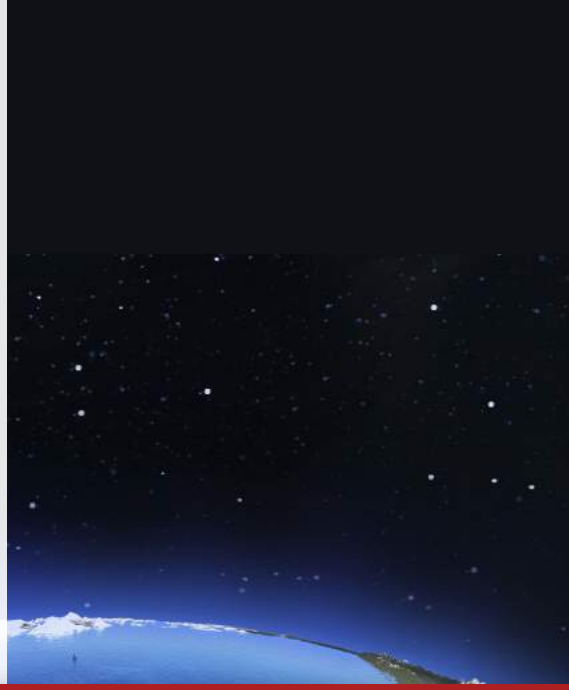
REINVENTING FIRE: CHINA

A ROADMAP FOR CHINA'S REVOLUTION IN ENERGY CONSUMPTION AND PRODUCTION TO 2050



重塑能源：中国

面向2050年能源消费和生产革命路线图研究

EXECUTIVE SUMMARY

SEPTEMBER 2016

ENERGY RESEARCH INSTITUTE OF THE NATIONAL DEVELOPMENT AND REFORM COMMISSION

LAWRENCE BERKELEY NATIONAL LABORATORY

ROCKY MOUNTAIN INSTITUTE

ENERGY FOUNDATION CHINA

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ENERGY RESEARCH INSTITUTE

Energy Research Institute (ERI) of the National Development and Reform Commission (NDRC) was established in 1980. The main obligation of ERI is to provide scientific and technological advice to the Chinese government, as well as private sector clients, on issues related to strategy, planning, policy, law and standards for energy development. The scope of research conducted by ERI covers all fields of energy production, distribution and consumption. The main focus is on policy research in the fields of energy economy and strategy, energy efficiency, energy environment and climate change, and renewable energy.

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Energy Foundation China, established in 1999, is a grantmaking philanthropic organization dedicated to China's sustainable energy development. It is registered under the Ministry of Civil Affairs as Energy Foundation Beijing Representation office and supervised by the National Development and Reform Commission of China. It is part of the Energy Foundation, which is based in San Francisco, California, U.S.

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LAWRENCE BERKELEY NATIONAL LABORATORY

Lynn Price, David Fridley, Ali Hasanbeigi, Nina Khanna, Hongyou Lu, Feng Wei, and Nan Zhou with additional support from Gang He, Lixuan Hong, Jing Ke, Xu (Angela) Liu, and Bo Shen.

ROCKY MOUNTAIN INSTITUTE

Jon Creyts, Josh Agenbroad, Michael Bendewald, Brett Bridgeland, Kate Chrisman, Kendall Ernst, Ellen Franconi, Claire Henly, Yi Ke, Ruosida Lin, Robert McIntosh, David Mullaney, Clay Stranger, Eric Wanless, Daniel Wetzel, and Cyril Yee with additional support from Evan Bouchier, Kitty Bu, Maiyue Cheng, Yifan Jia, Becky Li, Ting Li, Sha Liu, Amory Lovins, Darrin Magee, Zihe Meng, Meiling Shi, Jiayin Song, Kerui Zhou, and Zeqi (Zach) Zhu.

The authors would also like to acknowledge the contributions of Max Dupuy and Frederick Weston from The Regulatory Assistance Project.

Recommended Citation: Energy Research Institute, Lawrence Berkeley National Laboratory, and Rocky Mountain Institute, 2016, *Reinventing Fire: China – A Roadmap for China's Revolution in Energy Consumption and Production to 2050, Executive Summary.*

ABOUT THIS REPORT

In 2011 Rocky Mountain Institute (RMI) published *Reinventing Fire: Bold Business Solutions For the New Energy Era*, a synthesis of 34 years of RMI's experience on how the U.S. could profitably transition off of coal and oil by 2050. At that time, decades of work was underway by Energy Research Institute (ERI) and the China Energy Group of Lawrence Berkeley National Laboratory (LBNL) to model and understand China's potential for aggressive energy efficiency and renewable energy deployment.

In 2013 these three organizations joined forces. Together they created a common fact base for how China could use energy efficiency and renewable energy to meet the growing demand of its population for a clean, low-carbon, efficient, safe, reliable, and cost-effective modern energy system. This Summary report contains the most important insights from three years of research jointly conducted by these institutions.

Energy Foundation China supported the work by contributing both guidance and funding to the initiative. Support also came from an additional 36 foundations and individuals who gave directed funds for the research freely and without condition, in addition to general supporting funds from RMI's contributors. The Chinese government gave in kind to the research through the direct contribution of resources, analysis, and support.

It was the intent of the authors to ensure that the fact base was legitimately constructed using the best available public knowledge and data. The team went to great lengths to ensure all data were verified and that analytical methods were sound. Any errors or omissions contained herein are the sole responsibility of the authors and not the organizations to which they belong.

The authors wish to thank the many experts, donors, and contributors who have generously supported the success of this initiative. A special thanks goes to the Advisory Panel members and international expert reviewers who guided and substantially improved this research.

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INTRODUCTION

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INTRODUCTION

AFTER DECADES of rapid economic growth fueled primarily by fossil fuels, in June 2014 Chinese President Xi Jinping called for "a revolution in the production and consumption of energy." In November 2014, President Xi strengthened that call, setting a national goal to peak carbon dioxide (CO_2) emissions around 2030, making best efforts to peak early and increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030. In June 2015, China further committed to these goals and announced an additional goal of lowering CO_2 emissions per unit of gross domestic product (GDP) by 60–65% by 2030 from the 2005 level. In December 2015, China made an international commitment to the realization of these goals in support of the Paris Agreement's aim to keep average global temperature increase to between 1.5°C and 2°C and to realize a peak in global greenhouse gas (GHG) emissions as soon as possible.

Achieving China's domestic and internationally pledged goals requires a significant departure from the country's historical patterns of energy consumption and supply. *Reinventing Fire: China* answers President Xi's call with an energy roadmap that delivers cost-effective savings while achieving significantly improved environmental and energy security outcomes.

THE CHALLENGE

During the period 1980–2012, China's primary energy consumption grew over six times (6% average annual growth). By comparison, the world's primary energy consumption grew 1.8 times (2% average annual growth) over the same period. Despite China's rapid growth, its energy system remains relatively inefficient. While China consumed 22% of the world's primary energy in 2012, it created just 9% (market exchange rate) or 16% (purchasing power parity, PPP) of the world's GDP, with energy use per unit of GDP four to six times higher than in developed countries.

Endowed with vast coal resources, China has long depended on carbon-intensive development. While many developed countries are transitioning from an era of coal, oil, and gas to one fueled by renewable energy, and despite significant investment in renewable energy capacity in China, China's energy mix remains dominated by coal. China's past development pathway—one that expedited China's growth, grew its economy, urbanized the country, and pulled millions of people out of poverty—no longer supports its desire to achieve its two 100-year economic goals,[i] its vision of a Beautiful China, and its domestic and internationally-pledged GHG emission reduction goals.

Addressing environmental challenges and climate change requires a change in China's heavily fossil-fuel-based energy system. Nationwide, 30% of urban residents breathe air that does not meet air quality standards. Three hundred million rural residents lack access to clean water and 90 million urban residents drink water that fails to meet China's own standards. Currently, 25 of China's provinces experience some degree of smog or air pollution, affecting over 600 million people, with some cities having up to 200 days annually of smoggy skies. High concentrations of particulate matter (PM) harm respiratory and cardiovascular systems and threaten public health. Acid rain is serious in many cities as well. In some areas, emissions of heavy metals and persistent organic pollutants (POPs) are severe.

The world is entering a critical stage to address climate change and many countries are already taking action. In 2010, Germany proposed to decrease its primary energy consumption 50% by 2050 compared to 1990 and expand its renewable energy share to 60%.[1] In 2011, the European Commission published a roadmap to improve energy efficiency by 20%, increase the share of renewable energy to 20%, and reduce primary energy consumption 20% by 2020 compared to 1990.[2] In 2011, Denmark proposed to establish a fully fossil-fuels-free and nuclear-free energy system.[3] In the November 2014 *U.S.-China Climate Change Joint Announcement* and in its subsequent March 2015 Intended Nationally Determined Commitment submission, the United States proposed to cut net GHG emissions 26–28% below 2005 levels by 2025.[4,5] Running up to the Paris Agreement in December 2015, nearly 200 countries submitted their Intended Nationally Determined Commitments which outlined their 2025 or 2030 GHG emissions reduction goals and actions. In April 2016, 175 countries signed the Paris Agreement, further committing to reaching their GHG mitigation goals.

