REINVENTING FIRE: CHINA

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

重塑能源：中国

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FULL REPORT

NOVEMBER 2019

ENERGY RESEARCH INSTITUTE OF THE NATIONAL DEVELOPMENT AND REFORM COMMISSION

LAWRENCE BERKELEY NATIONAL LABORATORY

ROCKY MOUNTAIN INSTITUTE

ENERGY FOUNDATION CHINA

The original executive summary of the report, written in both English and Chinese, was published in 2016. A five-volume Chinese language version of this research was published in 2017. This English version contains the original executive summary along with key exhibits translated for an international audience.

Last updated November 2019

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面向2050年能源消费和生产革命路线图研究

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SUPPORTING PARTNER

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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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Lawrence Berkeley National Laboratory (LBNL) addresses the world's most urgent scientific challenges by advancing sustainable energy, protecting human health, creating new materials, and revealing the origin and fate of the universe. Founded in 1931, Berkeley Lab's scientific expertise has been recognized with 13 Nobel prizes. The University of California manages Berkeley Lab for the U.S. Department of Energy's Office of Science.

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Since 1982, Rocky Mountain Institute (RMI) has advanced market-based solutions that transform global energy use to create a clean, prosperous, and secure future. An independent, nonprofit think-and-do tank, RMI engages with governments, businesses, communities, and other institutions to accelerate and scale replicable solutions that drive the cost-effective shift from fossil fuels to efficiency and renewables.

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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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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. 2018, *Reinventing Fire: China – A Roadmap for China's Revolution in Energy Consumption and Production to 2050.*

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 under way 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 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.

The authors' intent was 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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ABBREVIATIONS

3pl - third-party logistics provider
ADB - Asian Development Bank
BRT - bus rapid transit
Btce - billion tons of coal equivalent
Btu - British thermal units
CCE - cost of conserved energy
CCHP - combined cooling, heat, and power
CCUS - carbon capture utilization and storage
CO_2 - carbon dioxide
Coking - coal-to-coke
CSC - conservation supply curve
CSP - concentrating solar power
CTG - coal-to-gas
CTL - coal-to-liquids
DG - distributed generation
DR - demand response
DREAM - Demand Resource Energy Analysis Model
EAF - electric arc furnace
EDO - Electricity and District Heating Optimization
EE - energy efficiency
EJ - exajoule
ERI - Energy Research Institute
ESCO - energy service company
ETS - emissions trading schemes
EVs - electric vehicles
FIT - feed-in tariff
G7 - Group of Seven
GDP - gross domestic product
GE - General Electric
GHG - greenhouse gas
GM - General Motors
Gt - gigaton
GWh - gigawatt-hour
HDTs - heavy-duty trucks
HSR - high-speed rail
IBR - Shenzhen Institute of Building Research
ICE - internal combustion engine
ICT - information and communication technology
IEA - International Energy Agency
IPCC - Intergovernmental Panel on Climate Change
IRP - Integrated Resource Planning
Jing-Jin-Ji or JJJ - Beijing-Tianjin-Hebei
km - kilometer
LBNL - Lawrence Berkeley National Laboratory
LCOE - levelized cost of electricity
LDT - light-duty trucks
LEAP - Long-Range Energy Alternatives Planning
LMP - locational marginal pricing
LNG - liquidified natural gas
MOHURD - Ministry of Housing and Urban-Rural Development
MRT - mass rapid transit
Mt - million ton
Mtce - million tons of coal equivalent
Mtoe - million tons of oil equivalent
NBS - China's National Bureau of Statistics
NEV - new energy vehicle
NO_x - nitrogen oxides
NPV - net present value
NREL - National Renewable Energy Laboratory
O&M - operations and maintenance
PHEVs - plug-in hybrid electric vehicles
pkm - passenger-kilometer
PM - particulate matter
POPs - persistent organic pollutants
PPCC - Power Plant Coal Consumption
PPP - purchasing power parity
PV - solar photovoltaic
R&D - research and development
RMI - Rocky Mountain Institute
RPS - Renewable Portfolio Standards
SEP - Superior Energy Performance Program
SMEs - small and medium enterprises
SO_2 - sulfur dioxide
SOHO - small office and home office
tce - tons of coal equivalent
TEU - twenty-foot equivalent units
toe - tons of oil equivalent
TOU - time-of-use
TW - terawatt
U.S. CEEM - U.S. Council for Energy-Efficient Manufacturing
U.S. DOE - U.S. Department of Energy
UHV - ultra-high voltage
UN - United Nations
V2G - vehicle-to-grid
VPP - virtual power plant
WECC - Western Electricity Coordinating Council
WHO - World Health Organization
WTO - World Trade Organization

OVERVIEW

ES: OVERVIEW

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 emissions 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

[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.*

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 during the period 2010–2020 and 2050 emissions should be 41–72% below 2010 levels. China is the world's largest emitter of CO_2; 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.

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-systems 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 consumption and/or carbon emissions 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.


KEY FINDINGS
ES

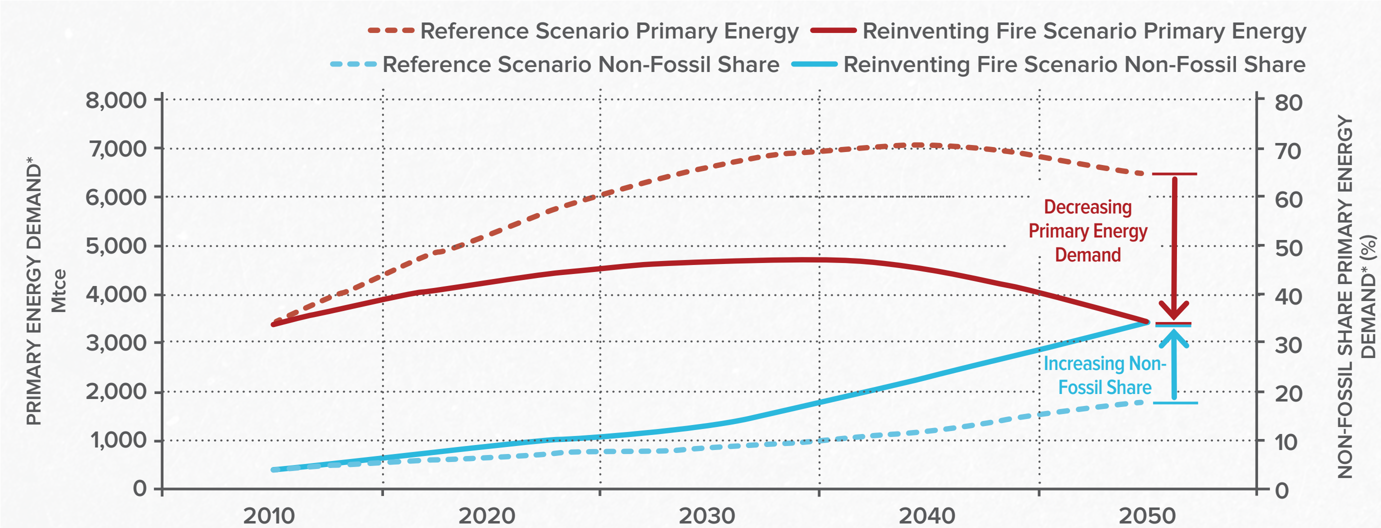
ES: KEY FINDINGS

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)*

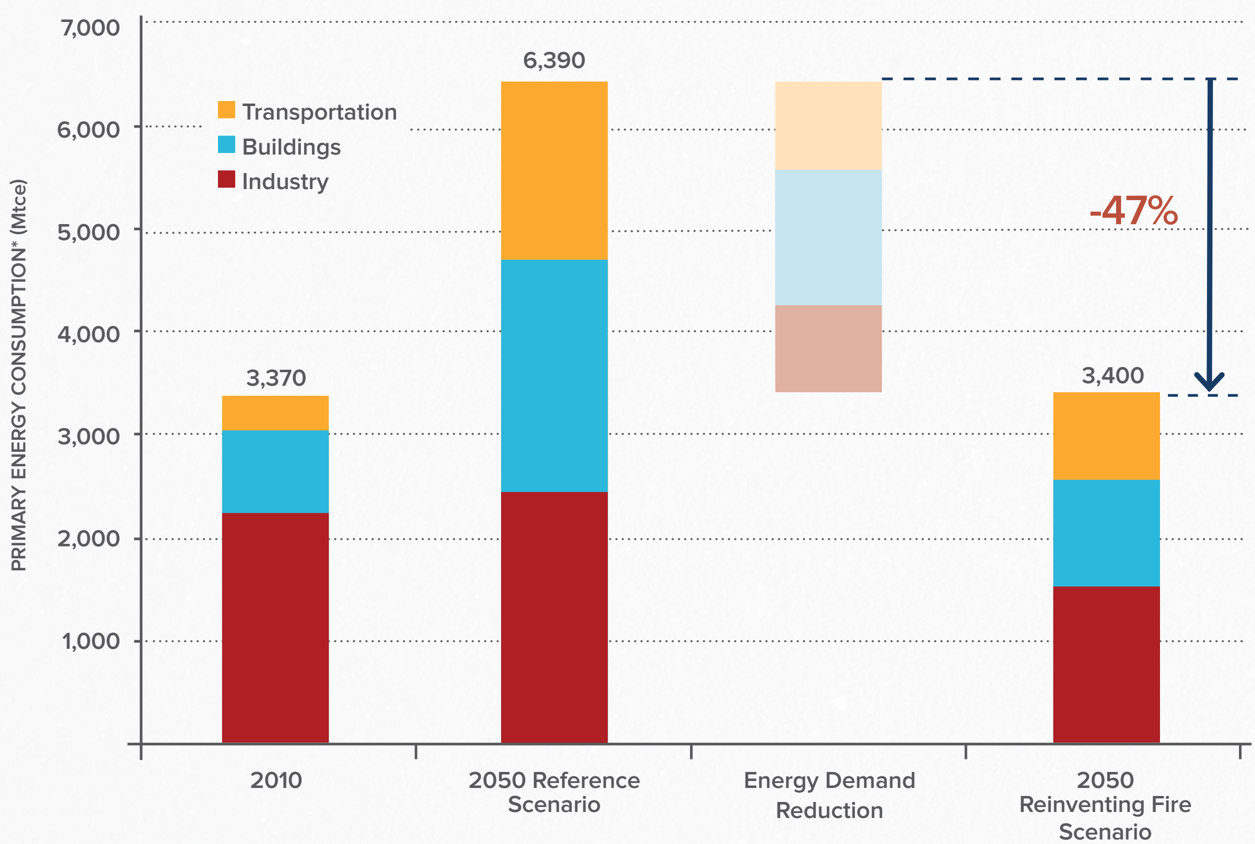
Source: Energy Research Institute China General Equilibrium Economic Model, Reinventing Fire: China team analysis

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 VS. REINVENTING FIRE SCENARIOS



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

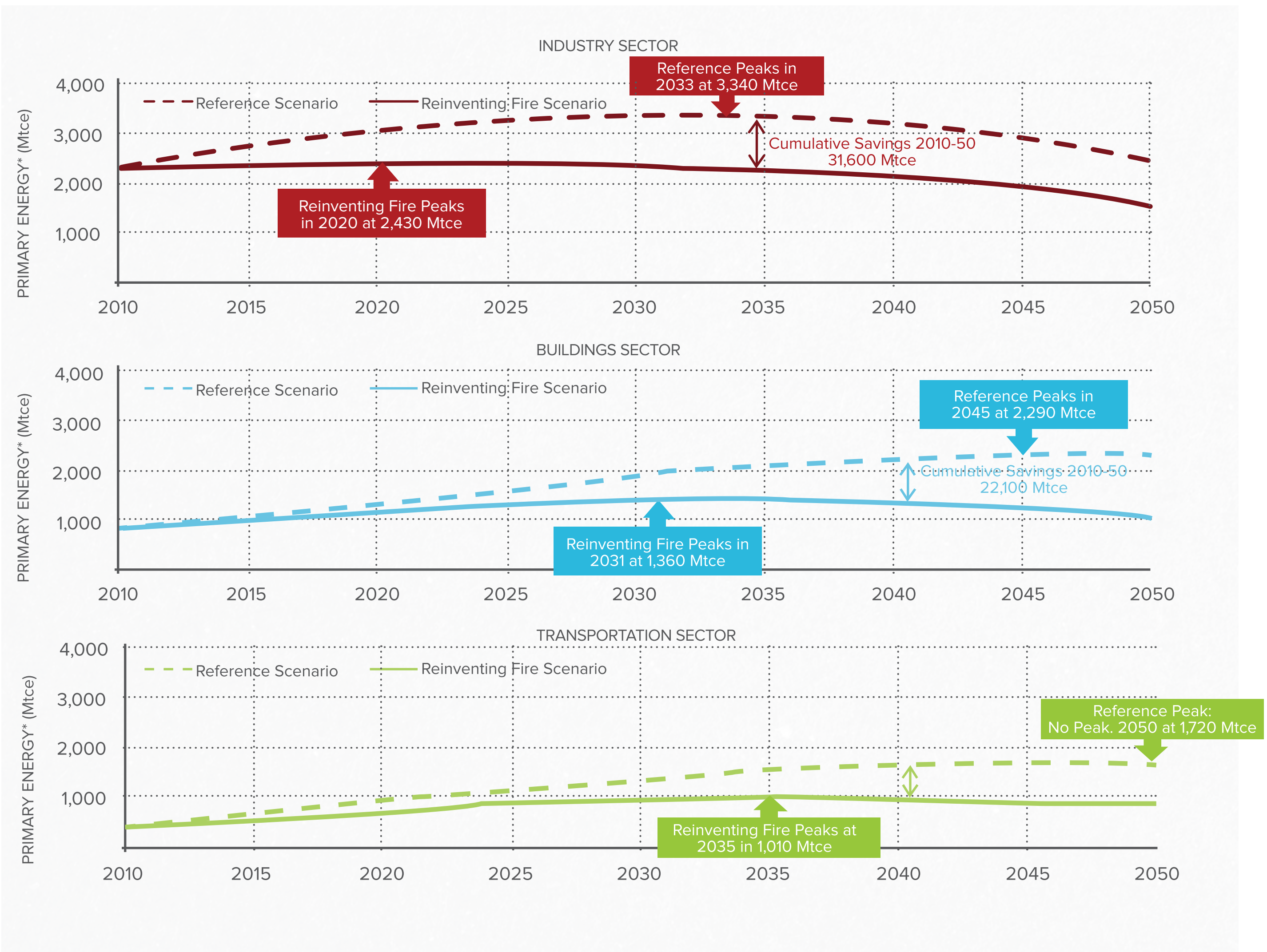
Source: Reinventing Fire: China team analysis

