

Reinventing fire: China – the role of energy efficiency in China’s roadmap to 2050

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Abstract

As part of its Paris Agreement commitment, China pledged to peak carbon dioxide (CO₂) emissions around 2030, striving to peak earlier, and to increase the non-fossil share of primary energy to 20 % by 2030. Yet by the end of 2014, China emitted 28 % of the world’s energy-related CO₂ emissions, 79 % of which were from coal use. How China can reinvent its energy economy cost-effectively while still achieving its commitments was the focus of a three-year joint “Reinventing Fire: China” research project completed in September 2016.

A team of Chinese and U.S. researchers developed a comprehensive bottom-up model of China’s energy demand and supply sectors and analyzed two scenarios to contrast a reference pathway of current development and a “Reinventing Fire” alternative path of meeting national needs by deploying the maximum feasible share of cost-effective energy efficiency and renewable supply through 2050. The results show that China’s CO₂ emissions could peak 11 years earlier than the reference pathway if the more aggressive Reinventing Fire pathway is pursued.

This paper focuses on the role of energy efficiency in realizing the CO₂ emissions reductions under the more aggressive pathway. We define energy efficiency broadly and include any actions that reduce energy demand through improved use of materials (e.g., longer product lifetimes), through energy intensity improvements, through structural shifts in industry from energy-intensive activities to more service-oriented activities as well as process and mode shifts in urbanization, industrialization, transport, societal consumption and awareness. In addition

to energy efficiency, we identify opportunities for moving away from carbon-intensive fuels through fuel-switching. We found that for the Reinventing Fire Scenario, energy efficiency improvements and strategies contribute 75 % of China’s 2050 total CO₂ emissions reduction potential while fuel switching was only responsible for 25 % of the emissions reduction. Barriers and additional policies needed to realize this significant cost-effective energy efficiency potential in China are discussed.

Introduction

During the period 1980–2012, China’s primary energy consumption grew over six times (6 % average annual growth), much faster than the world’s primary energy consumption growth of 1.8 times (2 % average annual growth) over the same period (IEA, 2016). After decades of rapid economic growth fuelled primarily by fossil fuels, China emitted 28 % of the world’s energy-related CO₂ emissions, with 79 % of these energy-related CO₂ emissions from coal use at the end of 2014 (calculated based on NBS, 2016). To address China’s domestic environmental concerns and support post-Paris global climate change action, China’s coal-dominated energy system needs to undergo a rapid transformation. Chinese President Xi Jinping recognized the need to transform China’s energy system in June 2014 when he called for a “revolution in the production and consumption of energy.” This was followed by China setting national goals to peak its CO₂ emissions around 2030 or earlier and lowering CO₂ emissions per unit of GDP by 60–65 % by 2030 from 2005 levels as part of its commitment to the Paris Agreement. In order to meet these national and internationally pledged goals while also addressing domestic environmental

challenges, China's path forward will require alternative means of energy consumption and production to sustain continued economic growth and rapid urbanization.

This paper describes an analysis of how China can achieve cost-effective savings while achieving significantly improved environmental and energy security outcomes and focuses on the central role that energy efficiency strategies must play in China's future buildings, industry and transport sectors in order to meet aggressive CO₂ emissions reductions. We define energy efficiency broadly and included any actions that reduce energy demand through improved use of materials (e.g. longer product lifetimes), through energy intensity improvements, or through structural shifts in industry from energy-intensive activities to more service-oriented activities as well as process and mode shifts in urbanization, industrialization, transport, societal consumption and awareness. In addition to energy efficiency, we identify opportunities for moving away from carbon-intensive fuels through fuel-switching. The analysis is based on a three-year collaborative "Reinventing Fire: China" research project completed by Energy Research Institute of the National Development and Reform Commission of China, and the China Energy Group of Lawrence Berkeley National Laboratory, and Rocky Mountain Institute in the U.S. in September 2016 (ERI, LBNL and RMI, 2016).

This paper begins by providing an overview of the modelling and analytical approach as well as the scenarios used for developing a roadmap for transforming China's energy system from now through 2050. The energy efficiency and fuel switching contributions to China's 2050 CO₂ emissions reductions under the Reinventing Fire Scenario are then presented, followed by a detailed discussion of energy efficiency and fuel switching strategies envisioned for the buildings, industry, and transport sectors. The potential energy and CO₂ reduction impacts of different efficiency strategies at the sectoral-level through 2050 are highlighted, as well as the future outlook for China's coal, energy use, and CO₂ peaking as a result of these strategies. Lastly, remaining barriers and additional policies needed to realize the significant cost-effective efficiency potential in China are discussed.

Methodology

MODELLING AND ANALYTICAL FRAMEWORK

This study used different modelling tools, analytical approaches, and scenario analyses to provide a detailed, bottom-up assessment of China's future energy demand based on primary demographic, economic, and technical drivers. It combines comprehensive, sector-based modelling of China's energy demand and supply sectors with cost-effectiveness calculations for technologies and measures and a granular least-cost electricity dispatch model. In addition, over 75 real-world international case studies were incorporated into the analysis by informing the development and calibration of modelling assumptions.