According to the Intergovernmental Panel on Climate Change's (IPCC's) *Fifth Assessment Report*, to limit the average rise in the earth's atmosphere to 2°C above pre-industrial levels, world GHG emissions must peak between 2010 and 2020 and 2050 emissions should be 41–72% below 2010 levels. China is the world's largest CO_2-emitting country; its total emissions will soon approach the combined emissions of the United States and the European Union. As the main contributor to incremental global CO_2 emissions, China intends to control its GHG emissions and take on more international responsibility. Since 90% of sulfur dioxide (SO_2) emissions, 67% of nitrogen oxides (NO_x) emissions, 70% of dust emissions, and 40% of atmospheric mercury come from human sources and 70% of CO_2 emissions come from coal combustion, an energy development model that relies largely on fossil fuels—especially coal—not only damages the environment, but also risks substantial loss to social and economic development.

China's path forward—one that aims to urbanize 300 million people, grow its economy, and substantially advance the welfare of all citizens—cannot follow the same patterns as the past 30 years. China's development over the past several decades has been characterized by high-input, high-consumption, high-pollution, high-speed, low-output, low-efficiency, and low-technology activities. This model is proving inadequate to realize the country's top goals, requiring China to forge a new path forward, setting an example for how other middle-income countries can modernize in the process. The new path will require exploring alternative means of energy consumption and production, fostering new incentives for modern development, engaging market forces, and accelerating the restructuring of China's energy system.

[i] The two 100-year goals refer to the doubling of China's GDP from 2010 to the hundredth anniversary of the Communist Party of China in 2021 and the attainment of the status of a "moderately developed country" by the hundredth anniversary of the founding of the People's Republic of China in 2049.

THE REINVENTING FIRE APPROACH

Reinventing Fire: China is a rigorous analysis that provides an innovative energy roadmap to 2050 in which China meets its energy needs and improves its energy security and environmental quality using the maximum feasible share of cost-effective energy efficiency and renewable energy supply.

Reinventing Fire: China uses a conservative approach:

- The analysis includes only commercially available, cost-effective technologies and autonomous technological improvements (future breakthroughs in technology are not included in the analysis),
- CO_2 emissions are not explicitly priced (despite China's pilot carbon emission trading schemes and commitment to commence a national trading scheme during the 13th Five-Year Plan period), and
- External economic benefits such as public health and environmental quality are not included in cost calculations.

Reinventing Fire: China analyzes two distinct pathways:

- **Reference Scenario:** only policies in place in 2010 continue to have effect and autonomous technological improvement occurs.
- **Reinventing Fire Scenario:** the maximum feasible shares of commercially available, cost-effective energy efficiency and renewable energy supply are adopted.

The resulting analysis provides pathways for four major economic sectors—industry, buildings, transportation, and transformation (the process of creating energy inputs to the economy, where the focus is primarily on electricity)—to reach a more energy-efficient and low-carbon future.

During the three years of research for this project, the Chinese landscape shifted. Prices for installed photovoltaic solar modules and lithium-ion battery packs dropped roughly 31%[6] and 40%,[7] respectively, between the first quarters of 2012 and 2015. China became more dependent on foreign oil and natural gas. The U.S. and China committed to ambitious GHG emissions reduction targets. Economic growth slowed and China lowered its GDP targets, prompting the analysis team to revisit the data and assumptions used in the following report. This analysis contains the most recent data and analysis available.

Despite slowing economic growth, President Xi's commitment to an energy revolution grew stronger as China vowed to build an "ecological civilization." The 13th Five-Year Plan introduces many of the concepts needed for such a revolution. These changes reinforce the need for the Reinventing Fire pathway and the actions outlined in this report.

The *Reinventing Fire: China* approach incorporates a four-step methodology:
1) Reduce demand,
2) Meet demand as efficiently as possible,
3) Electrify demand where practical, and
4) Shift to renewable or lower-carbon energy sources.

The study embraces whole-system thinking to ensure that the full benefits of each step are realized. For instance, the Reinventing Fire strategy aggressively pursues cost-effective efficiency measures in buildings and industry. These efficiency improvements decrease China's coal consumption, creating additional rail capacity from what once transported coal. The additional rail capacity can be used to shift freight cargo from road to rail—displacing diesel, decreasing road wear and tear, and reducing cement demand, which saves yet more coal. Such considerations in our integrative approach create cycles of energy, emissions, and capital savings, which are tracked in our analysis.

Reinventing Fire: China is a detailed, bottom-up assessment of China's future energy demand based on primary demographic, economic, and technical drivers. The study leverages scientific models, incorporating over 75 real-world case studies to calibrate assumptions. Over 1,000 off-the-shelf measures to reduce energy and/or carbon were considered. A distinguished Advisory Panel consisting of 14 leading Chinese energy experts met with the team to provide guidance and recommendations 10 times over the duration of the analysis. Numerous additional Chinese experts in leading ministries, think tanks, associations, and universities provided input and scientific review. Prominent international experts also reviewed the results. The next section summarizes key findings.

02 KEY FINDINGS

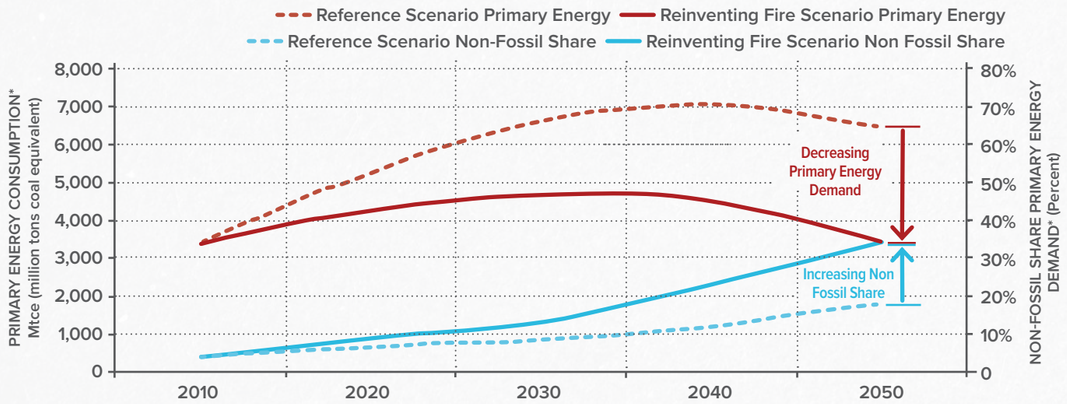
KEY FINDINGS

1

The Reinventing Fire pathway supports China's current growth plan accounting for GDP, population, and urbanization rates under the economic slowdown, or "new normal." Through first decreasing primary energy demand and then deploying increased shares of non-fossil energy supply to cover the remaining energy requirements, the Reinventing Fire Scenario supports China's desire to achieve 600% incremental GDP growth by 2050 with dramatically reduced environmental impacts.

FIGURE ES 1: PRIMARY ENERGY AND NON-FOSSIL SHARE TRENDS

2010 – 2050, REFERENCE AND REINVENTING FIRE SCENARIOS*



MODEL INPUT ASSUMPTIONS

	2010	2020	2030	2040	2050
GDP Trillion USD (2010 real)	6.0	12.0	20.7	31.0	41.4
Population Billions	1.34	1.42	1.44	1.42	1.37
Urbanization Rate Percent	50	60	68	74	78