3

Under the Reinventing Fire Scenario, primary energy consumption in China's industry, buildings, 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 and 27% lower than the Reference Scenario. 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: PRIMARY ENERGY PEAKING TRENDS BY SECTOR

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

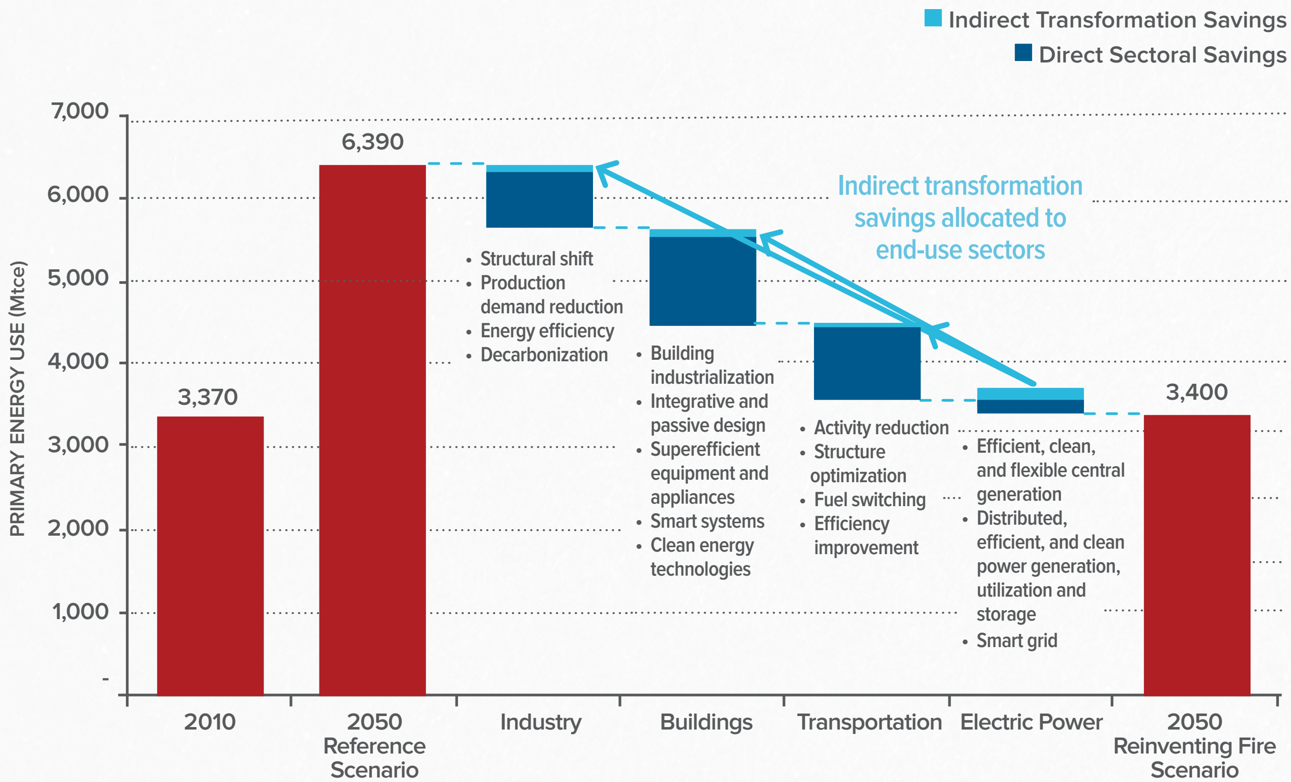


4

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: ENERGY SAVINGS BY SECTOR

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



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

Source: Reinventing Fire: China team analysis

5

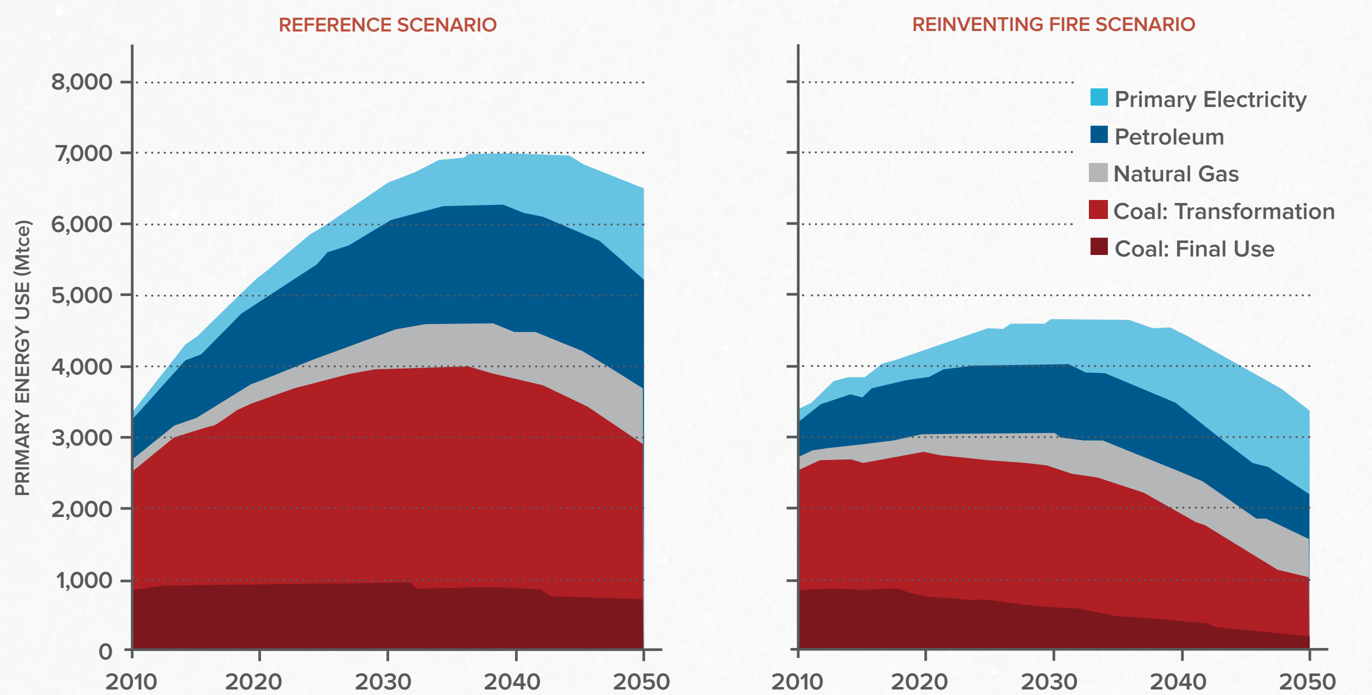
China's reduced energy demand allows it to dramatically increase its non-fossil share of primary energy by 2050. Demand reduction compresses both coal and petroleum consumption over time, reducing the fossil energy share from 82% in the Reference Scenario to 66% in the Reinventing Fire Scenario by 2050.* 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]

[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.

FIGURE ES 5: PRIMARY ENERGY FUEL MIX TRENDS

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS*



NON-FOSSIL SHARE OF PRIMARY ENERGY

Reference Scenario:

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

Reinventing Fire Scenario:

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

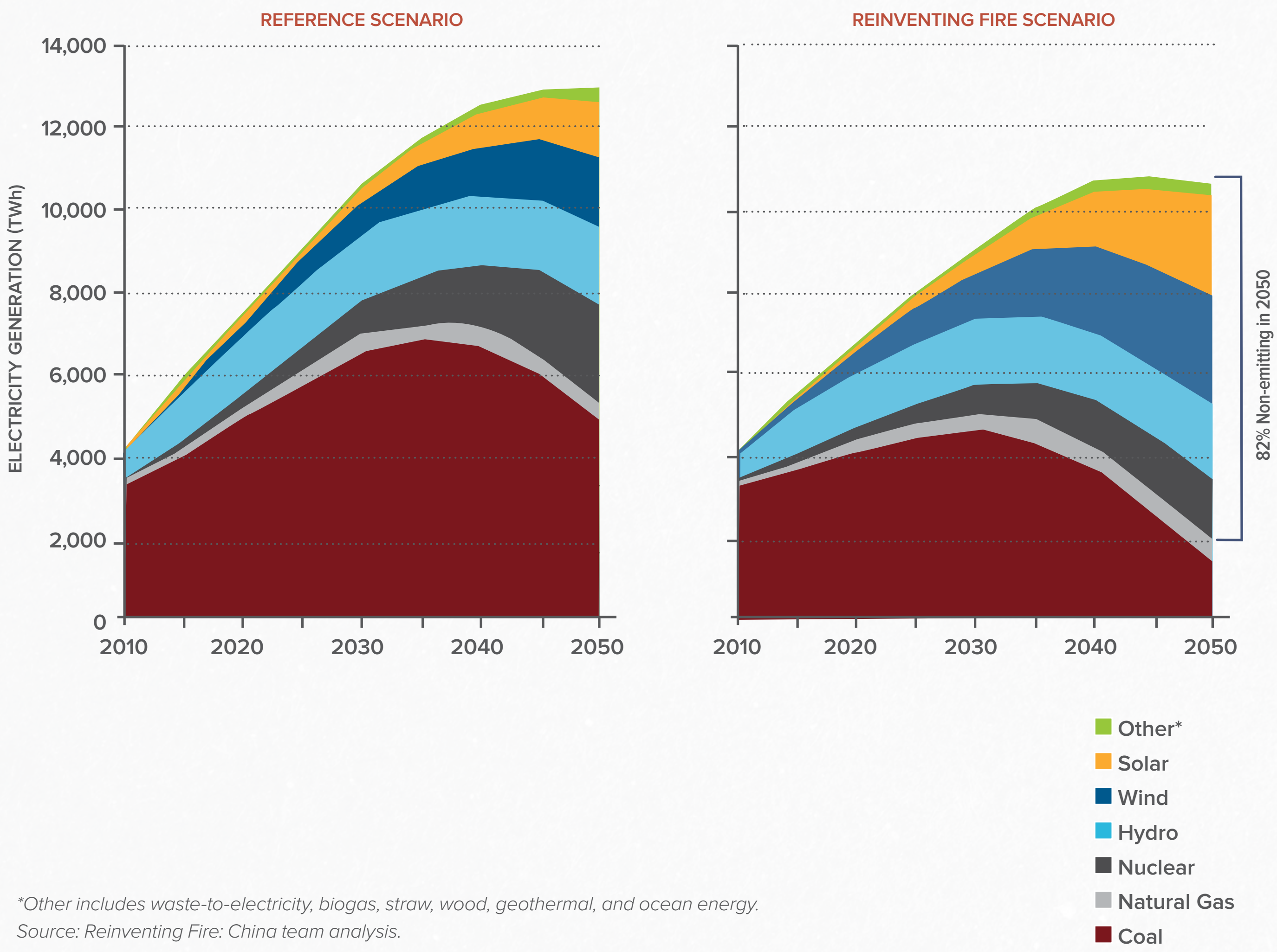
Primary electricity converted using the direct equivalent method (consistent with the IPCC). Source: Reinventing Fire: China team analysis

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 MIX TRENDS

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS



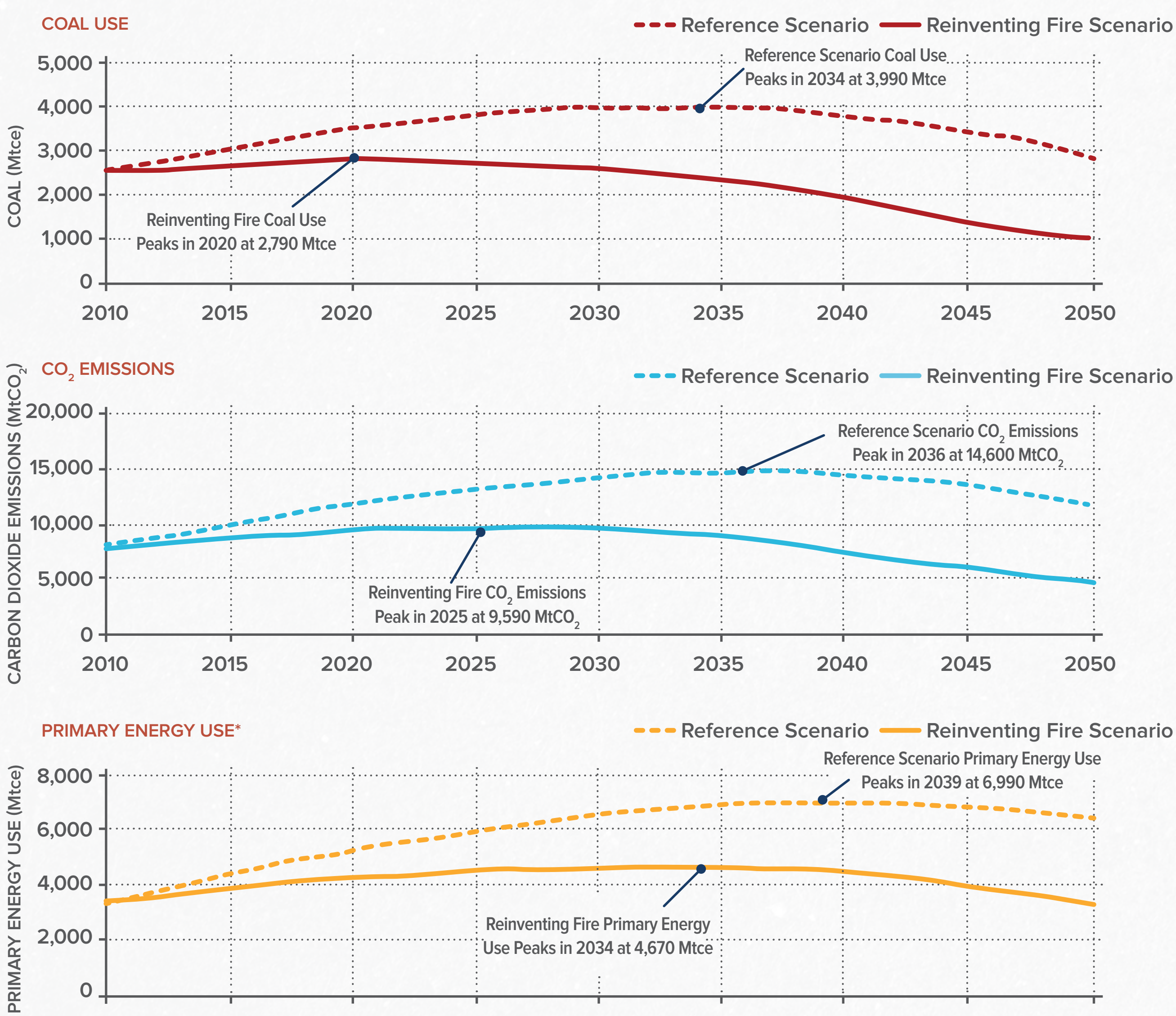
**Other includes waste-to-electricity, biogas, straw, wood, geothermal, and ocean energy.*
Source: Reinventing Fire: China team analysis.

