reaction process to produce iron all emit significant amount of CO_2 emissions. In China, over 90% of the steel is produced through the primary steelmaking process utilizing BFs and BOFs and is therefore heavily dependent on coal.

One commercially-available electrification technology for the steel sector is an electric arc furnace (EAF) which is used to melt scrap steel. Currently, scrap-based EAF steel production only accounts for 10% of China's total steel production, much lower than other industrialized countries such as Japan (24%), South Korea (33%), and United States (68%). The Chinese government has set a goal of increasing the share of EAF steel production to 15% by 2025 (MIIT, 2022). However, a key constraint for increasing EAF steel production is the limited scrap availability in China. Currently EAF production also faces higher costs, driven by high cost of scrap materials and high cost of electricity.

An emerging technology for decarbonizing the iron and steel industry is H_2-based direct reduction of iron (DRI) using renewable energy, thus significantly reduces CO_2 emissions associated with BFs. DRI can be charged hot or cold to the EAF for steelmaking. However, adoption of this emerging technology faces technical issues related to hydrogen, including significant electricity demand to produce renewable hydrogen, additional infrastructure needs to transport hydrogen, material challenges to store hydrogen (metal embrittlement), and potential leakage of hydrogen.

In addition to technical challenges, the steel industry involves a number of stakeholders from steel producers, suppliers of material inputs (iron ore, coal, coke, and scrap), engineers, designers, architects, construction companies, vehicle manufacturers, appliance manufacturers, other steel end-users, as well as demolishing and recycling companies. Coordinated strategies and policies are needed to overcome the institutional barriers as well as provide incentives to produce, use, and recycle low-carbon steel.

A complicating factor is that the current average age of China's BFs is about 13 years, or less than 1/3 of the typical BF lifetime. A fast energy transition, moving away from the BFs may result in stranded assets as well as social and equity implications.

Given these challenges, the Deep Mitigation Scenario modeled the following actions to increase electrification in the steel industry:

- Process change: assumed that scrap-based EAF steel reaches 20% by 2030 and 50% by 2050. H_2-DRI based steelmaking reaches 5% by 2030 and 15% by 2050.
- Electrification: Electricity accounts for 100% of total energy use in scrap-based EAF, and renewable H_2 use accounts for 75% of energy inputs in DRI by 2050.

7.4 Cement Sector Electrification and Challenges

The cement sector is one of the most hard-to-abate industrial sectors. The cement-making process requires very high temperature (>1,450°C) during the limestone calcination stage of production. Current electric technologies are not yet able to deliver process heating temperature at such a high level. Studies of the feasibility of emerging electric technologies, such as plasma heating, have been conducted for the cement industry (Global Cement, 2019). However, these technologies are still in the laboratory or conceptual stages. No pilot or demonstration projects to electrify clinker production have been implemented in the cement industry to date. Thus, this study did not consider electric technologies to decarbonize the cement industry.

7.5 Chemical Sector Electrification and Challenges

The chemical sector produces thousands of products and involves hundreds of processes. However, many of these chemical products are produced from key chemical building blocks, such as ethylene for plastics and ammonia for fertilizers. In this study, ethylene and ammonia are specifically modeled.

The chemical sector is difficult to decarbonize due to the current reliance on fossil fuels as feedstocks to turn them into final products, the requirement for high-temperature heat in current processes (for example, steam cracking, which is used to turn feedstocks into olefins and aromatics operates at about 1,000°C), and the demand for hydrogen (for making fertilizers, for example). In China, due to limited natural gas availability, chemical feedstocks rely mostly on coal or oil-based products, such as using coal for ammonia production and naphtha as feedstock for ethylene production.

Electrification technologies for the chemical sector, such as the electric steam crackers, are in the R&D stage. Some companies such as BASF, SABIC, and Dow Chemicals are in the process of developing these technologies (BASF, 2021; SABIC, 2021; Jasi, 2020). However, this study does not include such early-stage electric technologies due to the limited availability of data for technology assessment.

In the Deep Mitigation Scenario, key assumptions are made for ethylene production, including:

- Feedstock change: coal-based feedstock is reduced to zero by 2050; 65% of feedstock comes from naphtha by 2050.
- Efficiency improvement: 20% improvement from today's state-of-art level.
- Activity change: considers a number of material efficiency strategies, such as reducing packaging, increasing product lifetimes, implementing material-efficient design, and switching to low-carbon materials.