The Long-range Energy Alternatives Planning (LEAP)¹ model framework builds on a bottom-up accounting framework with physical and macroeconomic activity drivers to represent the

major energy demand sectors at the detailed end-use level. The results from cost-effectiveness calculations for specific end-use technologies and measures were used as inputs into the LEAP model to inform key modelling parameters such as the highest cost-effective efficiency and technology adoption rates. The projected installed power generation capacities by fuel type and hours of operation from the province-level least-cost electricity dispatch optimization (EDO) model were also integrated into the LEAP model's power sector module. Figure 1 provides a summary of the overall modelling framework for this study.

In addition to the integrated modelling framework, experts from key Chinese think tanks, academic institutions, and industrial associations were also interviewed and consulted throughout the study period to inform the analytical approaches, test assumptions and review the findings. An advisory panel of senior Chinese energy policymakers and advisors also provided feedback on the latest developments in China and policy considerations for future outlook.

SCENARIO ANALYSIS

Scenario-based assessment to compare and contrast two possible energy pathways for China to 2050 was used to identify the potential impact of energy efficiency in China's future roadmap. For both scenarios, the same macroeconomic drivers and assumptions were adopted based on existing Chinese and international projections as shown in Table 1. In general, a conservative approach was undertaken with respect to considerations for technological developments, carbon pricing, and social costs in developing both scenarios. For example, while China has existing pilot carbon emissions trading schemes and committed to commence a national trading scheme during the 13th Five Year Plan period (2016–2020), future CO₂ emissions were not explicitly priced in our analysis. External economic benefits such as public health and environmental quality were also not included in our cost calculations.

The Reference Scenario assumed that only policies in place in 2010 continue to have effect and that no new policies are adopted after 2010, but autonomous technological improvement occurs through 2050. The Reinventing Fire Scenario represented a transformative pathway for China's future energy development in which the maximum feasible shares of currently commercially available, cost-effective energy efficiency and renewable energy supply were adopted. Autonomous technical improvements were also considered. A four-step methodology was used in the development of the Reinventing Fire Scenario for China, including: reducing demand, meeting demand as efficiently as possible, electrifying demand where practical, and shifting to renewable or lower-carbon energy sources. For each end-use demand sector as well as the energy transformation sector, specific strategies to achieving these four steps for "reinventing" China's energy system were developed.

To evaluate the potential energy² and CO₂ emissions reduction impact of the individual sectoral strategies, individual Scenario runs based on the Reference Scenario were implemented in the LEAP model with modelling parameters changed to reflect only one strategy at a time. In this way, it was possible to determine

1. LEAP is a software system for integrated energy planning and climate change mitigation assessment developed in Stockholm Environment Institute's U.S. Center (<https://www.sei-international.org/leap>).

2. Primary electricity is converted using the direct equivalent method (consistent with the Intergovernmental Panel on Climate Change) in our analysis.

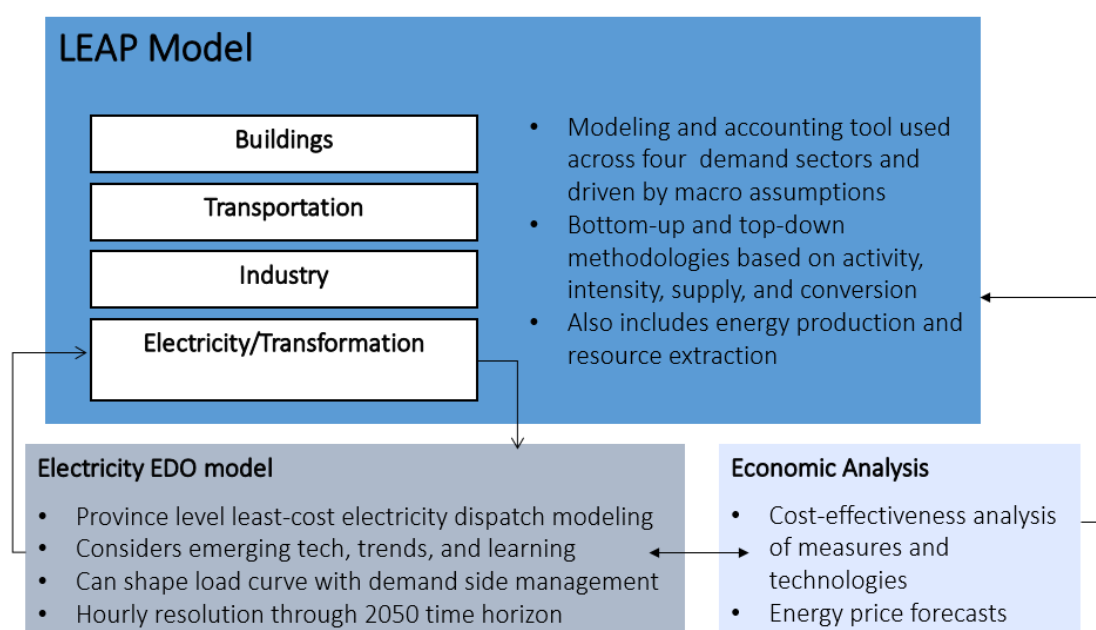


Figure 1. Summary of the Integrated Modeling Approach and Tools.