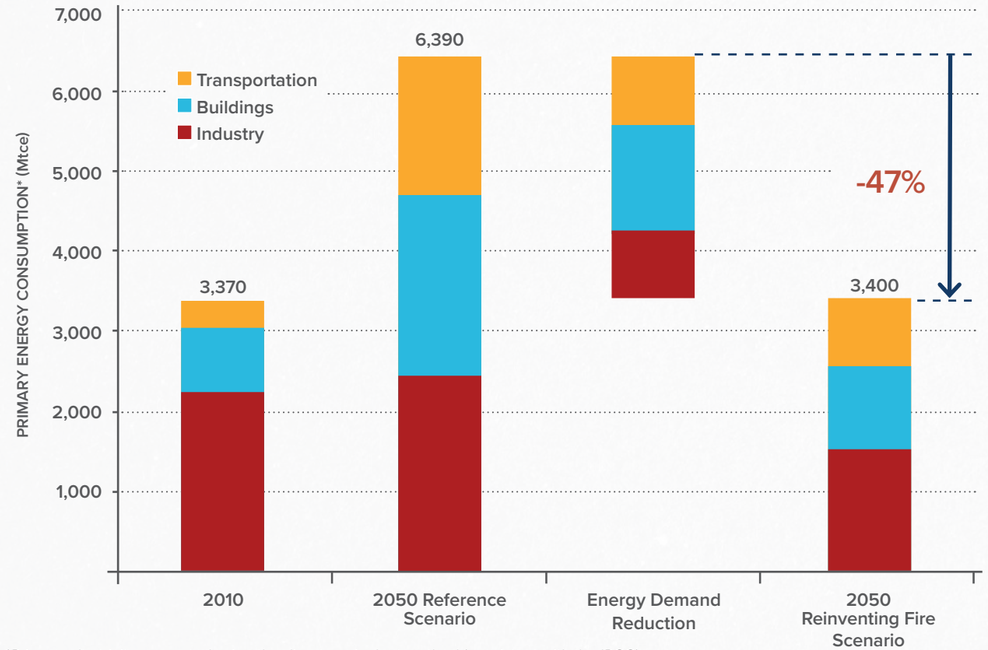
**Primary electricity converted using the direct equivalent method (consistent with the IPCC)*
Source: Energy Research Institute China General Equilibrium Economic Model, Reinventing Fire: China team analysis

2

Energy demand reduction strategies across the industry, building, and transportation sectors can support a significantly larger Chinese economy that uses about the same amount of energy in 2050 as in 2010. In the Reinventing Fire Scenario, China's primary energy demand in 2050 is within 1% of the country's primary energy demand in 2010. When compared to the Reference Scenario, China's 2050 primary energy requirements are 47% lower yet still deliver the energy required to fuel China's desired growth.

FIGURE ES 2: PRIMARY ENERGY DEMAND REDUCTION

2010 AND 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



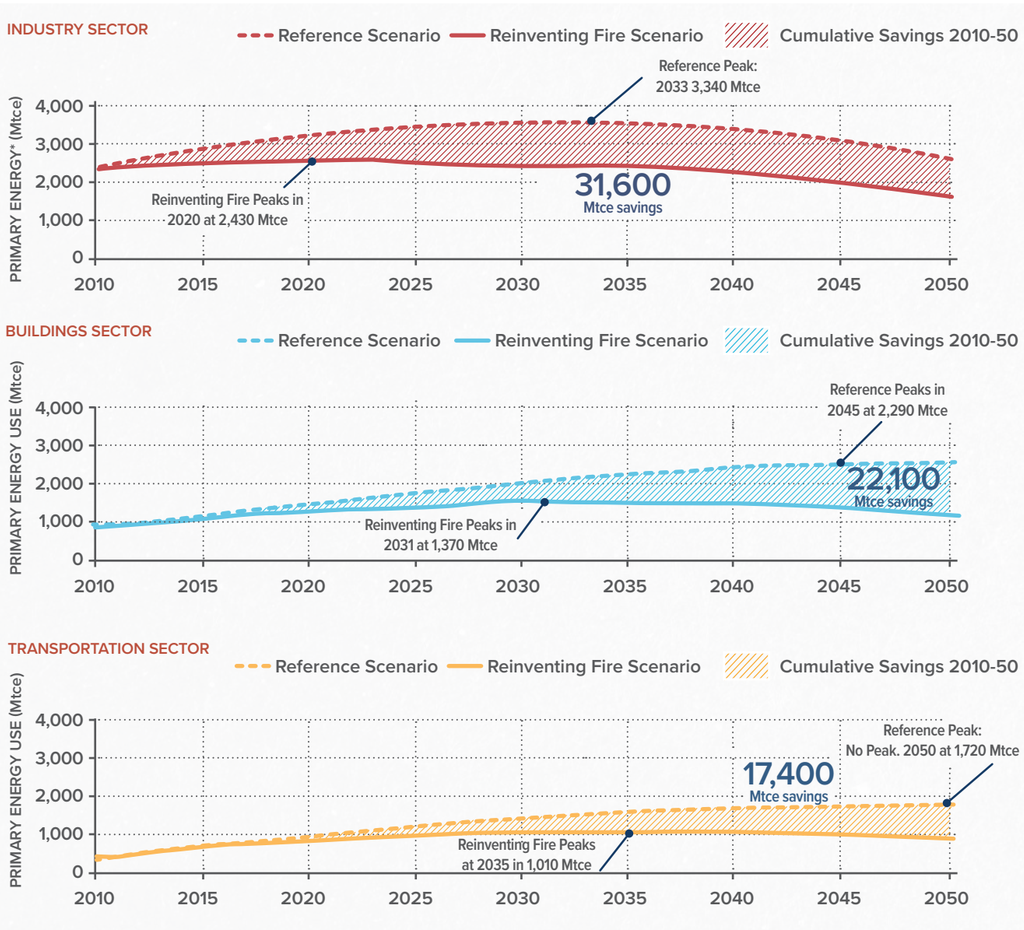
**Primary electricity converted using the direct equivalent method (consistent with the IPCC).*
Source: Reinventing Fire: China team analysis

3

Under the Reinventing Fire Scenario, primary energy consumption in China's industrial, building, and transportation sectors peaks sooner and lower than in the Reference Scenario, with the greatest cumulative energy savings in the industry sector. In the Reinventing Fire Scenario, primary energy consumption for the industry sector peaks in 2020, 13 years earlier than the Reference Scenario and at a level that is 27% lower. Building primary energy use peaks in 2045 in the Reference Scenario, and 2031 in the Reinventing Fire Scenario, 14 years earlier and 40% lower. Transportation primary energy use increases through 2050 in the Reference Scenario, but peaks in 2035 in the Reinventing Fire Scenario, 41% below the 2050 Reference Scenario value. The cumulative energy savings in each sector (the area between the two lines over the 40 years) is 31,600 million tons of coal equivalent (Mtce) for industry, 22,100 Mtce for buildings, and 17,400 Mtce for transportation.

FIGURE ES 3: SECTOR PRIMARY ENERGY PEAKING TRENDS

2010 – 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



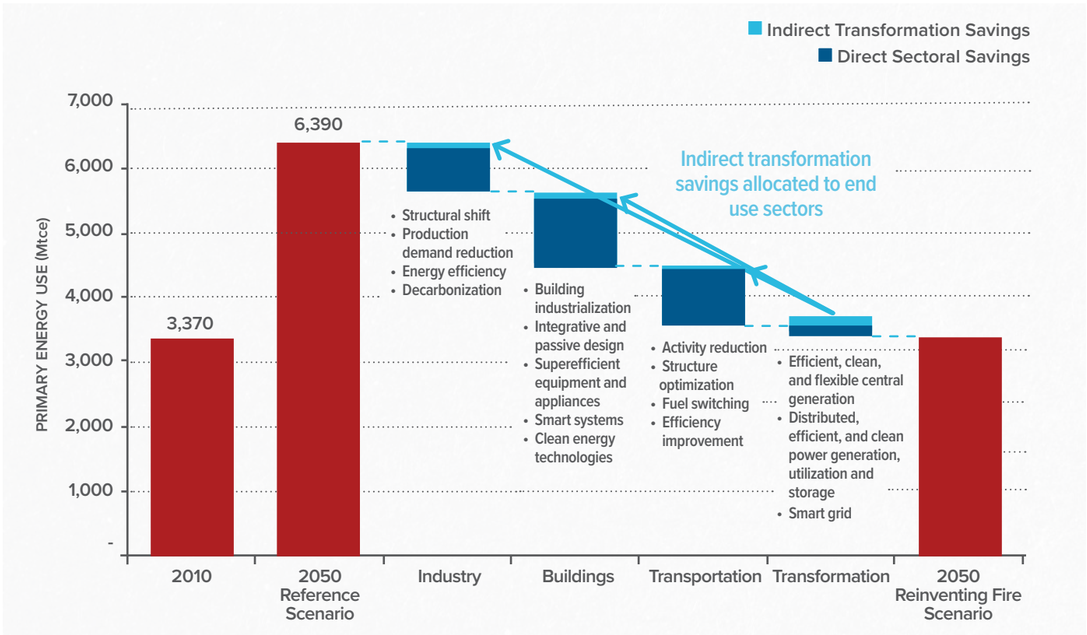
*Primary electricity converted using the direct equivalent method (consistent with the IPCC).
Source: Reinventing Fire: China team analysis.

4

Sector-level energy savings are captured by aggressively pursuing a range of existing and new economic demand reduction strategies. A snapshot of the 2050 reduction potential highlights the relative contributions of each sector and the key strategies that contribute to these reductions. While there are some direct and indirect energy reductions in the transformation sector from electricity and energy supply efficiency capture, 90% of the energy savings come from the industry, buildings, and transportation sectors. There is a shift in the relative composition of this savings potential over time. Through 2044, industry comprises the largest opportunity for energy savings (not pictured). By 2050, however, the largest savings potentials shift to the higher-growth buildings and transportation sectors.