In the Deep Mitigation Scenario, key assumptions are made for ammonia production, including:

- Feedstock change: 50% of feedstock comes from natural gas, 30% from coal, and 20% from non-fossil H_2 by 2050.
- Efficiency improvement: natural gas and coal-based production reaching today's best available technologies (BAT) levels by 2050; H_2-based production improves to be 10% more efficient than today's level by 2050.
- Activity change: considers a number of material efficiency strategies, such as increasing uptake efficiency of fertilizers, reducing leakage to water and air, improving timing of application, increasing precision of application, reducing food wastes, and switching to organic fertilizers.

7.6 Key Milestones for Electrification of the Industry Sector

The study highlights three sectoral-specific electrification milestones, as well as one industry-wide electrification milestone, as shown in Figure 23.

- Industry electrification rate: the share of electricity use in industrial final energy use increases from 28% in 2021 to 33% by 2030 and 39% by 2050 in the Continuous Improvement Scenario. Industry electrification rate improves in the Deep Mitigation Scenario, reaching 36% by 2030 and 51% by 2050.
- Steel industry: the share of secondary steelmaking (scrap-based EAF steelmaking) increases from 11% in 2021 to 20% in 2030 and 40% by 2050 in the Continuous Improvement Scenario. EAF secondary steelmaking is accelerated to 50% by 2050 in the Deep Mitigation Scenario.

- Steel industry: indirect electrification through non fossil-H_2 DRI increases from 2.1% in 2021 to 3% in 2030 and 5% by 2050 in the Continuous Improvement Scenario. The share of DRI is significantly increased in the Deep Mitigation Scenario to 5% by 2030 and 15% by 2050.
- Aluminum industry: recycled aluminum use is increased in both scenarios, but to a much higher share in the Deep Mitigation Scenario to 75% by 2050.

	2021	2025	2030	2050
Electrification rate in industry	28% 28%	30% 32%	33% 36%	39% 51%
Increase the % of EAF steel	11% 11%	15% 15%	20% 20%	40% 50%
Increase the % of H_2-DRI	2.1% 2.3%	2.5% 3.5%	3% 5%	5% 15%
Increase the % of secondary aluminum	24% 26%	29% 38%	37% 57%	58% 75%

Figure 23. Key Electrification Milestones of the Industry Sector

Note: blue boxes denote milestones for the Continuous Improvement Scenario and orange boxes denote milestones for the Deep Mitigation Scenario.

7.7 Energy Use and CO_2 Emissions of an Electrified Industry Sector

In the Deep Mitigation Scenario, with a combination of energy efficiency improvements, material efficiency, circular economy strategies to reduce demand, as well as switching to cleaner fuels, we find that industrial final energy demand peaks by early 2020sand declines by 42% from 2020's level by 2050 (Figure 24). Here industry does not include the energy supply sectors, such as petroleum refining, coking, coal-to-liquids, and other energy transformation sectors.

In addition, we find that the industrial final energy demand will still be dominated by heavy industries, especially chemicals (e.g., ethylene and ammonia), ferrous metals (iron and steel), non-ferrous metals (e.g., aluminum and copper), and non-metallic minerals (mainly cement and glass). These four subsectors account for more than 60% of the final energy demand in industry by 2050.