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 5 years earlier and 33% lower than the Reference Scenario.

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

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS



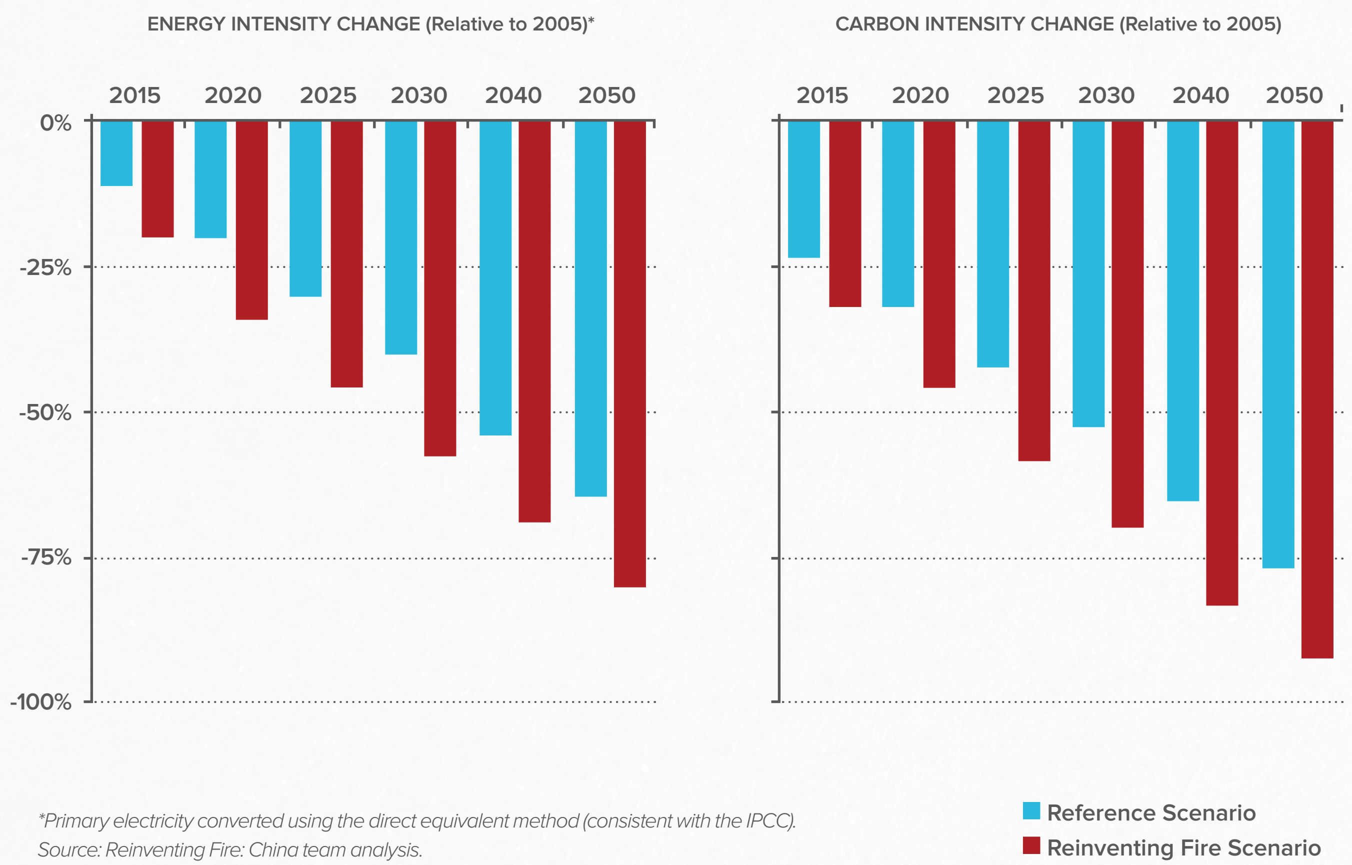
**Primary electricity converted using the direct equivalent method (consistent with the IPCC).*
Source: Reinventing Fire: China team analysis.

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 AND CARBON INTENSITY REDUCTIONS

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS



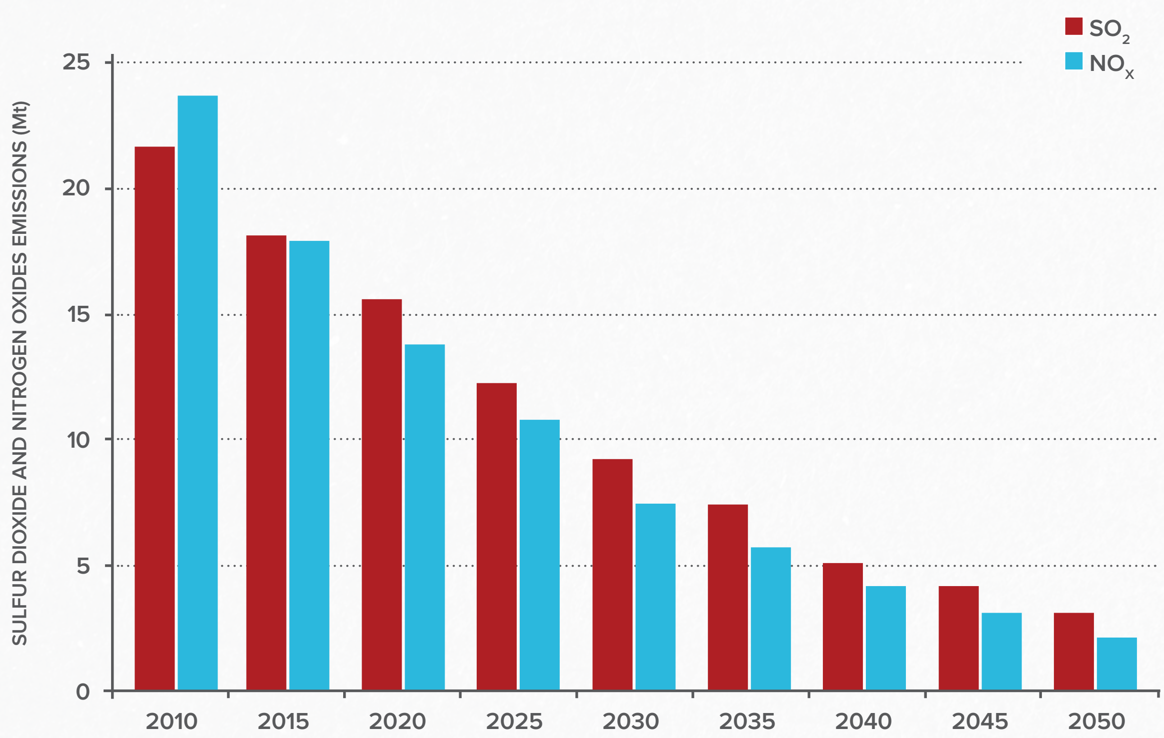
Primary electricity converted using the direct equivalent method (consistent with the IPCC).
Source: Reinventing Fire: China team analysis.

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 SO_2 AND NO_X EMISSIONS

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS



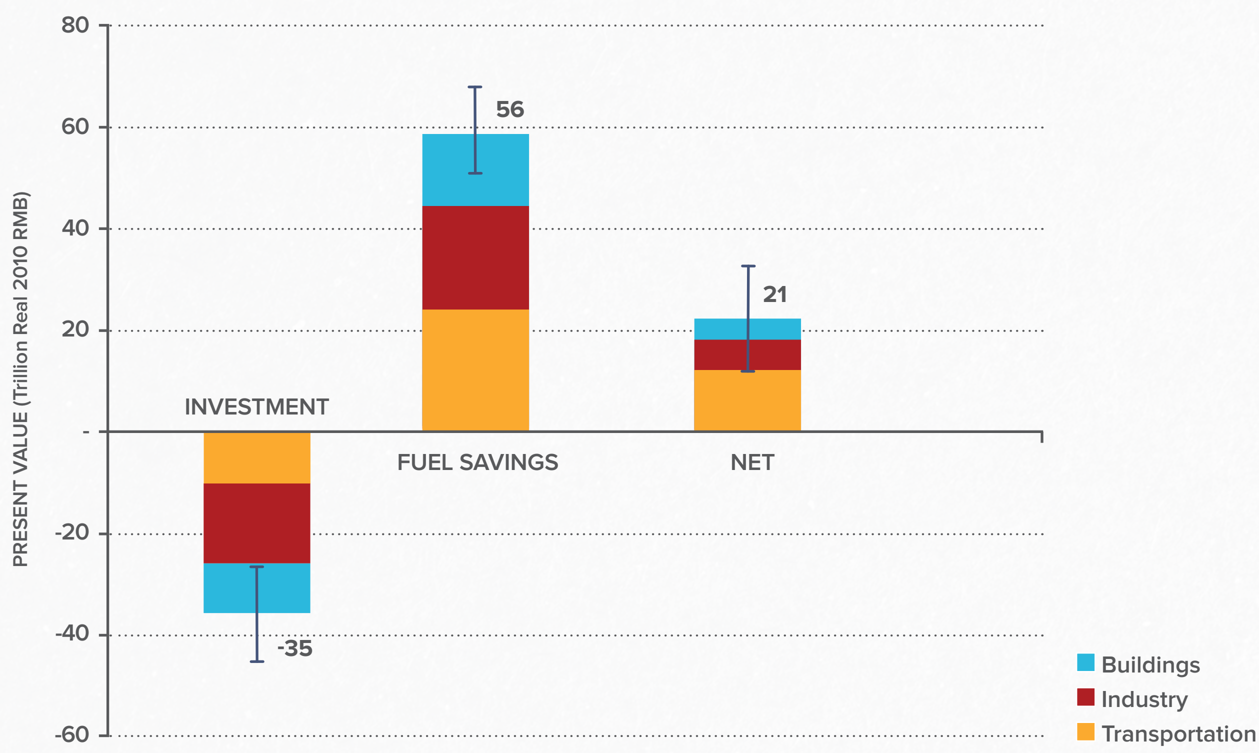
Source: Energy Research Institute emissions calculations; Reinventing Fire: China team analysis

10

Since the Reinventing Fire Scenario relies on cost-effective, commercially-available technologies, its implementation would save China 21 trillion RMB in net 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 an estimated 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: REINVENTING FIRE SCENARIO NET PRESENT VALUE

2010–2050, INCREMENTAL TO 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
ES

ES: SECTOR SNAPSHOTS

INDUSTRY

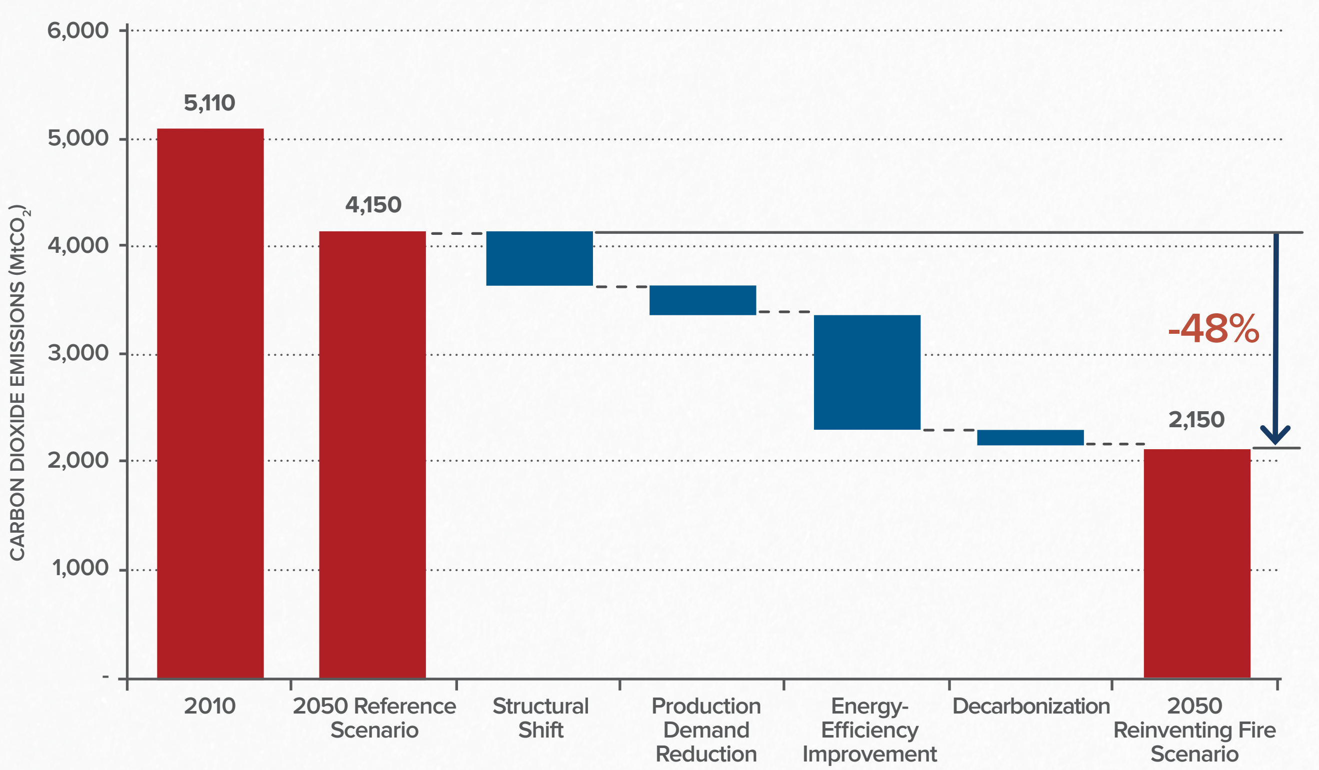
The Reinventing Fire strategy creates a China in 2050 where industry will be world class in terms of energy efficiency and will have moved away from carbon-intensive fuels.