Table 1. Macroeconomic Drivers and Assumptions for Both Scenarios.

| | 2010 | 2020 | 2030 | 2040 | 2050 |
|--|-------|-------|-------|-------|------|
| Total Population (billions) | 1.34 | 1.42 | 1.44 | 1.42 | 1.37 |
| Urbanization Rate (% of Population) | 50 % | 60 % | 68 % | 74 % | 78 % |
| Decadal Annual Average GDP Growth Rate (%) | 7.6 % | 5.9 % | 4.1 % | 2.9 % | |

the contribution of energy efficiency activities separately from fuel-switching activities to overall CO₂ emissions reductions.

Findings: Key role of energy efficiency

Figure 2 shows China's national CO₂ emissions peaks 11 years earlier in 2025 under the Reinventing Fire Scenario compared to 2036 under the Reference Scenario. The peaking level of CO₂ emissions under the Reinventing Fire Scenario of 9,590 Mt CO₂ is also 34 % lower than the Reference Scenario peaking CO₂ emissions of 14.6 GtCO₂.

Figure 3 shows that the 2050 CO₂ emissions of 11.8 GtCO₂ in the Reference Scenario are reduced to 4.62 GtCO₂ in the Reinventing Fire Scenario through efficiency reductions and fuel switching in the buildings, transport, and industry sectors. A closer factor analysis of the 2050 CO₂ emissions reductions under Reference and Reinventing Fire Scenarios revealed that the energy efficiency strategies (including demand reduction strategies) for each end-use sector contributed the majority of the CO₂ emissions reduction when compared to fuel switching strategies as seen in Figure 2. Adding all three sectors together, energy efficiency and related strategies accounted for 75 % of the annual CO₂ emissions reductions in 2050 compared to 25 % for fuel switching strategies. This underscores the critical need for continuing to improve energy efficiency through various end-use sectoral strategies to enable China to peak its national CO₂ emissions before 2030 and at a significantly lower level as it strives to meet its Paris Agreement goals.

Sectoral strategies in China's 2050 roadmap

RESIDENTIAL AND COMMERCIAL BUILDINGS

In 2010, China's buildings consumed 770 million tonnes of coal equivalent (Mtce³) or 26.3 exajoules of primary energy, or about 24 % of the national total based on our model's estimate⁴. China's energy use per capita is far lower than many developed countries, but this is expected to increase as urbanization progresses, household incomes rise, and the economy shifts away from heavy industry towards the service sector. Under the Reference Scenario, stock growth and growing demand for energy services in Chinese residential and commercial buildings result in a near tripling of buildings-related primary energy between 2010 and 2050, reaching 2,270 Mtce by 2050.

Five strategies are identified for helping China's building sectors cost-effectively deploy today's most energy-efficient building design and construction practices, super-efficient equipment, smart building systems, and clean energy sources under the Reinventing Fire Scenario. Of these five strategies, four focus on improving energy efficiency either directly (e.g., integrative/passive design and retrofits and super-efficient equipment)

3. Mtce is the standard unit for energy in China. 1 Mtce = 29.27 million gigajoules.

4. The reported statistics for building energy consumption in 2010 is 668 Mtce, which is lower than the value used in our analysis because of Chinese statistics accounting conventions that exclude buildings in industrial sectors, for example. Our estimate includes adjustments to include all building-related energy consumption. More information on the building statistical adjustments can be found in Fridley et al. 2007.