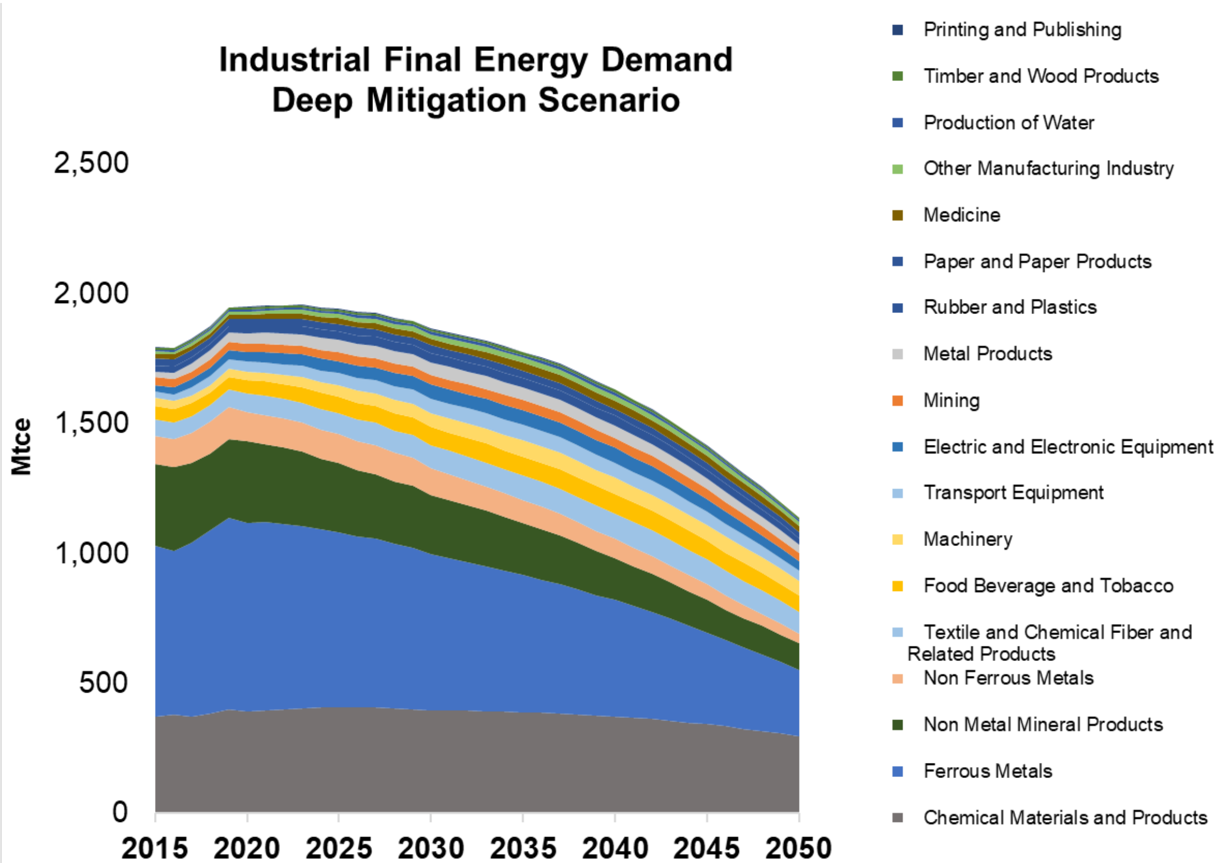

Figure 24. Industrial Final Energy Demand in the Deep Mitigation Scenario

Note: industry does not include petroleum refining, coking, coal washing, coal-to-liquids, and other energy supply sectors.

In the Deep Mitigation Scenario, we find that China's manufacturing sector energy use not only declines but also transitions away from coal. By 2050, the use of coal and coke in manufacturing final energy use is reduced from today's 50% to 15%, and limited to a few industries, such as cement and steel, due to the challenges of providing very high temperature heat and also providing the chemical reaction needed in these processes. More than 60% of manufacturing sector's final energy use comes from electricity, renewable heat, and hydrogen by 2050 (Figure 25).