Industry is the dominant sector in the Chinese economy, contributing roughly 45% of overall national GDP since the late 1970s.[8] China is now the world leader in output for most industrial products.[9] 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.[10] 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.[11,12] 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, INDUSTRY SECTOR

2010 AND 2050, REFERENCE VS. 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.

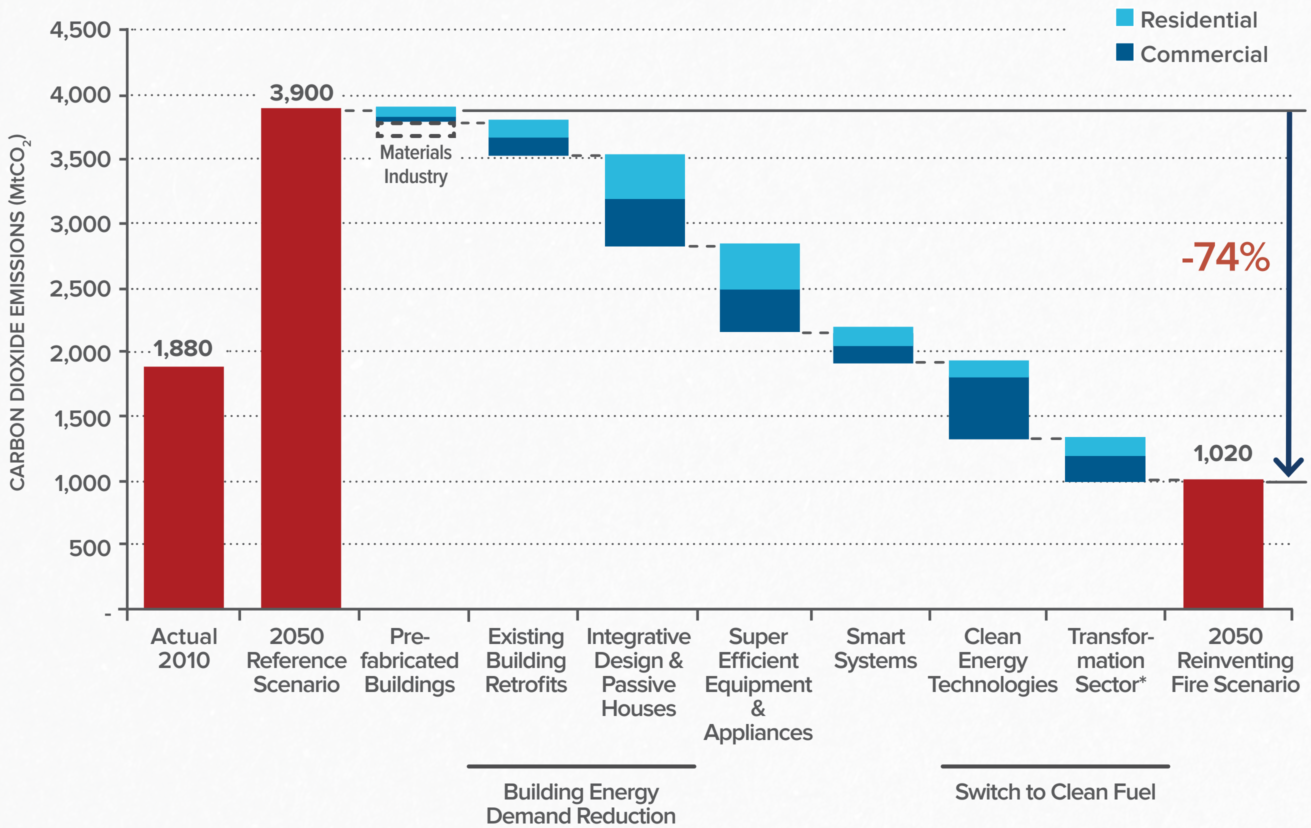
In 2010, Chinese buildings consumed 770 Mtce of primary energy, or about 24% of the national total.[13] China's energy use per capita is far lower than many developed countries,[14] but this is expected to increase as urbanization progresses, household incomes rise, and the economy shifts away from heavy industry towards the service sector.[15] 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 Scenario 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 **integrative/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 $MtCO_2$ (74%) 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, BUILDINGS SECTOR

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



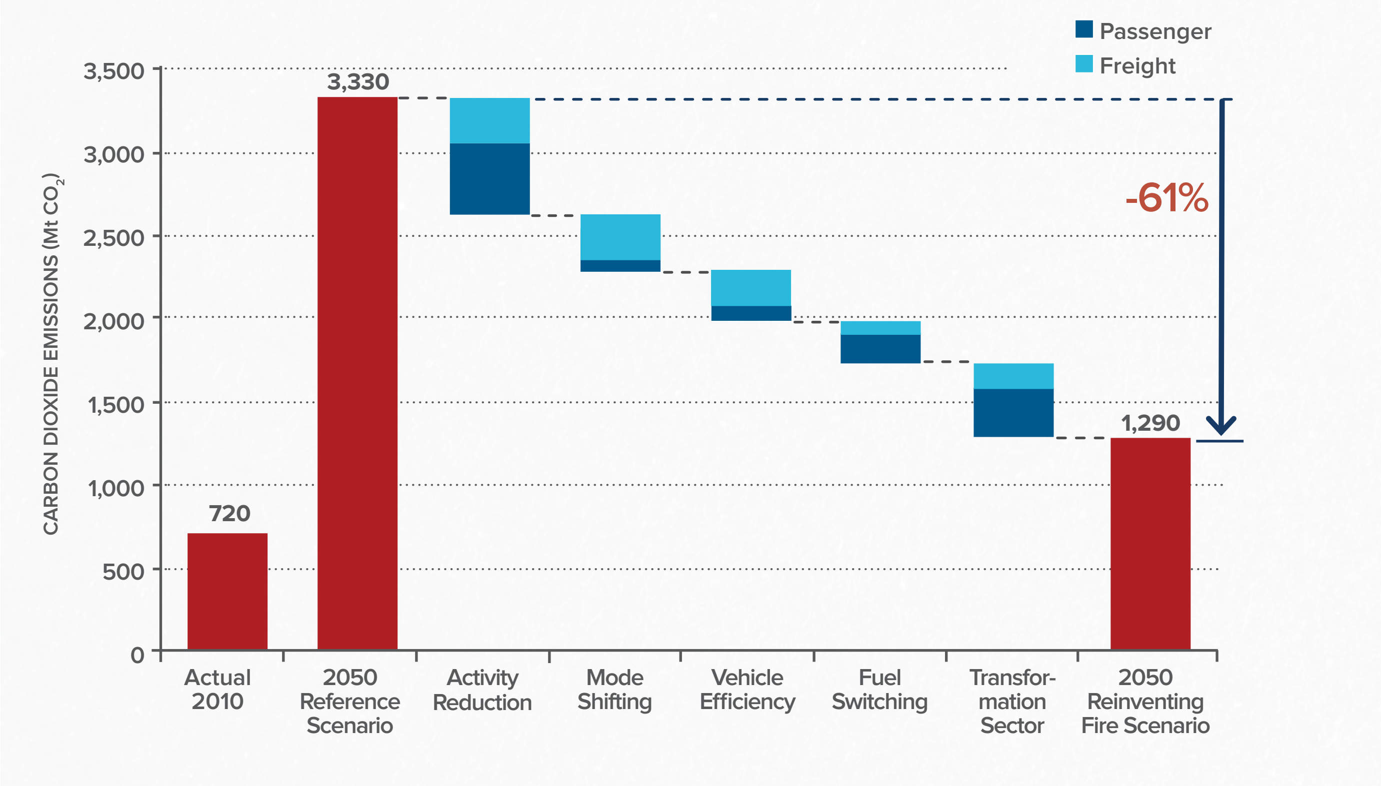
**Primary electricity converted using the direct equivalent method (consistent with the IPCC).*

***Includes 120 $MtCO_2$ savings from incremental rooftop PV.*

Source: Reinventing Fire: China team analysis.

FIGURE ES 13: CO_2 EMISSIONS SAVINGS, TRANSPORTATION SECTOR

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



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

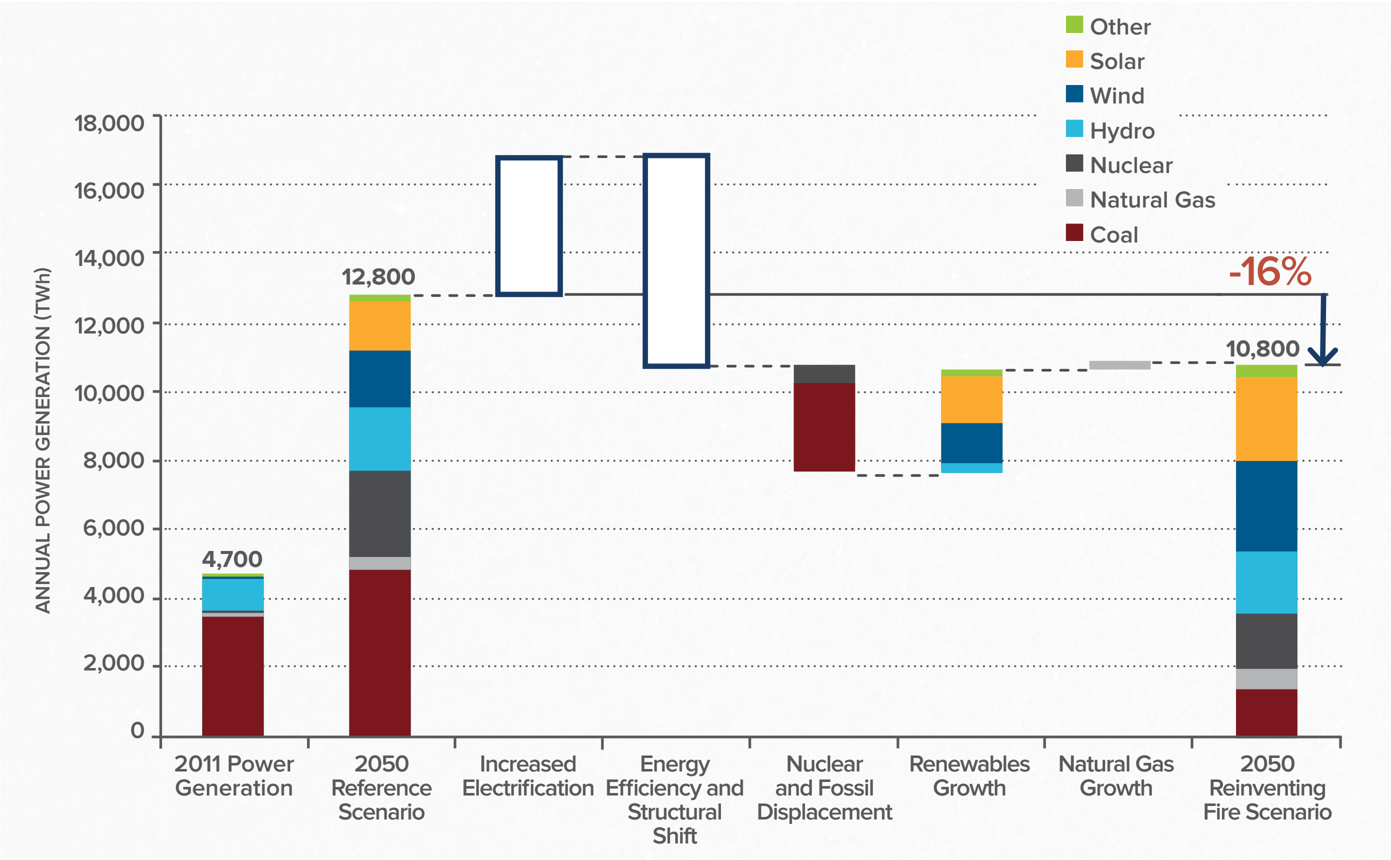
Despite extensive end-user efficiency, electricity demand in 2050 in the Reinventing Fire Scenario is 2.5 times higher than 2010 demand, with 41% of total final energy demand coming from electricity. Traditionally, China has met increased electricity demand by building coal-based electricity generation 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: ELECTRICITY GENERATION MIX

2010 AND 2050, REFERENCE VS. 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

ES: PHASES OF CHINA'S ENERGY REVOLUTION

Achieving the outcomes outlined in this report's 10 key findings 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 transportation 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