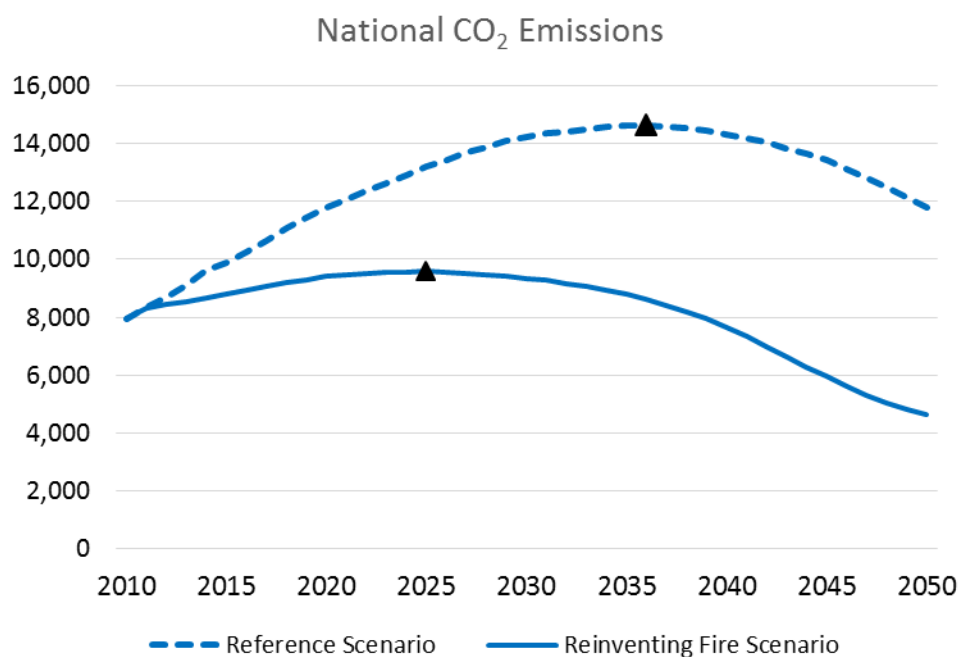


Figure 2. China's Total CO₂ Emissions under the Reference and Reinventing Fire Scenarios, 2010–2050.

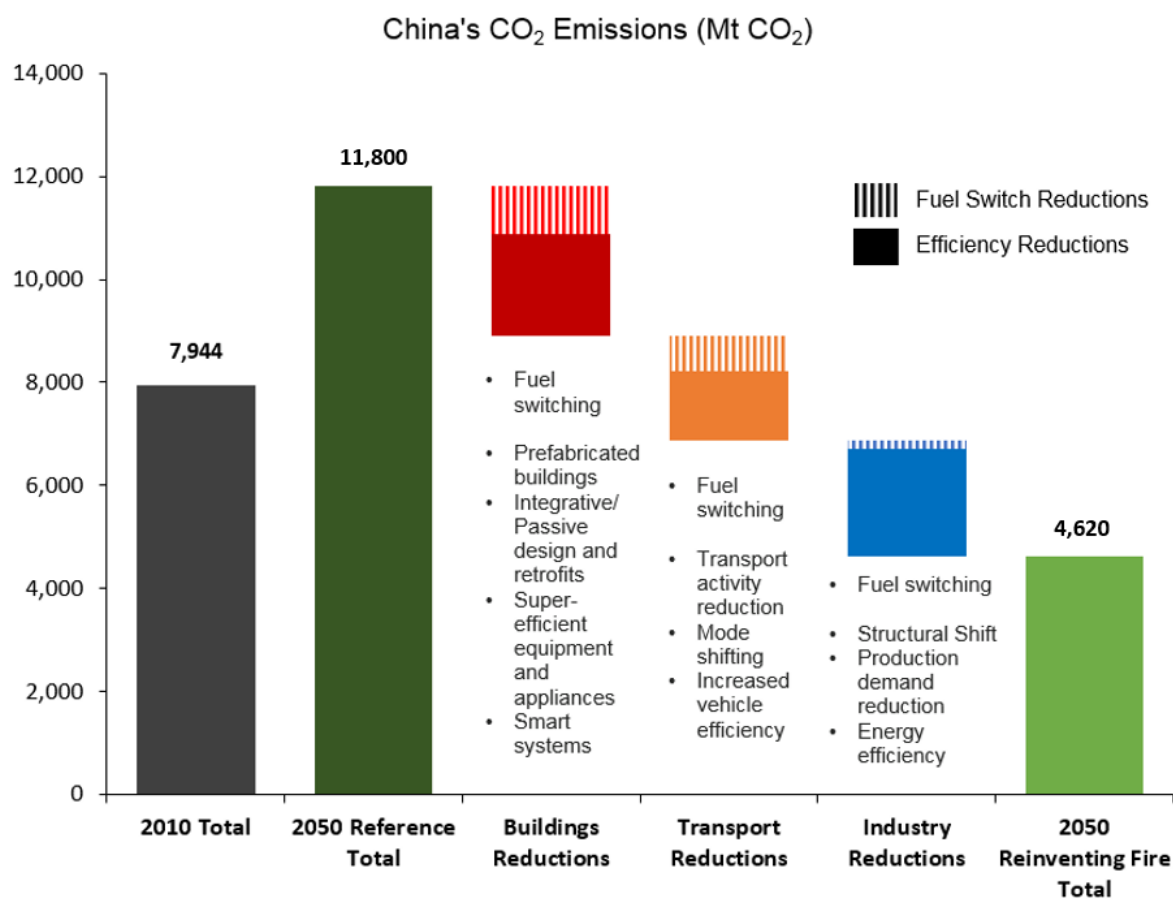


Figure 3. 2050 CO₂ Emissions Reduction Potential by Sector and Type of Strategy. Note: transformation (including power) CO₂ reductions are allocated to end-use sectors.

or indirectly (e.g., prefabricated buildings and smart systems) while the last strategy is focused solely on promoting switching to technologies that utilize cleaner fuels. In addition, we identify barriers that make full implementation of these strategies challenging.