FIGURE ES 4: SECTOR ENERGY SAVINGS CONTRIBUTIONS

2010 – 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



*Primary electricity converted using the direct equivalent method (consistent with the IPCC).
Source: Reinventing Fire: China team analysis

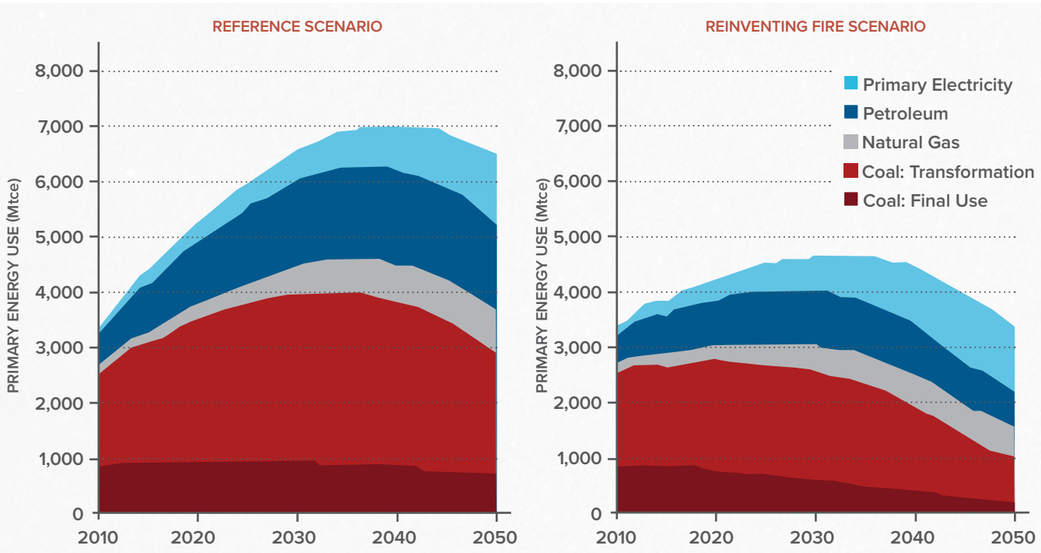
5

China's reduced energy demand allows it to dramatically increase its non-fossil share of primary energy by 2050. Demand reduction compresses both coal and petroleum consumption over time, reducing the fossil energy share from 82% in the Reference Scenario to 66% in the Reinventing Fire Scenario by 2050.* In 2050, petroleum and natural gas demand are 61% and 22% lower, respectively, in the Reinventing Fire Scenario than they are in Reference Scenario. In the Reinventing Fire Scenario, petroleum demand peaks in 2033 and natural gas demand peaks in 2045. Coal's share of primary energy in 2050 is 45% in the Reference Scenario and 30% in the Reinventing Fire Scenario, with the 2050 Reinventing Fire Scenario amount of coal consumed more than 60% below both the actual coal consumed in 2010 and the Reference Scenario 2050 value.

Using the IPPC conversion method for primary electricity sources to standard energy units, non-fossil, non-emitting resources provide 13% of China's energy demand in 2030 and 34% in 2050 under the Reinventing Fire Scenario, a significant increase over the 4% these resources provided in 2010. Using China's power plant coal consumption (PPCC) method for primary energy conversion, the non-fossil share in 2030 is 28% and in 2050 is 55%.[ii]

FIGURE ES 5: PRIMARY ENERGY FUEL MIX TRENDS*

2010 – 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



NON-FOSSIL SHARE OF PRIMARY ENERGY

	2010	2020	2030	2040	2050
IPCC	4%	7%	8%	12%	18%
PPCC	11%	17%	21%	28%	38%

	2010	2020	2030	2040	2050
IPCC	4%	9%	13%	23%	34%
PPCC	11%	21%	28%	42%	55%

ii For further information about the difference between the direct equivalent and China's power plant coal consumption (PPCC) methods of conversion, please see Lewis, J., Fridley, D., Price, L., Lu, H., and Romankiewicz, J., 2015. "Understanding China's Non-Fossil Energy Targets," Science Vol. 350, Issue 6264: 1034-1036.

**Primary electricity converted using the direct equivalent method (consistent with the IPCC)*

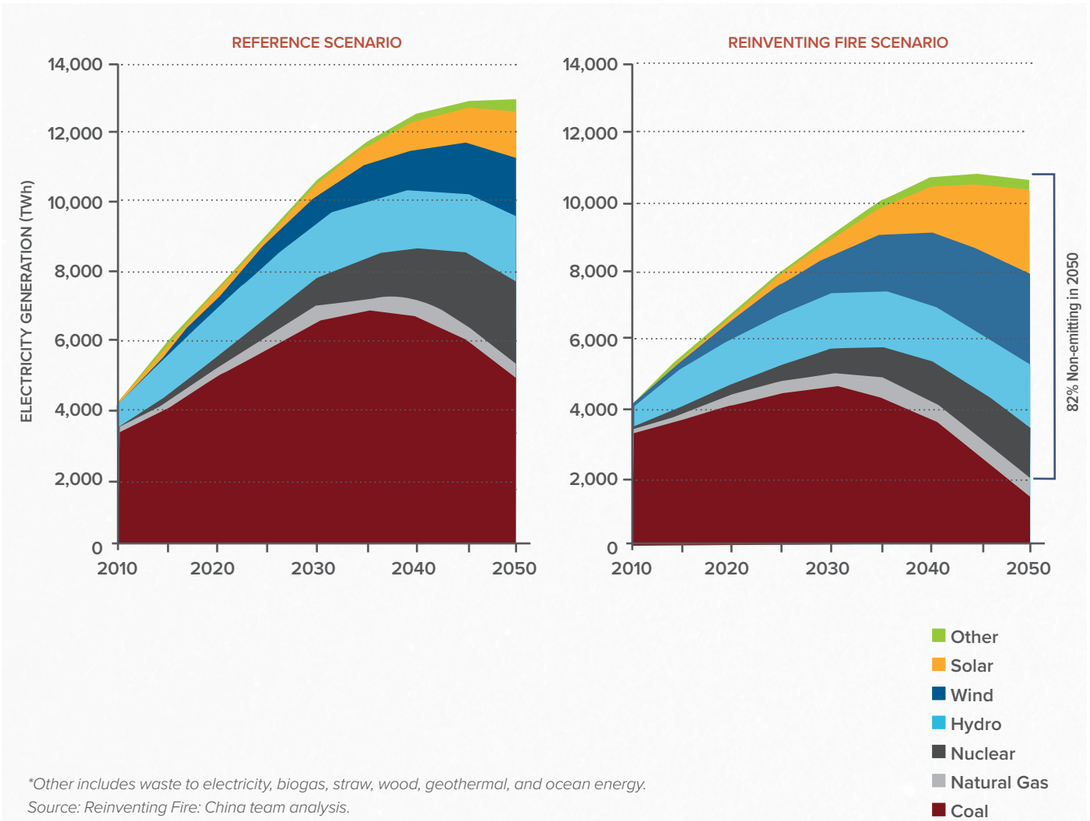
Source: Reinventing Fire: China team analysis

6

Non-fossil, non-emitting electricity sources contribute 82% of China's 2050 electricity needs. Renewable sources alone meet 68% of the demand on an absolute basis in 2050. Annual per capita electricity consumption grows to about 7,900 kWh by 2050 in the Reinventing Fire Scenario, roughly on par with Austria and Singapore today.