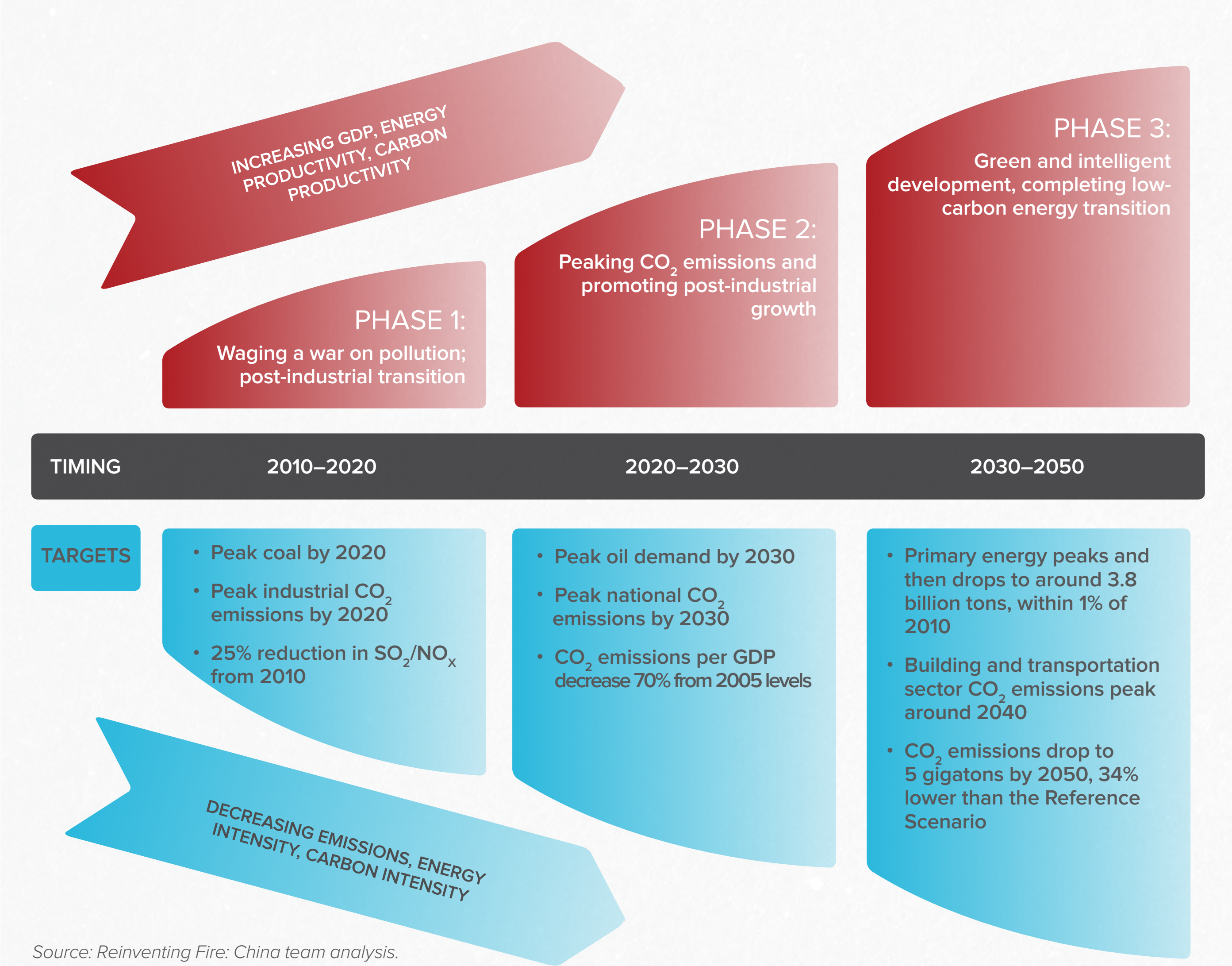
In addition to the policy elements that underpin these three phases, there is a common set of actionable themes that are essential to realizing the Reinventing Fire vision, including:

- 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, REINVENTING FIRE SCENARIO



Source: Reinventing Fire: China team analysis.

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

01

INTRODUCTION

INTRODUCTION

AFTER DECADES of rapid economic growth fueled primarily by fossil fuels, in June 2014 President Xi Jinping of China called for "a revolution in the production and consumption of energy."[1] 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 to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030.[2] In July 2015, China further committed to these goals and added an additional goal of lowering CO_2 emissions per unit of gross domestic product (GDP) by 60–65% from the 2005 level.[3] In December 2015, China made an international commitment to support the Paris Agreement's goals of keeping the increase of average global temperature between 1.5°C and 2°C and realizing a peak in global greenhouse gas (GHG) emissions as soon as possible.

Achieving these goals will require a significant departure from China's historic 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.

1.1 THE TRADITIONAL MODEL OF ENERGY DEVELOPMENT DOES NOT SUPPORT CHINA'S GOALS

Energy is fundamental for modern economic and social development. Since China's economic reforms began in 1978, China's energy sector has advanced significantly, providing support for poverty elimination, improving the living standards of millions of Chinese citizens, and contributing to long-term stable and rapid economic development.

Between 1980 and 2012, China's GDP increased 21 times, growing from 1,770 billion RMB (2005 prices) to 37,030 billion RMB (2005 prices),[i] led by growth in the secondary sector comprising mining, manufacturing, and electricity production, and closely followed by growth in the tertiary sector comprising services and construction (Figure 1.1).[ii]

From 1980 to 2012, China's primary energy consumption increased by six times (6% average annual growth) (Figure 1.2)[4]; over the same period, the world's primary energy consumption increased by 1.8 times (2% average annual growth).[5] China surpassed the U.S. in primary energy consumption in 2010, making it the largest primary energy consumer in the world.[6] In 2012, China's primary energy production reached 3.32 billion tons of coal equivalent (Btce),[7] accounting for 19% of global primary energy production.[8]

In 2012, primary energy consumption per capita in China reached 2.67 tce, increasing 132% compared to 2000.[9] In some areas and cities, per-capita energy consumption is close to that of developed countries. Energy services have also improved significantly. Between 1998 and 2012, an additional 36 million people in China gained access to electricity.[10]

Despite these achievements, China's energy system is relatively inefficient. While China consumed 22% of the world's primary energy in 2012,[iii] it created just 8.7% (market exchange rate) or 16% (purchasing power parity, PPP) of the world's GDP, with energy use per unit of GDP 4–6 times higher than in developed countries.[11]

China is constrained by insufficient domestic energy resources that are consumed by inefficient buildings, industries, and transportation systems. In 2012, the industrial sector used 70% of China's primary energy and as much as 63% of total coal use.[12,iv] Compared

[i] *$220 billion to $4,586 billion (2005 U.S. dollar prices). $1 = 8.0747 RMB (Source: http://www.oanda.com/currency/historical-rates/; based on the average 2005 market exchange rate)*

[ii] *All figures in this report are rounded.*

[iii] *These figures vary by sources. For example, the World Bank in 2012 reported China's energy consumption as a percentage of the world total to be 19%. Additionally, the figures for contribution to GDP vary. Again, the World Bank's data estimate the share to be 11.4% for 2012, which differs from the IEA value used in this report.*

[iv] *Based on 2012 data from NBS's 2013 China Energy Statistical Yearbook, the industrial sector was responsible for 63% of total coal use in China, including electricity used by industry. This calculation is based on the physical amount of coal that is consumed (and reported). The amount of coal used as electricity in the industrial sector is derived based on the share of total coal use in China's total electricity production in 2012.*

FIGURE 1.1: CHINA'S GDP BY SECTOR

1980–2012

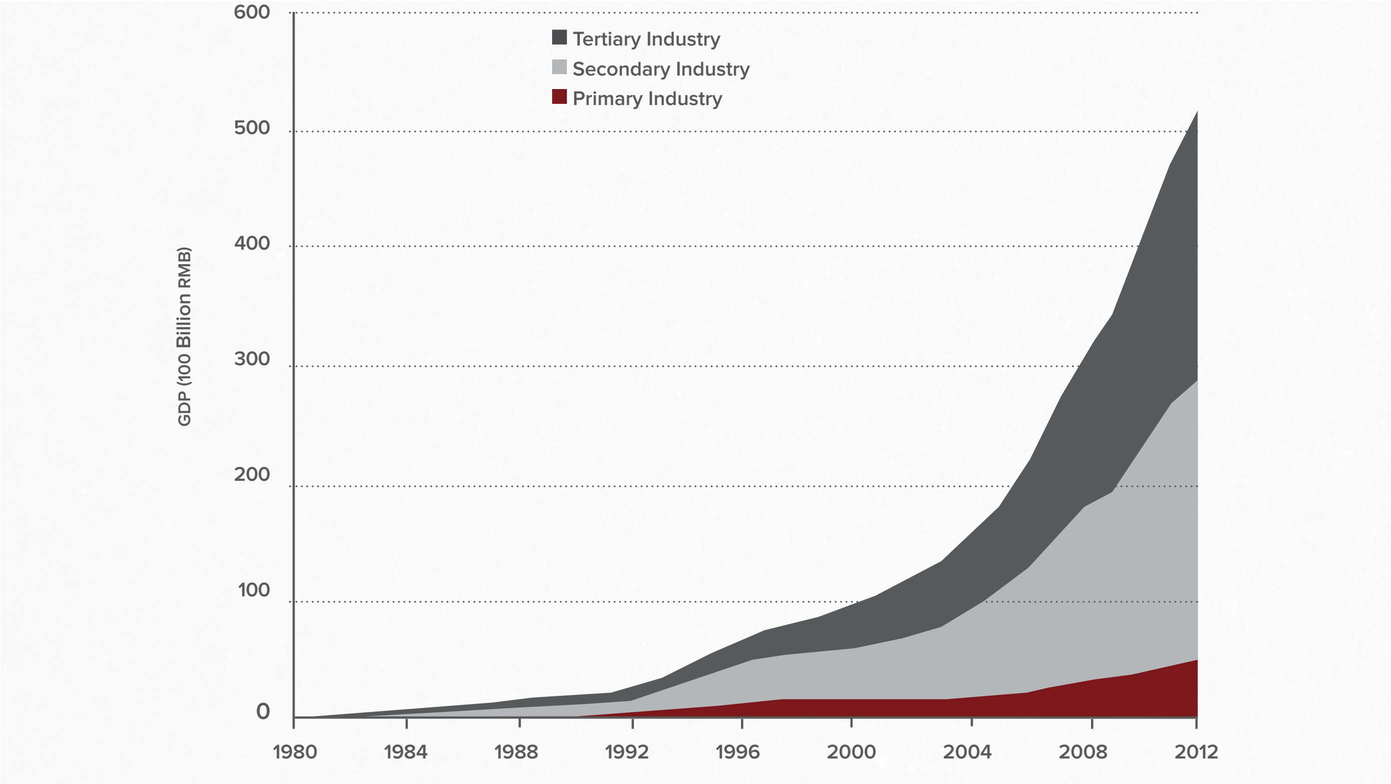
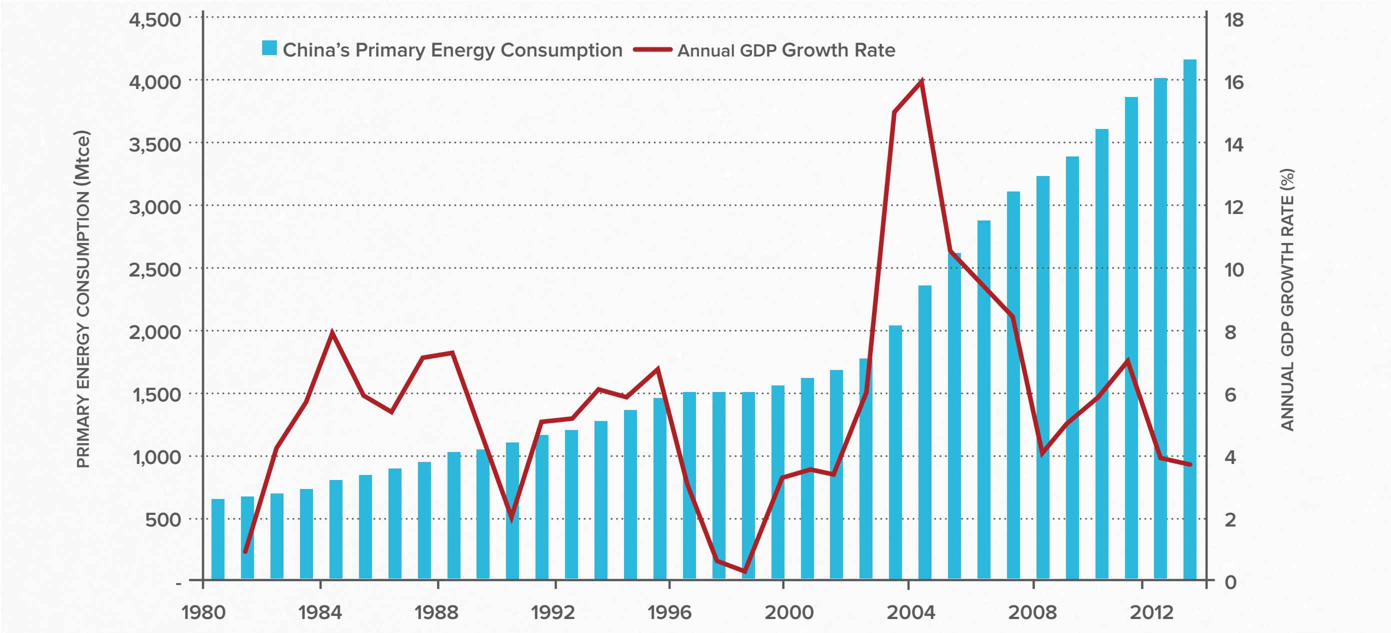