1. Prefabricated Buildings and Other Advanced Construction Practices.

Under this strategy, better materials and construction methods help extend the lifetime of new buildings which result in 13 % less new building floor area in 2050 under the Reinventing Fire Scenario compared to the Reference Scenario. In addition, new buildings can also be constructed for durability and adaptability through prefabrication, which can dramatically reduce waste and on-site construction time and improve quality and durability. Higher quality assurance also ensures greater building thermal integrity and better energy performance.

Barriers to the achievement of these strategies include practices by cities to demolish existing buildings before the end of their useful lives for economic stimulation and rapidly constructing buildings with low-quality materials that leads to structural and other issues earlier than the international standard and results in demolition.

2. Integrative/Passive Design and Retrofits to Reduce Building Energy Demand

Passively designed buildings and those following an integrative design process incorporate whole-systems thinking have substantially lower loads than conventional buildings. This is achieved through energy-saving passive strategies, such as envelope insulation, high-performance windows, infiltration control, natural ventilation, and daylighting. Minimizing building loads leads to simpler, smaller, and less expensive systems for heating, cooling, and lighting. The increased adoption of integrative design and passive design for new and existing commercial and residential buildings helps significantly lower heating and cooling loads. At the same time, mainstream implementation of energy-saving retrofits to existing buildings can also improve building operation, decrease operating cost, and improve occupant comfort. Deep energy retrofits, which reduce energy use by 30 % or more, often are achieved cost-effectively by following an integrative design process and bundling efficiency upgrades with planned capital improvements.

Barriers to realizing these strategies include distorted energy price and tariff structures, lack of information and awareness, non-supportive codes (e.g., prescriptive codes instead of codes based on whole-building energy use), lack of skilled work force, and upfront capital costs.

3. Installation of Super-efficient Equipment and Appliances

The Reinventing Fire Scenario incorporates aggressive adoption of today's global best-in-class technologies through the installation of super-efficient equipment and appliances in new and existing buildings. The Reinventing Fire Scenario assumes 100 % market penetration of super-efficient equipment and appliances across all building end-uses by 2050, compared to penetration of only 40 % by 2050 under the Reference Scenario.

Barriers to these strategies include limited financial benefits due to averaged tariff structures, upfront capital costs, and lack of awareness and comprehensive compliance information.

4. Utilization of Smart Systems

Smart system technologies for buildings include sensors, controls, data access, and analytics for performing fault detection and diagnosis, and optimizing operation across systems for improved efficiency, reliability, and maintainability. Utilizing smart systems also enables retrofit service providers and others interested in reducing energy use to target the buildings with greatest opportunity for efficiency improvement, and enables the tracking of national building energy use intensity.

Barriers to realizing these strategies include additional training requirements for installation, inexperienced users operating technologies, and limited financial benefits due to rate structure that do not support efficient end-uses.

5. Switching to Clean Energy Technologies

Under the Reinventing Fire Scenario, carbon savings by switching to cleaner energy sources can also be achieved for buildings through switching on-site equipment to cleaner energy sources, installing rooftop solar photovoltaic systems, purchasing electric power generated from low-polluting fuels, and utilizing waste heat as an energy source (where possible). Switching to clean site energy sources nearly eliminates coal boilers and coal stoves in northern climates and significantly reduces their use in transition climates. This includes the use of cleaner district heating in the north and increased use of electric heating, particularly air-source and ground-source heat pumps, in both the north and transition zones.

Barriers to the achievement of these strategies include non-supportive policies for self-generation and renewable resource integration, upfront capital costs, and distorted tariff and energy prices.

TRANSPORT

China's transportation sector consumed 9 % of total primary energy in 2010 (360 Mtce⁵) and this share is expected to increase in the future. Freight demand will continue to grow with increasing economic output, while urbanization and rising middle class incomes will create more rapid growth for urban and intercity passenger transportation. The transportation sector relies almost entirely on oil (87 % of 2010 primary energy supply) and transportation contributed 65 % of 2010 Chinese oil consumption. Under the Reinventing Fire Scenario, China's transportation systems in 2050 will provide increased mobility but more efficiently and with fewer emissions and lower costs through four key strategies. The first three strategies of transport activity reduction, mode shifting and increased vehicle efficiency focus on improving transport energy efficiency while the last strategy focuses on fuel switching to lower CO₂-emitting fuels.

1. Transport Activity Reduction

Lower demand for both passenger and freight transport activity can be achieved through economic structural shift that reduces freight transport demand, improved layout of cities and

5. The reported statistics for transportation energy consumption in 2010 is 260 Mtce, which is lower than the value used in our analysis because of Chinese statistics accounting conventions that include fuel use at the end-use sector (e.g., industrial vehicles' fuel use are considered industry instead of transport). Our estimate includes adjustments to include all transport-related energy consumption. More information on the transport sector statistical adjustments can be found in Fridley et al. 2007.

industry to reduce transport distance, and advanced logistics and telecommuting/teleconferencing to reduce demand for freight and urban transport.