FIGURE ES 6: ELECTRICITY GENERATION TRENDS

2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



**Other includes waste to electricity, biogas, straw, wood, geothermal, and ocean energy.*

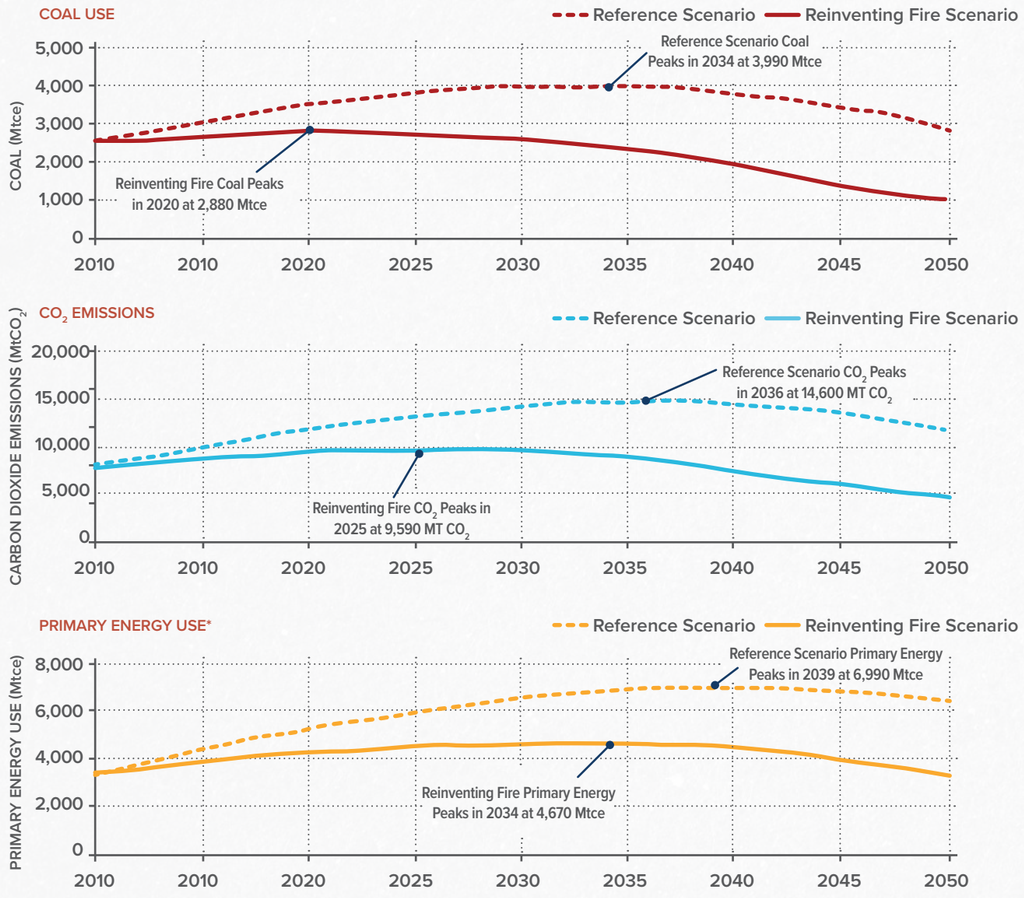
Source: Reinventing Fire: China team analysis.

7

China's coal demand, CO_2 emissions, and primary energy demand peak earlier and dramatically lower due to the combined shifts in energy demand and energy supply. The Reinventing Fire Scenario outlines a pathway for China to cost-effectively peak coal use 14 years earlier and 30% lower, CO_2 emissions 11 years earlier and 34% lower, and primary energy use five years earlier and 33% lower than the Reference Scenario.

FIGURE ES 7: CHINA'S THREE MAJOR ENERGY-RELATED TRENDS

COAL USE, CO_2 EMISSIONS, AND PRIMARY ENERGY USE, REFERENCE AND REINVENTING FIRE SCENARIOS



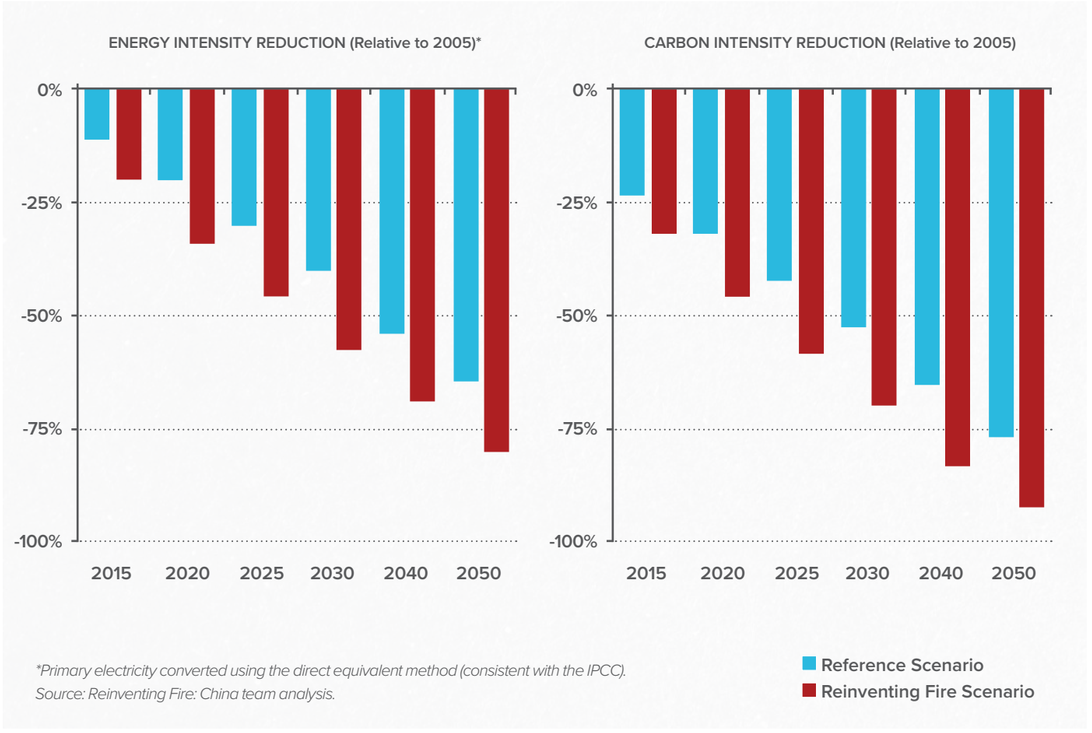
*Primary electricity converted using the direct equivalent method (consistent with the IPCC)
Source: Reinventing Fire: China team analysis.

8

Through reducing energy demand and shifting to lower carbon energy supplies, China largely decouples economic demand from energy growth under the Reinventing Fire Scenario, freeing the economy from energy and energy-related environmental constraints. Compared with 2005, energy intensity (primary energy per unit of GDP) decreases 42% by 2020, 64% by 2030, and 87% by 2050. Under the Reinventing Fire Scenario, China's carbon intensity (CO_2 emissions per unit of GDP) decreases 53% by 2020, 74% by 2030, and 93% by 2050, compared with 2005 levels.

FIGURE ES 8: ENERGY INTENSITY AND CARBON INTENSITY REDUCTIONS

2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



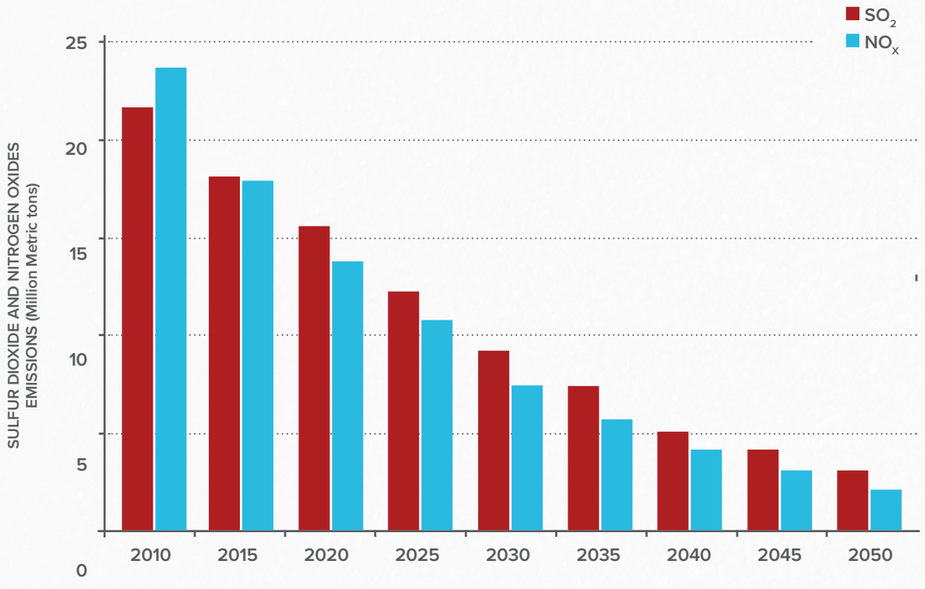
*Primary electricity converted using the direct equivalent method (consistent with the IPCC).
Source: Reinventing Fire: China team analysis.

9

China's SO_2 and NO_x emissions drop over 85% by 2050. In the Reinventing Fire Scenario, total emissions of sulfur dioxide (SO_2) and nitrogen oxides (NO_x) drop 85% and 90%, respectively, by 2050 compared with 2010 levels. Total key pollutant emission levels in China in 2050 will drop to levels experienced before the start of China's "Reform and Opening Up" policy of 1978 and will be at levels that are 25–30% below current levels of the U.S. and EU.