FIGURE 1.2: CHINA'S PRIMARY ENERGY CONSUMPTION AND ANNUAL GDP GROWTH RATE

1980–2013

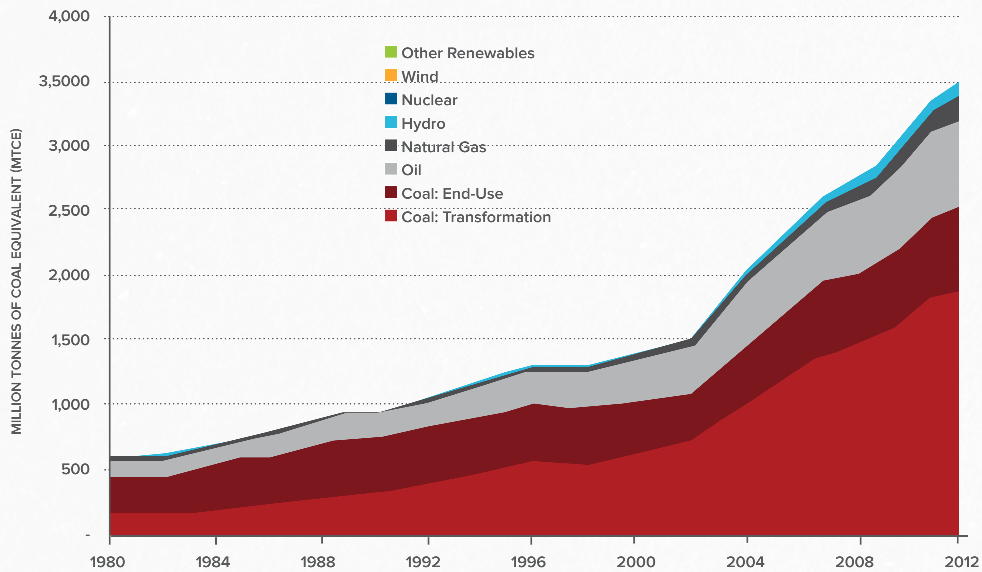


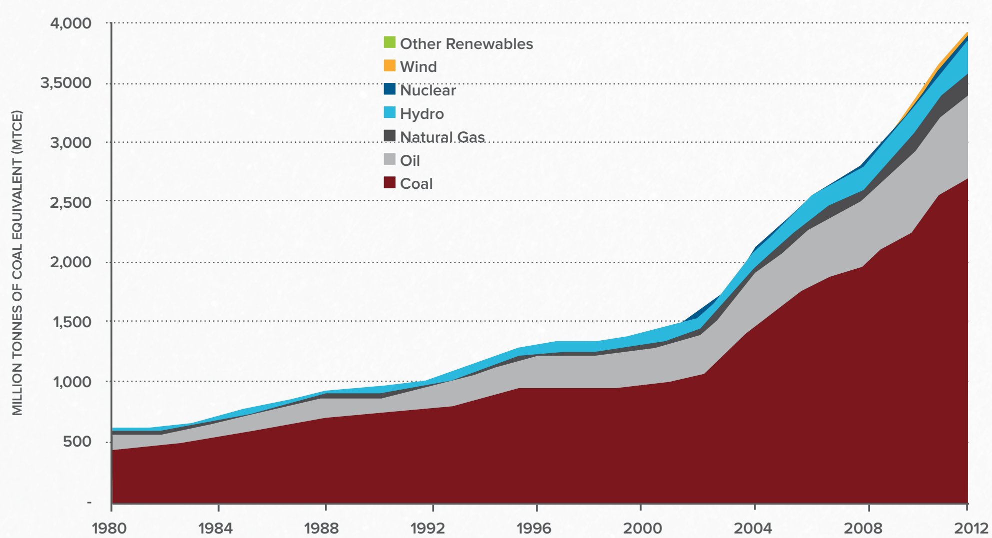
to developed countries, China's energy efficiency is reported to be almost 10% lower and energy intensity (energy consumption per unit of production) 40% higher on average for power, iron and steel, non-ferrous metals, petrochemicals, and other major industrial products.[13]

Fossil fuels still heavily dominate China's energy consumption, especially coal (Figure 1.3).[v] Between 1980 and 2012, coal use in China grew by 5.5 times, from 440 Mtce to 2,520 Mtce, and accounted for 67% of primary energy use,[14] far exceeding the coal shares in developed and many developing countries (Figure 1.4). From 1990 to 2012, China's coal consumption grew by 1,660 Mtce,[15] accounting for 86% of incremental global coal consumption.[16]

FIGURE 1.3: CHINA'S PRIMARY ENERGY FUEL MIX

1980–2012

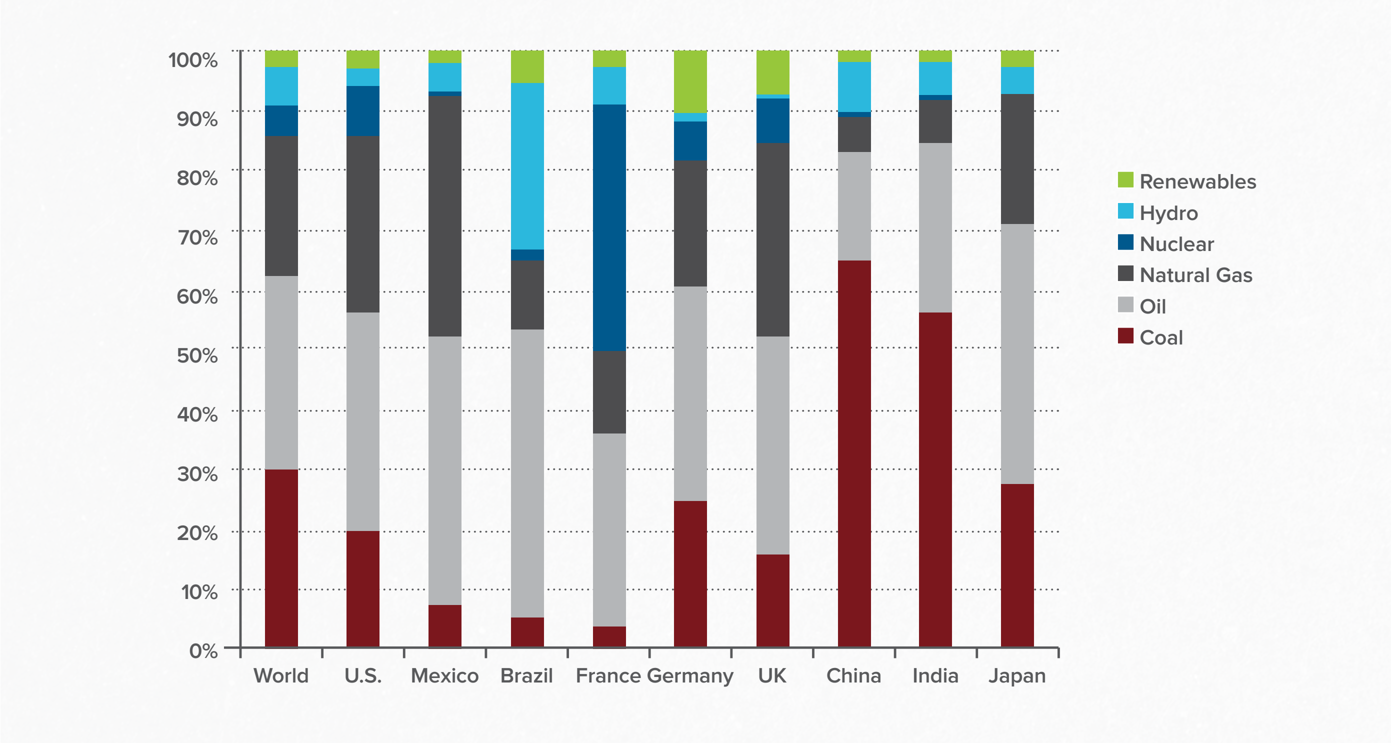




[v] *Note that this is using the China Coal Power Plant Equivalent Method to convert electricity to primary energy; using the Direct Equivalent Method the share of coal in total primary energy is 71% in 2012.*

FIGURE 1.4: PRIMARY ENERGY FUEL MIX FOR SELECT COUNTRIES[17]

2012



China's energy system is carbon-intensive. Surpassing the U.S. in energy-related CO_2 emissions in 2007, China is now the world's largest emitter of energy-related CO_2.[18] Even so, China's per-capita CO_2 emissions are relatively low compared to those of developed economies; in 2012, China's emissions were 6.08 tCO_2 per capita compared to about 10 tCO_2 per capita in Germany and Japan and just over 16 tCO_2 per capita in the U.S. (Figure 1.5).[19]

With the exception of coal, energy resources per capita in China are low—per capita reserves of natural gas and petroleum are only 9.9% and 5.5% of the global average, respectively.[20] If China repeats the development model of industrialized countries, it will strain resources and the ecosystem while negatively affecting the environment and energy security. With continuous growth in energy consumption, the largest development transition challenges for China are resource availability and environmental constraints.

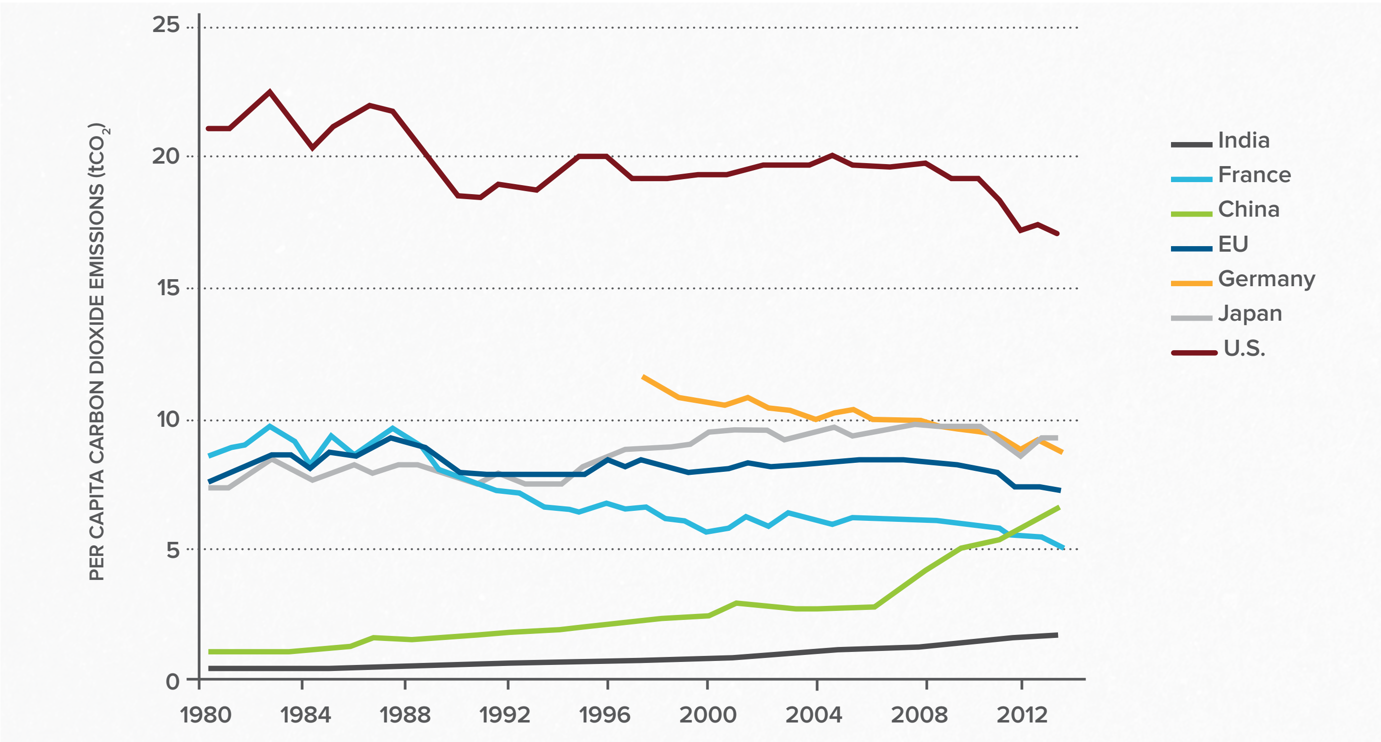
1.2 CONFRONTING ECOLOGICAL PRESSURES AND FACING CLIMATE CHANGE REQUIRES A CHANGE IN CHINA'S ENERGY SYSTEM

China's coal-based energy development brings significant environmental challenges. China's emissions of sulfur dioxide (SO_2), nitrogen oxide (NO_x), soot, and particulate matter are the world's highest. In 2013, SO_2 emissions were 20.44 million tons,[21] about three times those in Europe;[22] NO_x emissions were 22.27 million tons,[23] equal to those of the U.S. and 1.5 times the levels in Europe;[24] and releases of atmospheric mercury from human sources comprised 25–40% of the global total.[25]

Nationwide, 30% of China's urban population breathes air that doesn't meet air quality standards.[26] Acid rain falls in the Yangtze River Delta, the Pearl River Delta, the Beijing-Tianjin-Hebei (also known as *Jing-Jin-Ji* or *JJJ*) areas, and is expanding to other regions.[27] Haze and photochemical smog are serious problems in many cities as well. In some areas, emissions of heavy metals

FIGURE 1.5: PER-CAPITA ENERGY-RELATED CO_2 EMISSIONS FOR SELECT COUNTRIES

1980–2012



and persistent organic pollutants (POPs) are severe.[28] Because 90% of SO_2 emissions, 67% of NO_x emissions, 70% of dust emissions, 40% of atmospheric mercury from human sources, and 70% of CO_2 emissions come from coal combustion,[29] an energy development model that relies largely on coal not only irreversibly damages the environment, but also risks substantial economic loss to social and economic development. Analysis shows that the cost of environmental pollution and ecological damage was 1.54 trillion RMB in 2010, accounting for 3.5% of GDP that year.[30] The cost of environmental degradation in 2010 increased 3.7% compared to 2009 and this rate is 3.3% higher than the GDP growth rate of that year.[31]

Solving the pollution issue requires accelerating China's energy transformation. Without adequate control of pollution from traditional coal combustion and with the rapid growth of heavy chemical industries and vehicle ownership, regional composite air pollution with high concentrations of ambient fine particulate matter ($PM_{2.5}$) is worsening. Currently, 25 of China's provinces experience some degree of smog/pollution, affecting over 600 million people, with some cities having up to 200 days of smog events per year.[32] High concentrations of $PM_{2.5}$ harm respiratory and cardiovascular systems and threaten public health. A recent analysis found that air pollution from burning coal and other fossil fuels causes about 1.6 million premature deaths each year in China.[33] China's high consumption of energy and coal are the main causes of the country's compromised air quality. In 2012, China's coal consumption per land area was 370 tons/km^2—four times the U.S. level.[34] Coal consumption per land area was 2,270 tons/km^2 in the Yangtze River Delta, 1,790 tons/km^2 in the JJJ region, and 980 tons/km^2 in Guangdong province.[35] Under accelerated economic development and a sustained increase in energy consumption, total key pollutants need to decrease 70–80% to reach China's air quality improvement goals and by more than 90% in the JJJ area to reach the current levels of the U.S. and the EU.