Barriers to reducing transport activity include limited coordination between national, provincial and municipal transport planning authorities, as well as poor economies of scale in logistics and trucking firms, which limit the adoption of modern logistics practices and IT systems.

2. Mode Shifting

Encouraging the shift from high energy intensity modes to lower energy intensity modes can help reduce motorized transport energy consumption. For example, in passenger transport high speed rail, urban public transport and non-motorized transport can all displace private auto use. Similarly, in freight transport, rail and water can displace truck transport and, in some cases, trucks can substitute for air transport.

Barriers to successful transport mode shifting include extreme capacity shortage for freight rail, poor planning of multimodal logistics hubs, and limited high-speed rail convenience and user experience in China.

3. Increased Vehicle Efficiency

Adopting technology and design improvements can help increase vehicle energy efficiency across all transport modes, particularly in motorized vehicles. Key technology improvements include improved aerodynamics, reduced rolling resistance in tires, hybrid drivetrains, improved engine thermal efficiency, and more efficient transmissions.

Barriers to significantly increasing vehicle efficiency include weight-based standards that do not incentivize light-weighting, pervasive overloading and low-quality fuel use in freight vehicles, and no access to capital for trucking firms.

4. Fuel Switching

Reliance on oil products for transport as well as transport CO₂ emissions can be reduced through fuel switching to electricity for passenger motor vehicles, rail, and some light-duty trucks operating in urban environments, to natural gas and biofuels for heavy duty trucks.

Barriers to fuel switching in the transport sector include regional EV protectionism that leads to lower quality vehicles and insufficient access to charging. Lack of sufficient natural gas distribution infrastructure and an insufficient supply of bio-fuels are barriers to fuel switching for trucks.

INDUSTRY

Industry is the dominant sector in the Chinese economy, contributing roughly 45 % of overall national GDP since the late 1970s. China is now the world leader in output for most industrial products. This is driven by high demand for energy-intensive raw materials and products to meet the needs of rapid urbanization and the associated increase in domestic commodity consumption along with increased exports. While China's industrial energy efficiency improved over the past decade, the energy intensity of China's major industrial subsectors lags behind international levels. As a result, China's industrial sector consumes more than 66 % of national primary energy (NBS, 2016). Under the Reference Scenario,

industrial primary energy use grows from 2,236 Mtce⁶ in 2010 to 2,400 Mtce in 2050.

In the Reinventing Fire Scenario, four strategies of structural shift, production demand reduction, energy efficiency improvement, and fuel switching are identified for helping reduce the industrial sector's total energy use and energy-related CO₂ emissions through 2050.

1. Structural Shift to the Service Sector and Higher Value Added Industries

Structural shift is reflected in changes in the balance of high value added, less energy-intensive industries and low value added, high energy-intensive industries in China in the Reinventing Fire Scenario relative to the Reference Scenario.

Barriers to enabling successful structural shift in industry include concerns with unemployment, continued domestic demand for energy-intensive products, stranded assets of new energy-intensive plants, and lack of domestic market development for high value added products.

2. Production Demand Reduction

Changing production and construction techniques so that products last longer and require less thereby reducing demand for manufacturing certain materials in China is embodied in the Reinventing Fire Scenario. Reducing the need for manufacturing of primary materials by using more recycled materials in industries such as aluminium, steel and paper industries also helps reduce industrial production demand. In addition, reducing unnecessary exports of low value added energy intensive products also helps reduce industrial production demand.

Barriers to reducing demand for industrial production include a lack of standards and enforcement for high-quality and low-material intensity products, continued rapid urbanization with short building lifetime and low-quality materials, and a lack of comprehensive and integrated waste planning and management systems.

3. Energy Efficiency Improvement

Reductions in the energy required per unit of production for all industrial subsectors are achieved through energy efficiency, system optimization, and integrative design. Under the Reinventing Fire Scenario, all industries also achieve current international best practice energy intensities much earlier than under the Reference Scenario.

Barriers to industrial energy efficiency improvement are the lack of financial resources and information and knowledge, especially in small and medium enterprises, the lack of top management commitment/understanding/vision, the lack of enforcement of government regulations, and the lack of coordination between different government agencies.

6. The reported statistics for industrial energy consumption in 2010 is 2,423 Mtce, which is higher than the value used in our analysis because of Chinese statistics accounting conventions that included diesel consumption by industrial vehicles in industry instead of transport. Our estimate includes adjustments to include all industry-related energy consumption. More information on the industrial sector statistical adjustments can be found in Fridley et al. 2007.