FIGURE ES 9: ENERGY-RELATED SULFUR DIOXIDE AND NITROGEN OXIDES AIR EMISSIONS

2010 - 2050, REINVENTING FIRE SCENARIO RESULTS



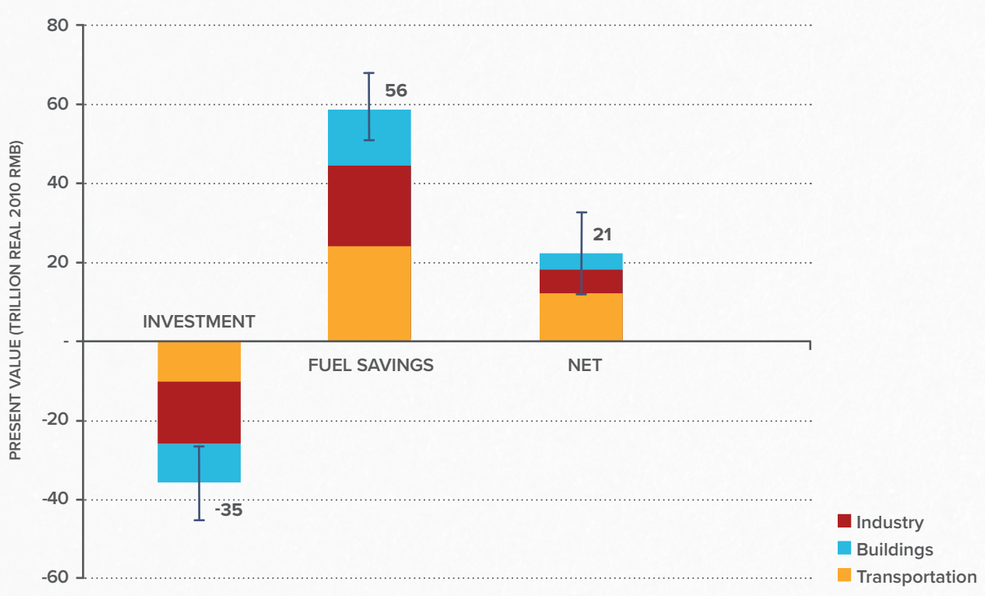
Source: Energy Research Institute emissions calculations; Reinventing Fire: China team analysis

10

Since the Reinventing Fire Scenario relies on cost-effective, commercially-available technologies, implementation of this scenario would save China 21 trillion RMB in energy costs. From 2010 to 2050, implementing the Reinventing Fire Scenario yields a potential energy savings of 56 trillion RMB ($8.3 trillion) relative to the Reference Scenario. Incremental new investment required beyond the Reference Scenario to realize these energy savings is estimated to be 35 trillion RMB ($5.2 trillion), yielding a net present value savings of 21 trillion RMB ($3.1 trillion, all figures 2010 real).

FIGURE ES 10: NET PRESENT VALUE OF THE REINVENTING FIRE SCENARIO*

2010 - 2050, INCREMENTAL TO THE REFERENCE SCENARIO



**Estimating energy costs in China is often difficult due to lack of data availability. As a result cost estimates were derived from both domestic and international sources. The ranges depicted represent the uncertainty associated with the methods applied.*
Source: Reinventing Fire: China team analysis.

SECTOR SNAPSHOTS

03

SECTOR SNAPSHOTS

INDUSTRY

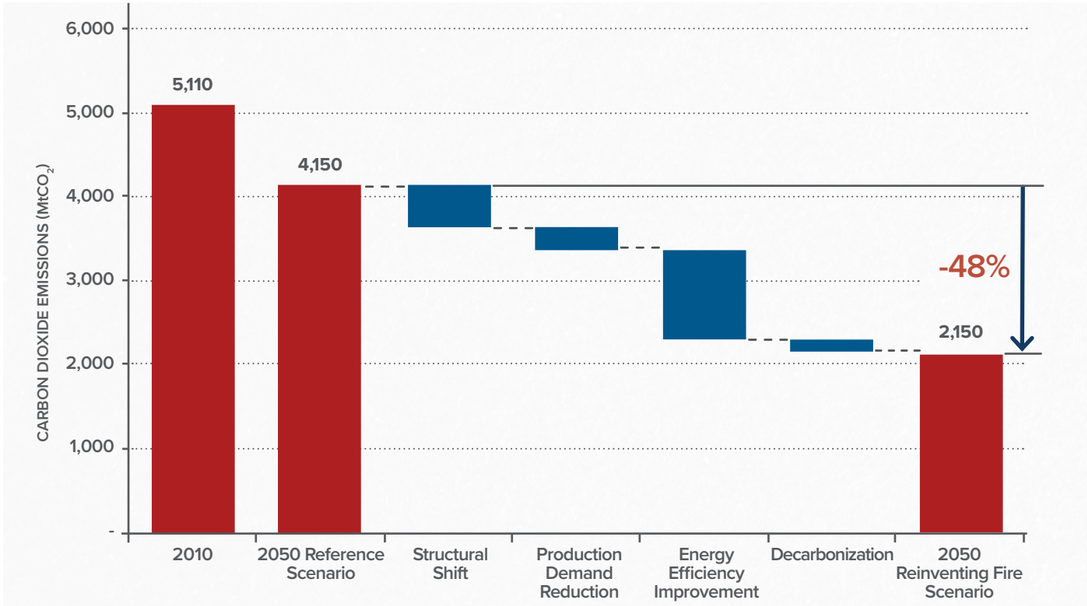
The Reinventing Fire strategy creates a China in 2050 where industry will be world class in terms of energy efficiency and will have moved away from carbon-intensive fuels.

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 of these combined factors, China's industrial sector consumes more than 66% of the country's primary energy, more energy than the U.S. buildings and transportation sectors combined. Despite the recent downturn in industrial activity associated with China's decreasing GDP growth, the industrial sector remains a critical component for realizing the overall Reinventing Fire vision for China.

In the Reinventing Fire Scenario, China ushers in a new wave of industrial revolution and the sector peaks energy use and CO_2 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.

FIGURE ES 11: CO_2 EMISSIONS SAVINGS IN THE INDUSTRY SECTOR

2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



**Primary electricity converted using the direct equivalent method (consistent with the IPCC).*
Source: Reinventing Fire: China team analysis.

The 2050 energy savings are greater than the energy consumption of the entire U.S. industrial sector in 2012. Cumulatively through 2050, the Reinventing Fire Scenario generates 19.7 trillion RMB in savings through a 12.9 trillion RMB investment, generating a net benefit of 6.8 trillion RMB for China's economy (2010 real).

In the Reinventing Fire Scenario, the pathways of **structural shift** to the service sector and higher-value-added industries; **production demand reduction** driven by longer-lasting buildings and infrastructure, improved material quality, increased recycling, and changes to the import/export structure; **energy efficiency improvement**; and **fuel-switching** to lower-CO_2-emitting fuels and electrification following decarbonization of the electric grid reduce energy-related emissions by 2,000 $MtCO_2$ in 2050 compared to the Reference Scenario (Figure ES 11).

BUILDINGS

In the Reinventing Fire Scenario, by 2050 China's buildings sector will have cost-effectively deployed today's most energy-efficient building design and construction practices, super-efficient equipment, smart building systems, and clean energy sources, producing higher-quality buildings with improved comfort, health, and productivity for occupants.

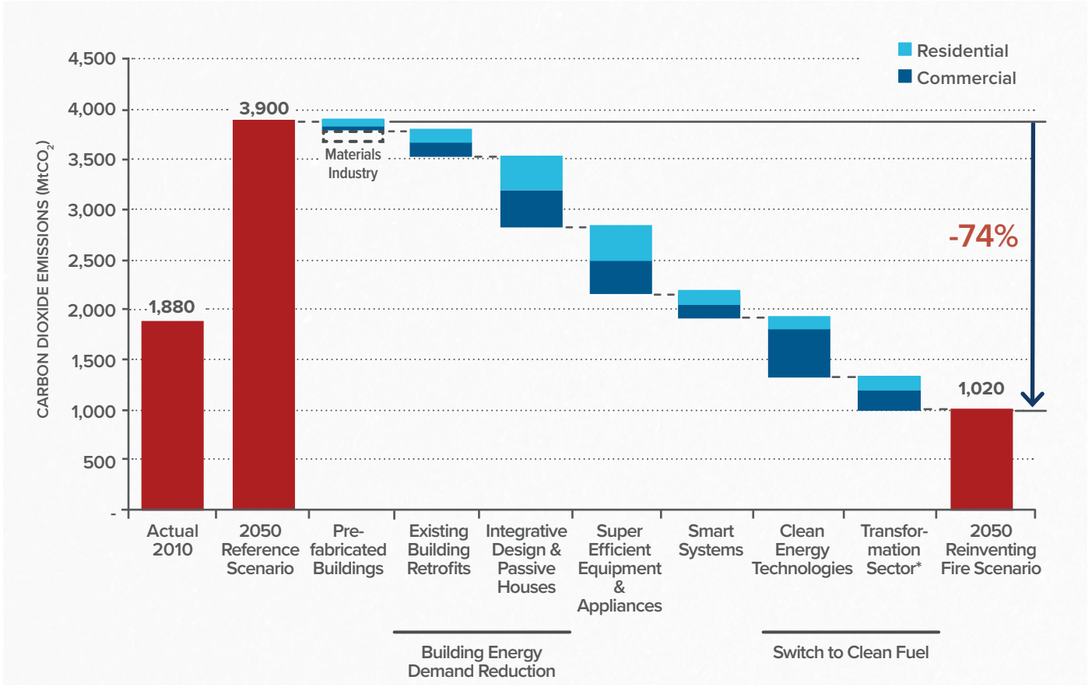
In 2010, Chinese buildings consumed 770 Mtce of primary energy, or about 24% of the national total. China's energy use per capita is far lower than many developed countries, but this is expected to increase as urbanization progresses, household incomes rise, and the economy shifts away from heavy industry towards the service sector. Because of China's continued urbanization, construction of new buildings will continue, and these buildings represent nearly three-quarters of the potential 2050 Reinventing Fire buildings sector energy savings. Decisions made now will determine the long-term future of the Chinese building stock and future energy use patterns.