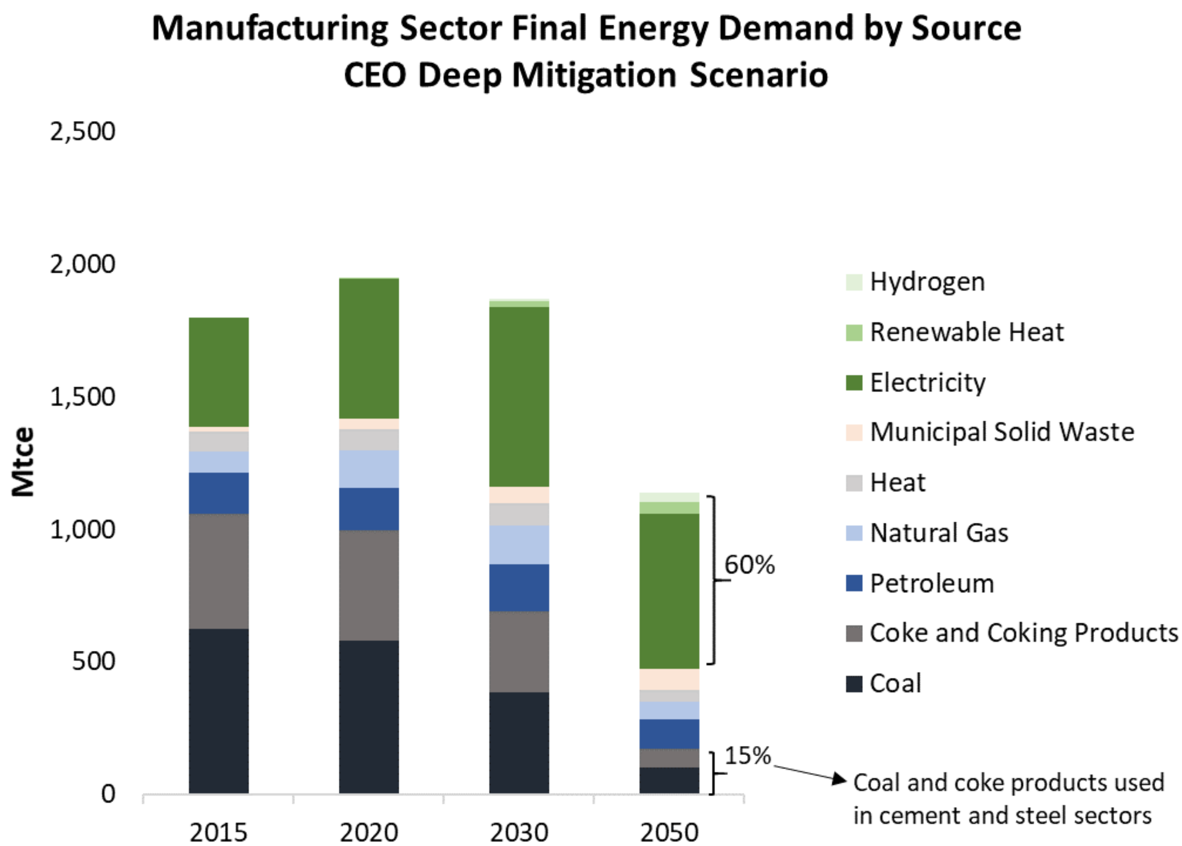

Figure 25. Manufacturing Sector Final Energy Demand by Source

When combining energy-related CO_2 emissions from manufacturing, mining, production and supply of water with energy supply sectors, we find that in the Deep Mitigation Scenario, emissions can peak in early 2020sand decline 77% by 2050 from the level in 2020 (Figure 26). Compared to the Continuous Improvement Scenario, energy-related CO_2 emissions in the Deep Mitigation Scenario declines at a faster rate, reducing 2.5% per year in 2020–2030, 4% per year between 2030 and 2040, and almost 8% per year during 2040–2050.