4. Fuel-switching to Lower-CO₂-emitting Fuels and Electrification

Increased utilization of lower CO₂-emitting fuels, increased electrification and on-site electricity generation, and heat recovery all help reduce the CO₂ emissions related to industrial energy consumption.

Barriers to promoting fuel switching and electrification in industry include regional unemployment concerns and a lack of domestic sources of cleaner fuels such as natural gas.

Sectoral energy and CO₂ results

BUILDINGS

Under the Reinventing Fire Scenario, 2050 primary energy consumption for residential and commercial buildings total 1,000 Mtce, a savings of 56 % compared to the Reference Scenario 2050 total. Primary energy peaks in 2031 at 1,370 Mtce and decreases thereafter. In terms of energy-related CO₂ emissions, buildings' annual CO₂ emissions grow from 1,880 MtCO₂ in 2010 to 3,900 in 2050 under the Reference Scenario. Under the Reinventing Fire Scenario, the five pathways of prefabricated buildings, integrative/passive design and retrofits, super-efficient equipment and appliances, smart systems and switch to clean energy technologies together reduce 2050 CO₂ emissions by 2,880 MtCO₂ (74 %) compared to the Reference Scenario when including related savings in the materials industry and transformation sectors.

The largest CO₂ emissions reductions in the buildings sectors come from key energy efficiency related strategies of integrative/passive design (690 MtCO₂) and super-efficient equipment/appliances (670 MtCO₂), building retrofits (270 MtCO₂) and smart systems (245 MtCO₂). As with primary energy savings, integrative/passive design and super-efficient equipment/appliances are the largest CO₂ emissions reduction opportunities, with 47 % of the overall reduction potential. Prefabrication accounts for 100 MtCO₂ reduction in the buildings sector with additional 130 Mt CO₂ reduction in the industrial sector when less construction material waste is included. Clean energy sources for on-site end-use equipment (600 MtCO₂) and clean energy sources for power generation (315 MtCO₂) together account for nearly one-third of the total emissions reductions. Fuel switching also has a relatively large impact on CO₂ emissions reductions in the buildings sector because of the combined effects of increased electrification with significant decarbonization of the power sector.

TRANSPORTATION

Under the Reinventing Fire Scenario, by 2050 oil's share of primary energy supply for transportation is reduced to 45 %, compared to 73 % in the Reference Scenario. The Reinventing Fire Scenario reduces congestion and creates equitable access to transportation services without sacrificing cost, convenience, or reliability. Applying the four strategies of activity reduction, mode shifting, vehicle efficiency improvement, and fuel switching reduce 2050 transportation CO₂ emissions by nearly 2,040 MtCO₂, contributing to a 61 % reduction in overall carbon emissions under the Reinventing Fire Scenario, compared to the Reference Scenario.

Activity reduction has the largest share of transport CO₂ emissions reductions under the Reinventing Fire Scenario with annual reduction of 700 Mt CO₂ (34 %). Decarbonization of the

power sector contributes 450 Mt CO₂ (22 %) in 2050 because of the high degree of electrification in the road and rail transport sectors, while fuel switching to natural gas and biofuels contributes an additional 240 Mt CO₂ (12 %). Mode shifting and vehicle efficiency improvements also contribute 350 Mt CO₂ (17 %) and 300 Mt CO₂ (15 %), respectively, in 2050.

For the transport sector, fuel switching has a larger impact on CO₂ emissions reductions and accounts for about one-third of the 2050 emissions reductions under Reinventing Fire Scenario because of the combined effects of increased electrification with significant decarbonization of the power sector.

INDUSTRY

In the Reinventing Fire Scenario, China's industrial sector undergoes a dramatic transformation with the sector peaking its energy use and CO₂ emissions before the transportation and buildings sectors. Under the Reinventing Fire Scenario, the industrial sector grows by 55 trillion RMB (a five-fold increase relative to 2010), mainly through high value-added subsectors. Primary industrial energy consumption is 990 Mtce (30 %) less than the Reference Scenario in 2030 and 840 Mtce (35 %) less in 2050, a 30 % absolute reduction in 2050 relative to 2010 levels. The 2050 energy savings are greater than the energy consumption of the entire U.S. industrial sector in 2012.

The reductions in CO₂ emissions are also significant, with 48 % lower industrial CO₂ emissions in 2050 under the Reinventing Fire Scenario when compared to the Reference Scenario. By 2050, industrial CO₂ emissions total 2,150 MtCO₂ under the Reinventing Fire Scenario, a 58 % reduction from the 2010 level.

The largest contributions of industrial CO₂ emissions reductions are from energy efficiency improvement with 54 % share (or 1,080 MtCO₂) of the total reduction in 2050, followed by structural shift with 25 % (500 MtCO₂), and production demand reduction with 13 % (260 MtCO₂). Together, the three energy efficiency-related strategies contributed 92 % of the CO₂ emissions reductions while fuel switching and decarbonization have the smallest contribution to industrial CO₂ emissions reductions, with only 8 % share in 2050.