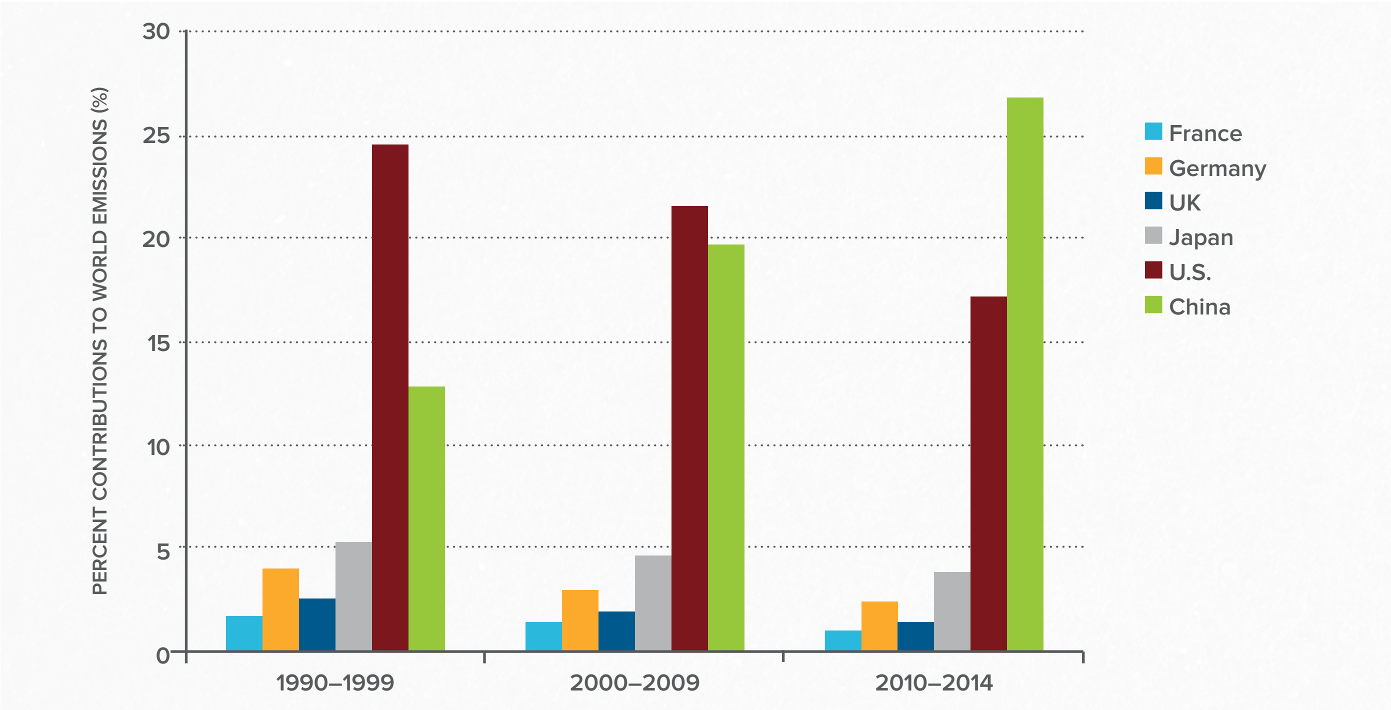
1.3 THE WORLD IS ENTERING A CRITICAL STAGE TO ADDRESS CLIMATE CHANGE; ENERGY PRODUCTION AND CONSUMPTION POSE CONSTRAINTS

The long-term objective to limit the increase in global average temperatures by no more than 2°C (3.6°F) above pre-industrial levels, as outlined in the recent Paris Agreement, will depend on whether global GHG emissions can peak and decline by 2050.[36] According to the Intergovernmental Panel on Climate Change's (IPCC's) *Fifth Assessment Report*, to achieve the 2°C goal, world GHG emissions must peak between 2010 and 2020, and 2050 emissions should be 41–72% below 2010 levels.[37] China is the world's largest emitter of CO_2; its total emissions will soon approach the combined emissions of the U.S. and the EU.

China's CO_2 emissions per capita exceed those of some EU countries[vi,38] and continue to grow (Figure 1.6 and Figure 1.7). Because China is the main contributor to global incremental CO_2 emissions, China intends to control its GHG emissions and take on more international responsibility. As such, the Chinese government proposed to peak CO_2 emissions around 2030 and will strive to peak earlier. To realize this goal, coal consumption needs to peak quickly to accommodate future increases in natural gas and oil consumption.[39] During the 13th Five-Year Plan period, more developed cities and regions will need to lead in peaking CO_2 emissions early, making it even more urgent to change China's energy and economic development model.

FIGURE 1.6: CONTRIBUTIONS TO WORLD CO_2 EMISSIONS FOR SELECT COUNTRIES

1990–2014



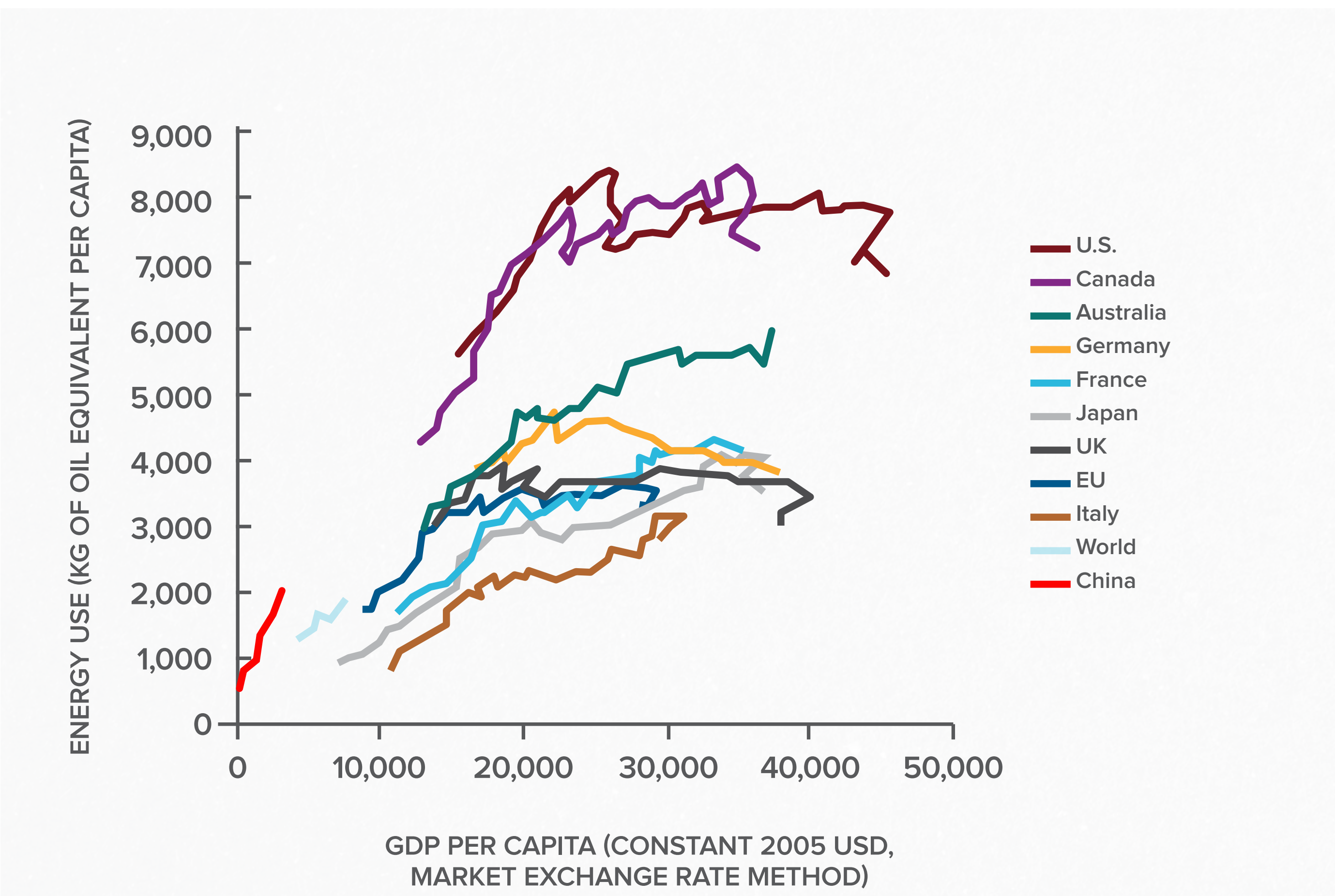
[vi] *Romania, Portugal, and Lithuania.*

1.4 BUILDING A MODERN CHINESE ECONOMY REQUIRES ACCELERATING CHINA'S ENERGY REVOLUTION

Energy is the basis of modern economic and social development. China's traditional economic growth model is characterized by imperfect and emerging markets, insufficient resources, environmental degradation, a lack of competitiveness, and other constraints. Together these factors created a system composed of "four highs and four lows": high inputs, high consumption, high pollution, and high speed, but low output, low efficiency, low profit, and low technology.

Resource availability and environmental issues are universal challenges. A recent study shows that since 1966, global human demands on natural resources doubled.[40] If current trends continue, by 2050 humanity would need 2.9 planet Earths to meet its needs.[41] For the majority of developing countries, the development path and model used by developed countries are difficult to replicate. Instead, these countries have the opportunity to explore new cost-effective sources of energy production, new consumption patterns, and foster new means to realize modern development.

FIGURE 1.7: PER-CAPITA ENERGY CONSUMPTION AND GDP FOR SELECT COUNTRIES



1.5 REINVENTING FIRE IS CHINA'S PATH FORWARD

Many developed countries are entering a period of energy transformation and building more-sustainable energy systems. With the significant changes in the world economy after the 2008 financial crisis, growth in global energy demand has slowed. Energy demand in some developed countries has plateaued or even declined. China, India, and other developing countries have become the world's new sources of energy demand.

Developed countries are taking actions and making commitments to improve the environment, energy security, and accelerate the development of energy-efficient, low-carbon energy systems. The European Union (EU) committed to cut CO_2 emissions by at least 40% by 2030 over a 2010 baseline.[42] Further, the EU proposed to improve energy efficiency by 20%, increase the share of renewable energy to 20%, and reduce primary energy consumption 20% by 2050 compared to 1990. By 2050, GHG emissions will be cut by 80–95% compared to 1990 and the share of renewable energy in final energy consumption will reach 75%.[43] Germany has proposed that its primary energy consumption decrease 50% by 2050 compared with 1990, expanding the renewable energy share to 60%.[44] Denmark proposed to establish a fully fossil-fuels-free and nuclear-free energy system.[45]

In the November 2014 *U.S.-China Climate Change Joint Announcement* and in the subsequent March 2015 Intended Nationally Determined Commitment (INDC) submission in accordance with the Paris Agreement, the United States committed to reduce net GHG emissions 26–28% below 2005 levels by 2025.[46,47] In June 2015, China submitted its INDC, committing to "achieve the peaking of CO_2 emissions around 2030 and making best efforts to peak early, lower CO_2 emissions per unit of GDP by 60%–65% from the 2005 level, and increase the share of non-fossil fuels in primary energy consumption to around 20%."[48] At the recent Group of Seven (G7) summit, member countries acknowledged the latest IPCC recommendation of 40–70% reductions in GHG emissions by 2050 compared to 2010 levels and committed to "doing our part to achieve a low-carbon global economy in the long term including developing and deploying innovative technologies striving for a transformation of the energy sectors by 2050."[49]

Global energy market changes and technological innovation are accelerating. Since the international financial crisis, the world's major countries have increased investment in energy research and development (R&D), focusing on breakthroughs in energy conservation, low-carbon technologies, energy storage, and other key areas to accelerate the development of strategic new industries and to foster a new round of global energy revolution. For example, in 2009, the U.S. spent $27.2 billion in energy efficiency, renewable energy research, and investments

to promote energy efficiency, electric vehicles, smart grids, wind turbine manufacturing, solar energy, biomass fuels, and other technologies under the *American Recovery and Reinvestment Act*.[50] The European Commission has developed the *European Strategic Energy Technology Plan* to accelerate the development and deployment of low-carbon technologies with new energy and renewable energy technology innovation as the core.[51] In late 2016, 23 countries representing 80% of global clean energy investment vowed to double their clean energy R&D funding to around $30 billion in 2021.[52] Private money is flowing too; in 2015, Bill Gates launched the Breakthrough Energy Coalition that seeks to accelerate innovation in new energy technologies.