Under the Reference Scenario, stock growth and modernization result in a near tripling of buildings-related primary energy between 2010 and 2050, reaching 2,270 Mtce by 2050. Under the Reinventing Fire Scenario, 2050 primary energy consumption is 1,000 Mtce, a savings of 56%. Primary energy peaks in 2031 at 1,370 Mtce and decreases thereafter. Cumulatively through 2050, the Reinventing Fire Scenario generates 13 trillion RMB in energy savings with a 9.5 trillion RMB investment, for a net present value (NPV) of 3.5 trillion RMB for China's economy (2010 real).

There are five pathways that together achieve the Reinventing Fire vision and goals: advanced construction practices including **prefabricated buildings**; reduced building energy demand through i**ntegrative/passive design and retrofits**; installation of **super-efficient equipment and appliances**; employment of **smart systems**; and a switch to **clean energy technologies** for on-site building equipment and power generation. These pathways reduce 2050 CO_2 emissions by 2,880 $MtCO_2$ compared to the Reference Scenario when including related savings in the materials industry and transformation sectors (Figure ES 12).

FIGURE ES 12: CO_2 EMISSIONS SAVINGS IN THE BUILDING SECTOR

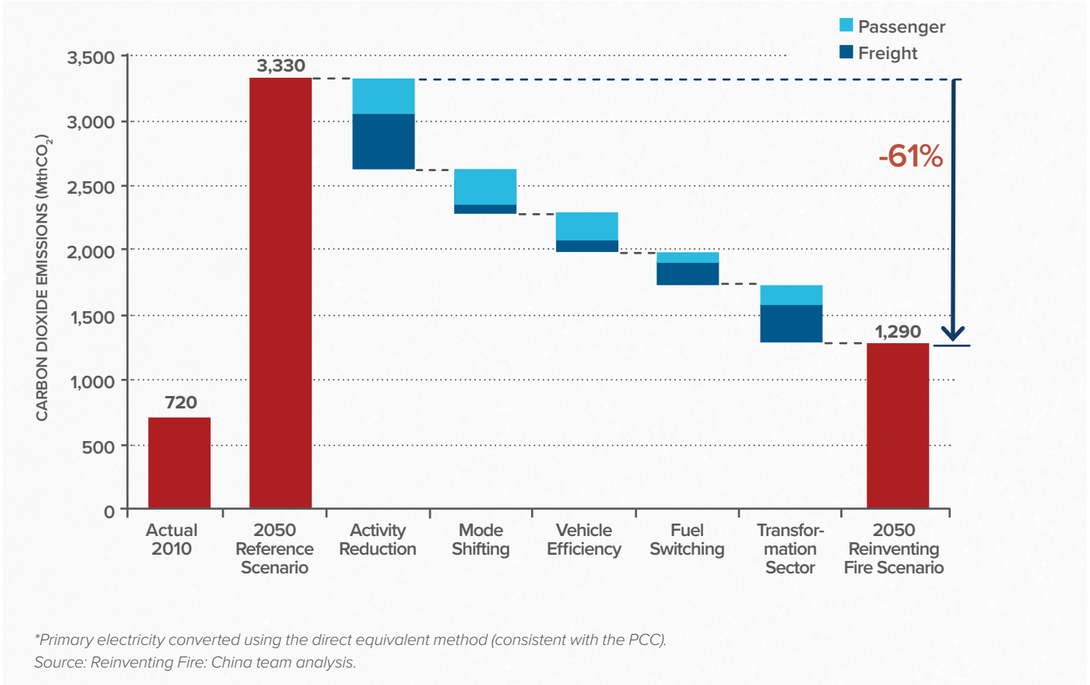
2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



**Primary electricity converted using the direct equivalent method (consistent with the IPCC).*
***Includes 120 $MtCO_2$ savings from incremental rooftop PV.*
Source: Reinventing Fire: China team analysis.

FIGURE ES 13: CO_2 EMISSIONS SAVINGS IN THE TRANSPORTATION SECTOR

2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



**Primary electricity converted using the direct equivalent method (consistent with the PCC).*
Source: Reinventing Fire: China team analysis.

TRANSPORTATION

The Reinventing Fire strategy creates a China in 2050 where transportation systems provide increased mobility, but more efficiently, and with fewer emissions and lower costs.

China's transportation sector consumed 9% of total primary energy in 2010 and this share is increasing. 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. Congestion and urban air pollution from vehicles greatly affects quality of life in Chinese cities.

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. Cumulatively through 2050, the Reinventing Fire Scenario generates 23.4 trillion RMB in savings through a 12.2 trillion RMB investment, generating an NPV of 11.1 trillion RMB for China's economy (2010 real).

There are four key pathways to Reinventing Fire in the transportation sector: **activity reduction** due to economic structural shift, improved layout of cities and industry, advanced logistics, and telecommuting/teleconferencing; **mode shifting** from trucks, airplanes, and private autos to more-efficient rail, water, high-speed rail, and public or non-motorized modes of transport; increasing **vehicle efficiency** using technology and design improvements; and **fuel switching** to electricity, natural gas, and biofuels. Applied in this order, these pathways reduce 2050 transportation CO_2 emissions by nearly 2,040 $MtCO_2$, contributing to a 61% reduction in overall carbon emissions, compared to the Reference Scenario (Figure ES 13).

TRANSFORMATION (ELECTRICITY FOCUS)

In the Reinventing Fire Scenario, China's power sector shifts away from fossil fuel generation to supply the increasingly efficient end-use sectors with clean, secure, and affordable energy.

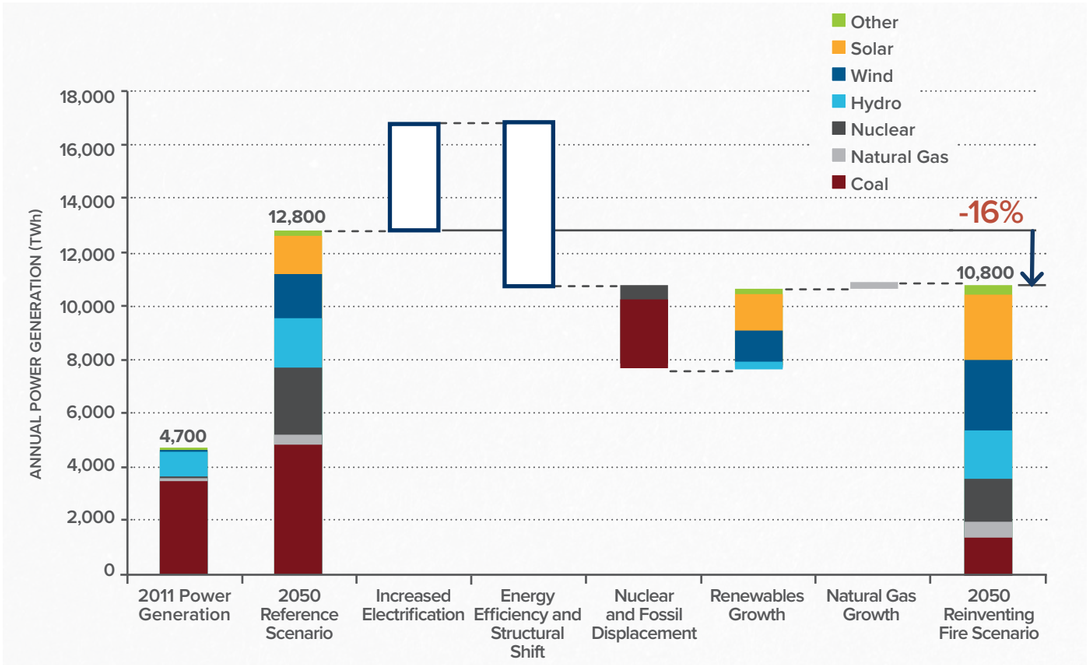
Despite extensive end-user efficiency, electricity demand in 2050 in the Reinventing Fire Scenario is 2.5 times higher than 2010 demand, with 41% of total final energy demand coming from electricity. Traditionally, China has met increased electricity demand by building coal-based electricity generation capacity. In 2012, nearly 75% of China's power generation was coal-based, resulting in emissions that negatively impact the environment and human health.