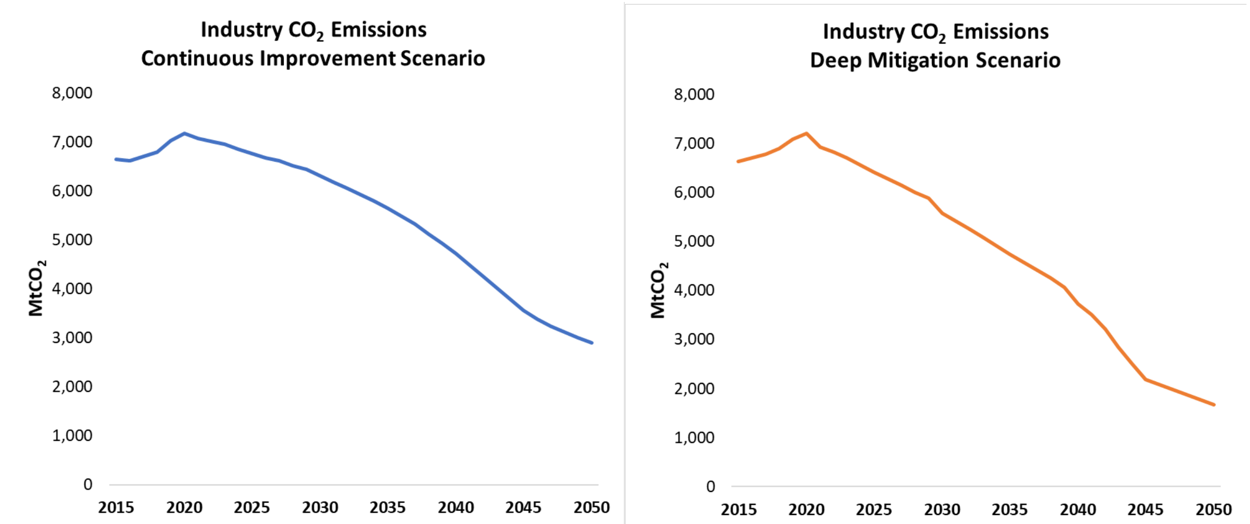

Figure 26. Industry Sector CO_2 Emissions under the Continuous Improvement and Deep Mitigation Scenarios

Notes: 1) include both manufacturing, mining, production and supply of water, and the energy supply sectors. 2) Results do not include process-related CO_2 emissions.

8. Power Sector Decarbonization

Accelerated power sector decarbonization will be a crucial enabling factor for electrification's role in contributing to China's climate mitigation goals. Without rapid growth of renewable and non-fossil generation and the concurrent phase-out of coal and natural gas generation, electrification could have ambiguous impacts on CO_2 emissions.

Under the Deep Mitigation Scenario, China's power generation is modeled to be completely fossil fuel-free by 2045 as electrification increases. Total generation capacity for wind and solar PV increases significantly from 561 gigawatt (GW) in 2020 to 2,775 GW by 2030, and 7,930 GW by 2050. Wind and solar PV become the largest sources of electricity production, accounting for 51% and 21.7% of total power generation by 2050, respectively, as shown in Figure 27. Nuclear, hydro, and biomass represent 12.9%, 12.5%, and 1.9% of total generation by 2050. Growth in utility-scale storage, particularly pumped hydro and batteries, is also needed to address the intermittence and variability in renewable generation.

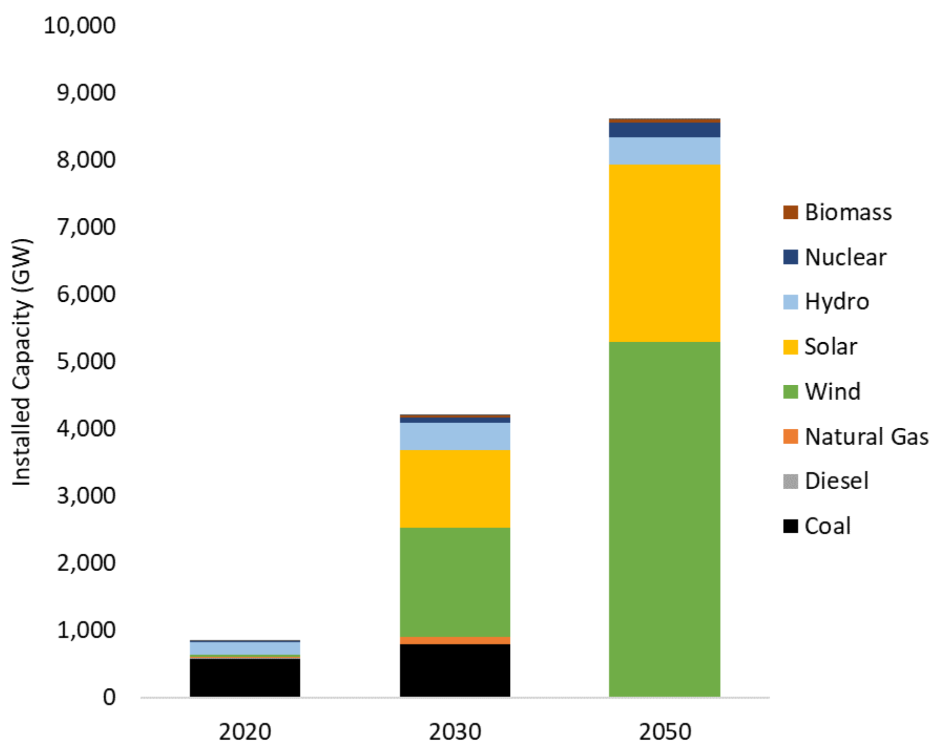

Figure 27. Installed Capacity of Power Generation in China in the Deep Mitigation Scenario

By 2050, China's electricity generation increases 67% from 2020's level, reaching 12,034 TWh in the Deep Mitigation Scenario (Figure 28). The power sector is fully decarbonized by 2045, with electricity completely produced from renewables and non-fossil fuels.