Figure 4 summarizes the 2050 annual CO₂ emissions reduction by each sector and each sectoral strategy under the Reinventing Fire Scenario when compared to the Reference Scenario. The solid colors represent the emissions reductions from energy efficiency improvement strategies while the dashed colors represent the emissions reductions from fuel switching strategies.

Conclusions and policy implications

The scenario analysis from this study demonstrates that China can meet its domestic and international energy and CO₂-related targets and commitments by fully deploying energy-efficient technologies and renewable supply options that are cost-effective today. Energy demand reduction strategies across the building, industry and transportation sectors – including many focused on improving energy-efficiency – can support a significantly larger Chinese economy that uses about the same amount of energy in 2050 as in 2010 when primary electricity is calculated based on the IPCC direct equivalent method. Combined with continuous decarbonization of the power sector and fuel-switching in the demand sectors, China's reduced energy demand allows it to dramatically increase its non-fossil share of primary energy

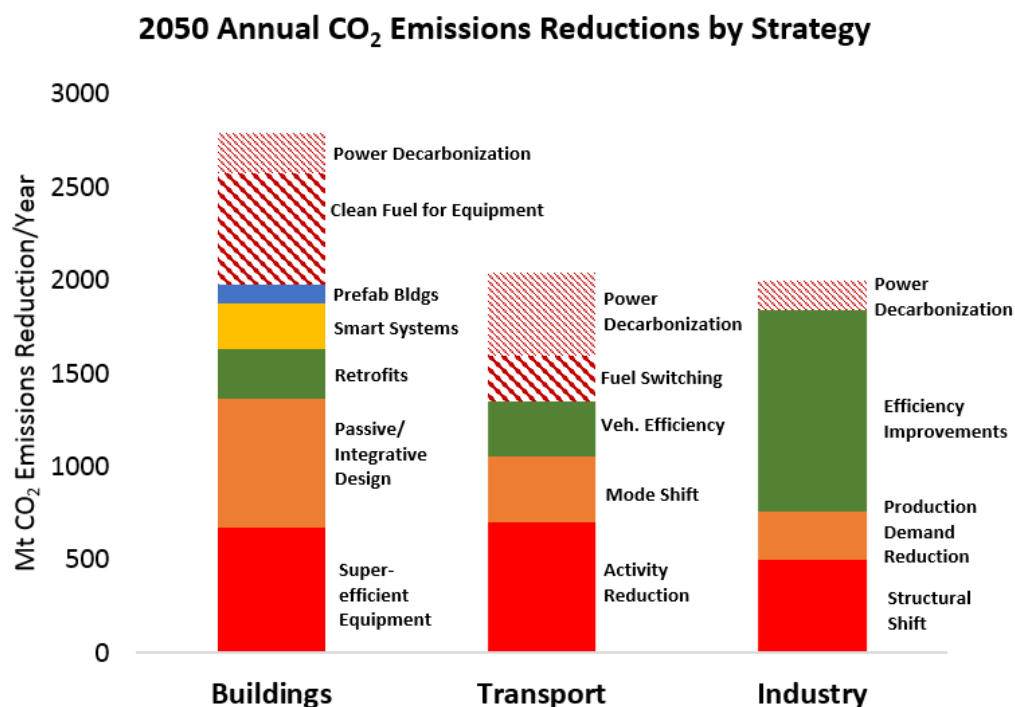


Figure 4. Comparison of 2050 Annual CO₂ Emissions Reductions Potential by Detailed Sectoral Strategies.

by 2050. As a result of the combined shifts in energy demand and energy supply, China's CO₂ emissions can both peak earlier in 2025 and with 34 % less CO₂ emissions under the Reinventing Fire Scenario when compared to the 2036 CO₂ peak under the Reference Scenario. Energy efficiency strategies that reduce energy demand contribute the majority of the CO₂ emissions reduction in 2050 across all demand sectors.

Achieving the energy and CO₂ reductions under the Reinventing Fire Scenario will require overcoming a multitude of barriers that exist in the building, industry and transportation sectors for the full deployment of the energy efficiency and fuel switching strategies and will require the sustained and targeted support of China's government, enterprises, and society at large, including with policies that target common actionable approaches, including:

- Aligning government policies and business interests to the strategic goals embodied by the Reinventing Fire strategies
- Prioritizing demand reduction and energy efficiency as critical drivers that make the energy transformation affordable
- Promoting electrification and reforming the electricity sector to support clean and low-carbon supply options
- Spurring technological innovation and integrative design to minimize investment in smart and shared infrastructure
- Driving institutional and structural reforms that promote new industries, technologies, and business models as driving forces of productivity improvement

Assuming successful barrier removal and implementation of the strategies outlined in the Reinventing Fire Scenario, China can achieve aggressive, cost-effective energy savings and CO₂ emissions reductions with energy efficiency strate-

gies playing a central role in China's future buildings, industry and transport sectors.

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