In the Reinventing Fire Scenario, near-term generation capacity growth is minimized through demand-side management (efficiency and demand response), achieving China's near-term targets for renewables and nuclear development, and improving the utilization of existing assets. Any new coal generating capacity will be required to comply with strict pollution controls; any need for new capacity must be clearly demonstrated in order to prevent stranded investments in the future. The gradual retirement of existing coal power plants provides additional rationale for deploying increasingly economic non-fossil renewables. Over 1,800 GW of solar and 1,140 GW of wind capacity are added to the system by 2050, supported by hydro, natural gas, battery storage, nuclear power, and customer-side resources to manage renewable generation variability. Under the Reinventing Fire Scenario, 82% of all electricity comes from non-fossil sources by 2050.

To realize this revolution, China will likely need to change how it invests in and operates its central generation fleet, the transmission and distribution system, and demand-side assets. By reforming how China conducts its resource planning, generator dispatch, and compensation mechanisms, China will be able to economically support the rapid development of renewable generators.

FIGURE ES 14: POWER GENERATION BY FUEL

2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



Source: Reinventing Fire: China team analysis.

In addition to the electricity system, the Reinventing Fire analysis covers the transformation of other fuels into usable forms of energy in China's transformation sector, including a range of important energy supplies and demands on the economy, such as:

- Heat Supply/Cogeneration: Heat generated from district heating facilities and industrial process heat boilers; heat and electricity from cogeneration plants for use by buildings and industrial processes.
- Resource Extraction: Production of coal, natural gas, and crude oil within China.
- Coal Conversion: Coal-to-coke (coking), coal-to-gas (CTG), and coal-to-liquids (CTL).
- Crude Oil Refining: Conversion of crude oil into usable fuels and base chemicals.
- Biofuel Production: Production of ethanol from either starch or cellulosic feedstocks; production of biodiesel through transesterification or conversion from biomass.

PHASES OF CHINA'S ENERGY REVOLUTION

04

PHASES OF CHINA'S ENERGY REVOLUTION

Achieving the outcomes outlined in the ten key findings above requires sustained and targeted support of China's government, enterprises, and society at large. This support comes in three broad phases, each building on the previous one.

PHASE 1

During the first phase (2010–2020), the government pursues a "war on pollution" and initiates a restructuring of the country's industrial system. This phase sees coal consumption peak and an economy-wide move towards efficiency improvements, and seeks to limit technological "lock-in" effects from any new coal-fired generation. This is a priming phase. The work done here—including limiting new coal generation, creating markets that favor efficiency and flexibility, rationalizing industry over-capacity and shifting industrial production towards higher-value-added products, stemming excessive building construction and ensuring building codes meet international best practices, and laying out significant and smart transportation infrastructure—will not only provide immediate benefits, but will set China up for long-term success.

PHASE 2

The second phase (2020–2030) focuses on peaking CO_2 emissions and promoting post-industrial development. Growth of CO_2 emissions slows and begins to reverse during this period, but challenges remain as urbanization continues (leading to increased demand for building and transport services). Energy-intensive industries like steel, cement, and chemicals are displaced by higher-value-adding industries such as pharmaceuticals and equipment manufacturing. Highly efficient buildings that use passive techniques and integrative design will flourish. Electrification and fuel switching in transport fleets to lower-carbon sources will increase, while urban rail mobility increases. Non-fossil power generation capacity—nuclear, hydro, wind, and solar power—increase significantly.

PHASE 3

Finally, the third phase (2030–2050) harvests the efforts from the first two phases. Policy during this phase focuses on both shifting to a high proportion of non-fossil energy and ushering in green and intelligent development. This phase is a decisive period for China to realize its second 100-year goal to reach the status of a moderately developed country by 2050. Integrating low-carbon technologies with intelligent technologies creates a new generation of energy savings in the industry, buildings, and transportation sectors. Industry will have highly networked and digital production. Passive and net-zero design combined with superefficient equipment will dominate the building stock. Electric and highly automated mobility supports the transportation of goods and people. A large number of coal power plants will economically retire and be displaced by renewable energy alternatives.

REALIZING THE REINVENTING FIRE VISION

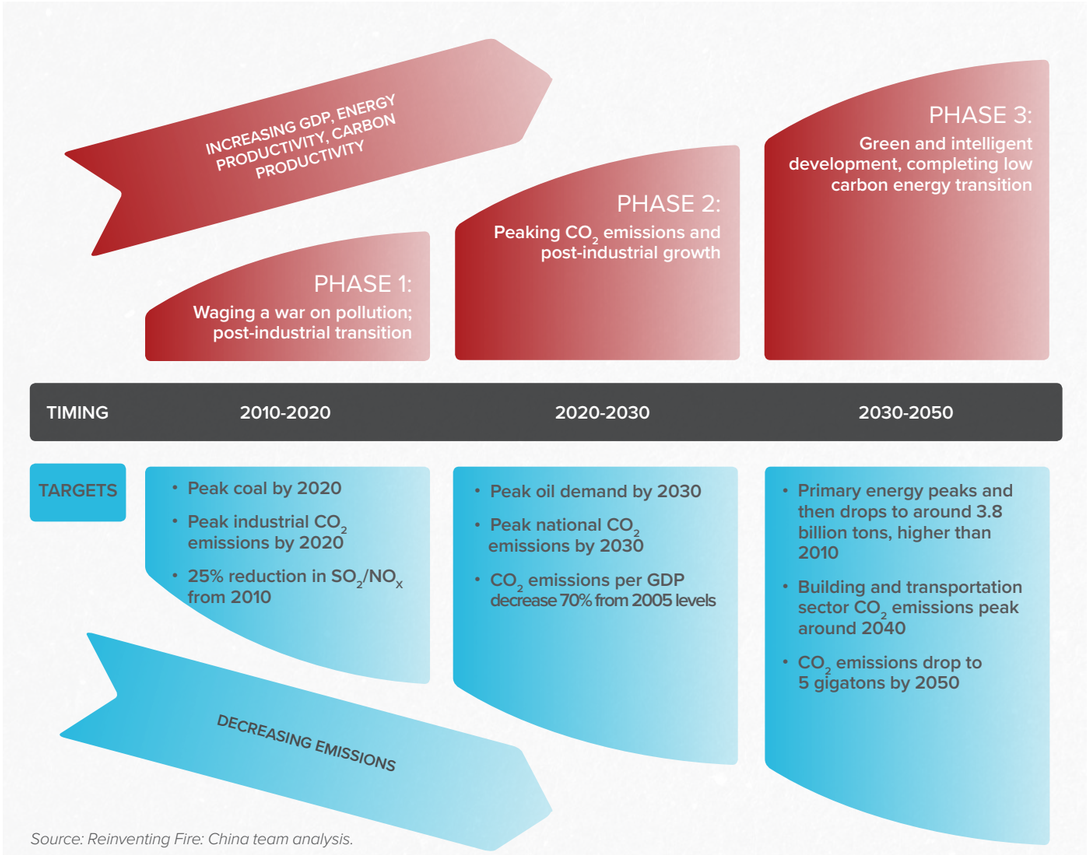
In addition to the policy elements that underpin these three phases, there is a common set of actionable themes that are essential to realizing the Reinventing Fire vision, including:

- Aligning government policies and business interests to the strategic goals of Reinventing Fire.
- Prioritizing demand reduction and energy efficiency as critical drivers that make the energy revolution 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.

Together, when these top level themes are integrated in support of the three phases of China's energy transformation, the vision of Reinventing Fire becomes a realistic and achievable roadmap toward a China that meets its needs and improves its energy security and environmental quality using the maximum feasible share of cost-effective energy efficiency and renewable energy supply.

FIGURE ES 15: THREE PHASES OF CHINA'S ENERGY REVOLUTION

2010 - 2050, REFERENCE AND REINVENTING FIRE SCENARIOS



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Energy Conversion Standard:
1 million tons coal equivalent (Mtce) =
0.0293 exajoules (EJ) =
0.0278 quadrillion British thermal units (Quads)

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LBNL Funding Note:
Lawrence Berkeley National Laboratory was supported by Energy Foundation China through the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

REINVENTING FIRE: CHINA

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