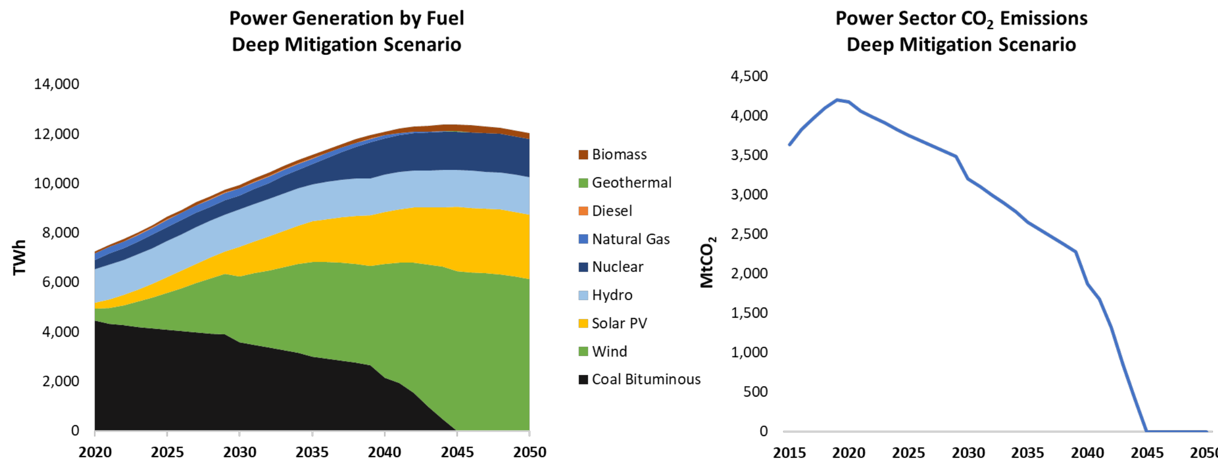

Figure 28. Power Generation by Fuel and CO_2 Emissions in the Deep Mitigation Scenario

9. Conclusions

The analysis shows that China's overall electrification penetration level can be improved from 22% in 2015 to 37% by 2050 in the Continuous Improvement Scenario, and can be significantly increased to 60% by 2050 in the Deep Mitigation Scenario. End-use electricity demand in the Deep Mitigation Scenario will increase from 6,954 TWh in 2020 to 10,874 TWh by 2050, or 17% higher than the Continuous Improvement Scenario.

The study finds that the transport sector can significantly increase adoption of electric vehicles in passenger transport, as well as light and medium-duty transportation. The electrification rate in the transport sector increases the most of all sectors, reaching 39% by 2050, compared to 5% in 2020. However, significant challenges remain to completely electrify heavy-duty trucks, shipping, and aviation.

We also find that China's buildings sector has the greatest potential to be largely electrified, reaching 88% of electrification penetration in buildings final energy demand by 2050 in the Deep Mitigation Scenario. The buildings sector needs to sharply increase a number of electric, renewable, energy-efficient, and building integrative technologies, such as heat pumps, electric cooking technologies, distributed renewables, waste heat utilization between industries and buildings, as well as net-zero buildings. Electrification challenges, such as lack of awareness, lack of government support, and high electricity cost, need to be addressed through innovative fiscal, financial, and deployment policies.

The use of electricity in industry can be increase to 51% of total final industrial energy use by 2050, driving by accelerated adoption of electric technologies and processes in key industries, such as iron and steel, aluminum, copper, and glass sectors. When combined with material efficiency and circular economy strategies, industrial electricity demand only increases 9% from the level in 2020 by 2050 in the Deep Mitigation Scenario. However, significant technological challenges exist, such as how to electrify very-high temperature heat on a large-scale. Industry electrification remains challenging—it requires policy support on research and development, demonstration, and pilots to test, verify, and scale-up emerging electric technologies.

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