The third industrial revolution relies on innovation in energy technology combined with innovation in information technology, Internet of Things (IoT), cloud computing, and smart cities. Five pillars support this new revolution:

1. transition from fossil energy system to renewable energy,
2. transition from centralized to distributed production and use,
3. development of energy storage technology,
4. internet technology with energy sharing, and
5. zero-emissions and clean vehicles.[53]

Compared with developed countries, China's major energy-intensive sectors still have the potential for significant technological advances. Both advanced and outdated production capacity co-exist in China, and there is room for greater adoption of advanced and mature energy-saving technologies. While energy intensity in some of China's industries and companies is on par with international advanced levels, the average level of industrial equipment and technology still lags compared with advanced levels. Particularly in small and medium enterprises (SMEs), there is a large potential for technological advances. The focus of China's current energy-saving technology still emphasizes energy savings of a single technology, without sufficient attention to energy system optimization of upstream and downstream equipment, across sectors and across industries.

Annual GDP growth in China averaged 10.0% from 1984 through 2014, but growth has slowed in recent years. Between 2011 and 2015 growth averaged 7.8%, a gradual slowdown that is referred to as the "New Normal." Slower growth is inevitable as China's economy matures. China must find new ways to increase the value it produces for the energy and effort applied by its citizens if it is to avoid the middle-income trap that has previously ensnared many developing economies.[54] At the Asia Pacific Economic Cooperation Forum in Beijing in November 2014, President Xi Jinping explained that "a new normal of China's economy has emerged with several notable features: First, the economy has shifted gear from the previous high speed to a medium-to-high-speed growth. Second, the economic structure is constantly improved and upgraded. Third, the economy is increasingly driven by innovation instead of input and investment."[55] Restructuring the economy and increasing innovation are critical approaches to ensure China's development objectives.

As the world's largest energy-producing and -consuming country, China has the largest market for energy production and energy-using technology. Potential advances for China include adopting smart grids and intelligent energy management systems, innovating energy-intensive industrial processes (e.g., non-blast furnace ironmaking through direct reduction and smelting reduction, co-processing municipal waste technology in cement and iron and steel enterprises), promoting efficient building construction and retrofits, and deploying low-carbon mobility systems. All of these improvements are greatly enhanced by information technology advances. Reinventing China's energy production and consumption systems is critical to cultivating a new source of growth, breaking through the middle-income trap, and realizing China's modernization and development goals.

The Reinventing Fire research results presented in this report provide an energy roadmap that achieves China's revolution in energy production and consumption while supporting both national development and global solutions to our common energy challenge.

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02 ANALYSIS APPROACH & METHODOLOGY

ANALYSIS APPROACH & METHODOLOGY

IN 2013, Energy Research Institute (ERI), the energy think tank of China's National Development and Reform Commission, the China Energy Group of Lawrence Berkeley National Laboratory (LBNL), independent energy think tank Rocky Mountain Institute (RMI), and Energy Foundation China undertook a joint three-year research effort to understand how energy efficiency, demand reduction, system optimization, product quality improvement, renewable energy sources, and other options could be deployed to address China's most pressing energy challenges and support China's development goals.

The study's vision is that through pursuing a "Reinventing Fire" pathway, China can meet the growing energy needs of its population with a clean, low-carbon, efficient, safe, reliable, and cost-effective modern energy system. Successfully achieving the Reinventing Fire vision will support Chinese government goals to create a "Beautiful China" (a balanced ecological and economic system), support efforts to achieve the country's "Two 100-Year" and "China Dream" goals, promote the development and scaling of solutions to global energy challenges,[1] and support China's Paris Agreement commitments.

2.1 REINVENTING FIRE: CHINA ANALYSIS APPROACH

Reinventing Fire: China provides an analytical assessment of a pathway 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 through 2050.

The Reinventing Fire: China analysis is a scenario-based assessment that compares two possible energy pathways for China to 2050. The Reinventing Fire: China analysis is designed to support China's development goals through calibrating assumptions around key inputs such as population, GDP targets, and urbanization rates. An Advisory Panel comprising Chinese government and academic advisors guided the analysis; key assumptions were vetted with topic-specific experts in China.

2.2 REINVENTING FIRE: CHINA METHODOLOGY

Reinventing Fire: China uses scenario analysis, system analysis models, best-practice case studies, international comparison analysis, and cost-effectiveness analysis to produce its results. The approach combines top-down and bottom-up analysis techniques, relies on energy consumption and other data from China combined with international information and data sources, and uses a robust analytic model to assess the technical and economic potential of alternative energy pathways in China through 2050. The team systematically and quantitatively researched mid- and long-term energy development and analyzed specific technical roadmaps, cost effectiveness, and environmental and social impacts. This research used experiences and lessons from the U.S., Europe, Japan, and other developed and developing countries, including more than 80 technical and policy case studies from China and other countries.

The Reinventing Fire: China analysis is based on public statistics, domestic and international references, literature, case studies, and investigative research. It considers the latest energy statistical adjustment made by the National Bureau of Statistics (NBS)[2] and the government's most recent GDP projections. Significant changes occurred during the 36-month analysis process that the research team incorporated into the results. In 2016 the research team recalibrated the analytic model to reflect China's revised GDP growth forecasts, reducing 2016–2020 GDP growth rates (the period covered by the 13th Five-Year Plan), from 7.3% to 6.5%. The analysis team made corresponding adjustments to mid- and long-term GDP growth rates and reduced freight and passenger activity in the transport sector and manufacturing value added and physical inputs in industrial subsectors accordingly. As a result of the revisions, this report contains a roadmap for China to deliver on its near- and long-term goals, taking account of the most current reported statistics and forecasted growth rates.

The top-down analysis is based on macro-level inputs of GDP, population, and urbanization (see Appendix A), the experiences and lessons of advanced countries, combined with China's conditions, development stages and levels, and forecasts of future economic development, activity levels, energy demand, and environmental status while helping to realize China's modernization development goals.

The bottom-up analysis is focused on the energy end-use sectors of China's economy: industry, buildings, transportation, and transformation (focusing on electricity but also including other energy supply sectors). The analysis includes assessments of sectoral energy demand and activity levels, structural change, and fuel switching, and provides technical and policy roadmaps, calculates cost effectiveness, and discusses related environmental impacts under the two scenarios.

2.3 MACROECONOMIC ASSUMPTIONS

Three key macroeconomic assumptions were used in the Reinventing Fire: China analysis: population growth, urbanization rates, and GDP growth rates (see Appendix A). The projected population growth and urbanization rates to 2050 are based on data from China's NBS[3] and the projected GDP growth rates to 2050 are based on data from China's NBS[4] and the China Microeconomic information network.[5,6] Each macroeconomic assumption was compared to international projections from the United Nations,[7] the U.S. Census Bureau,[8] the World Bank,[9,10] the U.S. Federal Reserve System,[11] the International Energy Agency (IEA),[12] the U.S. Energy Information Administration,[13] PricewaterhouseCoopers,[14] the Organization for Economic Cooperation and Development (OECD),[15] and the Integrated Assessment Modeling Consortium.[16]

These key macroeconomic variables were used to inform key assumptions used in the models, including:

- **Population:** China's population will peak in 2030 at 1.43 billion, an increase of 93 million over 2010 levels and then decline to 1.37 billion in 2050 (Figure 2.1).
- **Urbanization:** In 2050, China's urbanization rate will be 78%, with 400 million more people living in cities than in 2010 (Figure 2.2).
- **GDP:** Adjusted for the "New Normal," China's GDP will grow 6.5% during 2016–2020, and slow to 2.6% during 2046–2050 (Figure 2.3).
- **Overall:** China's GDP will reach 245 trillion RMB ($40.87 trillion in 2010 dollars), 6.9 times the 2010 level and GDP per capita will be 179,390 RMB ($29,900 2010 dollars), increasing 6.7 times compared to 2010.

FIGURE 2.1: CHINA'S PROJECTED POPULATION

2010–2050

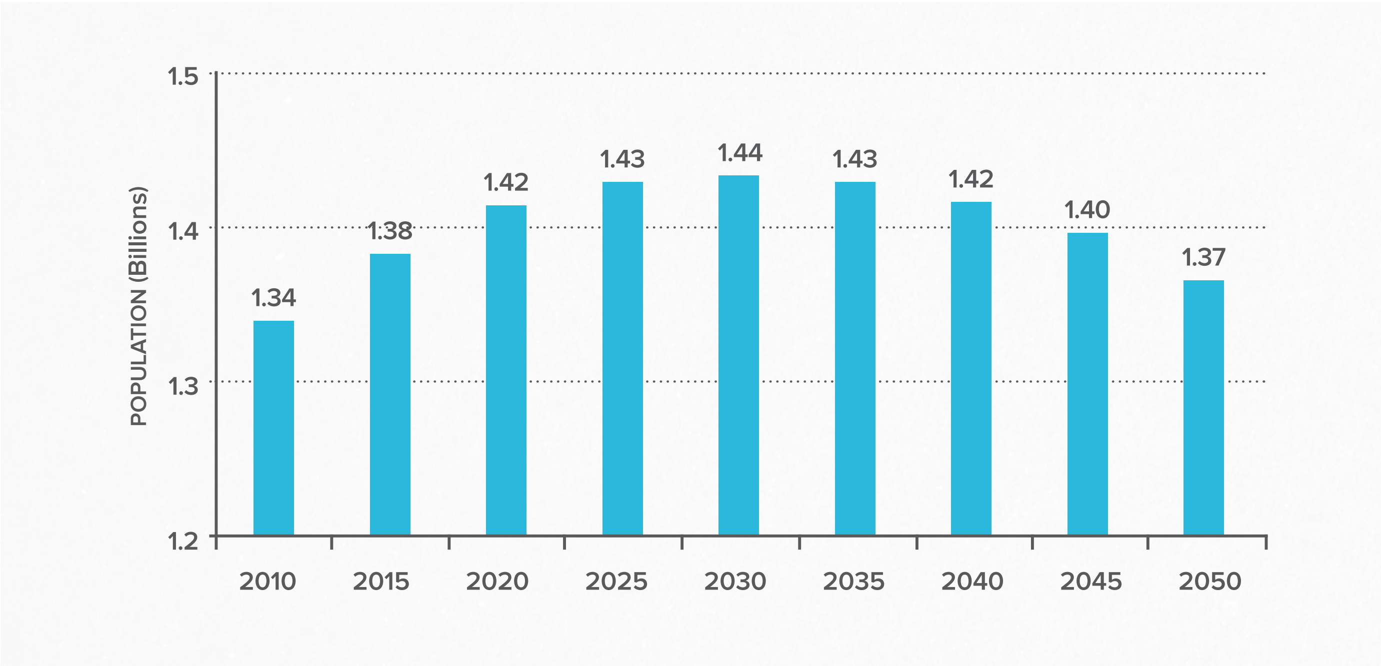


FIGURE 2.2: CHINA'S PROJECTED URBANIZATION RATE

2010–2050

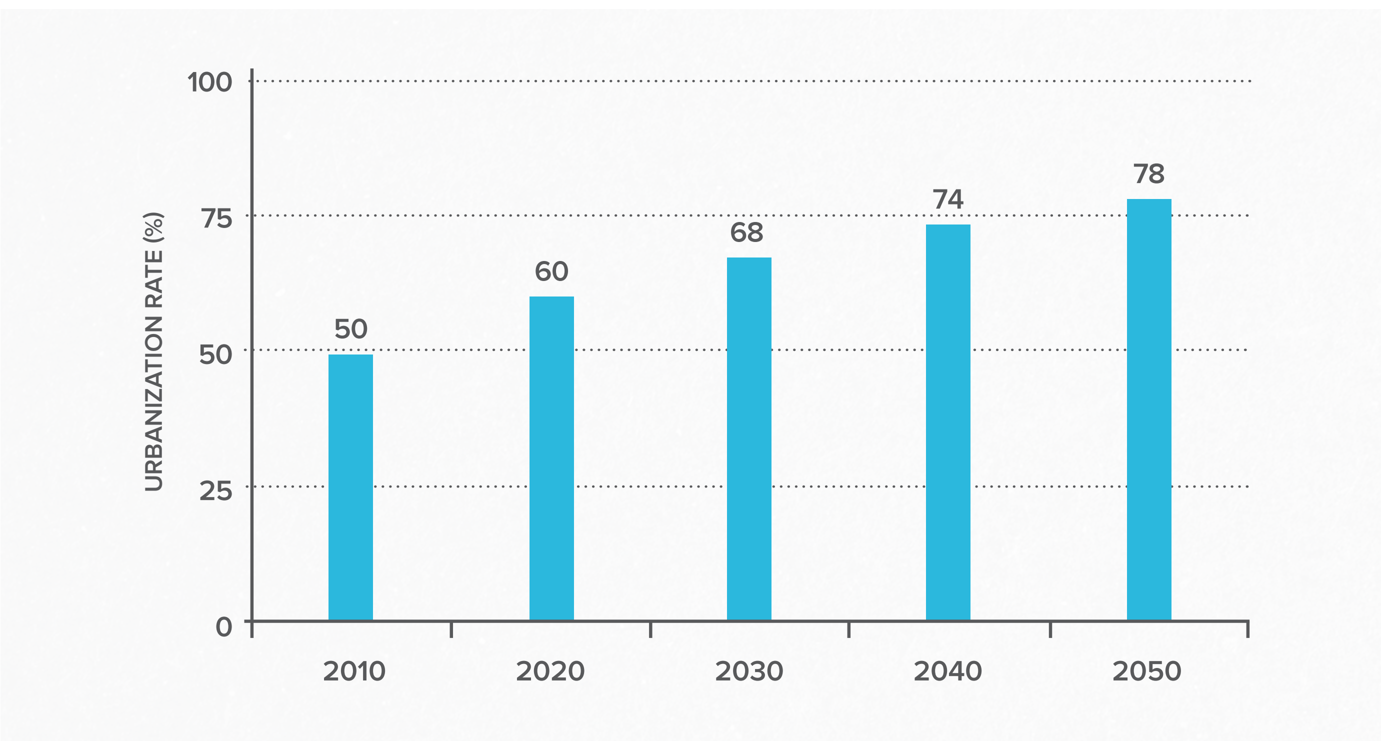
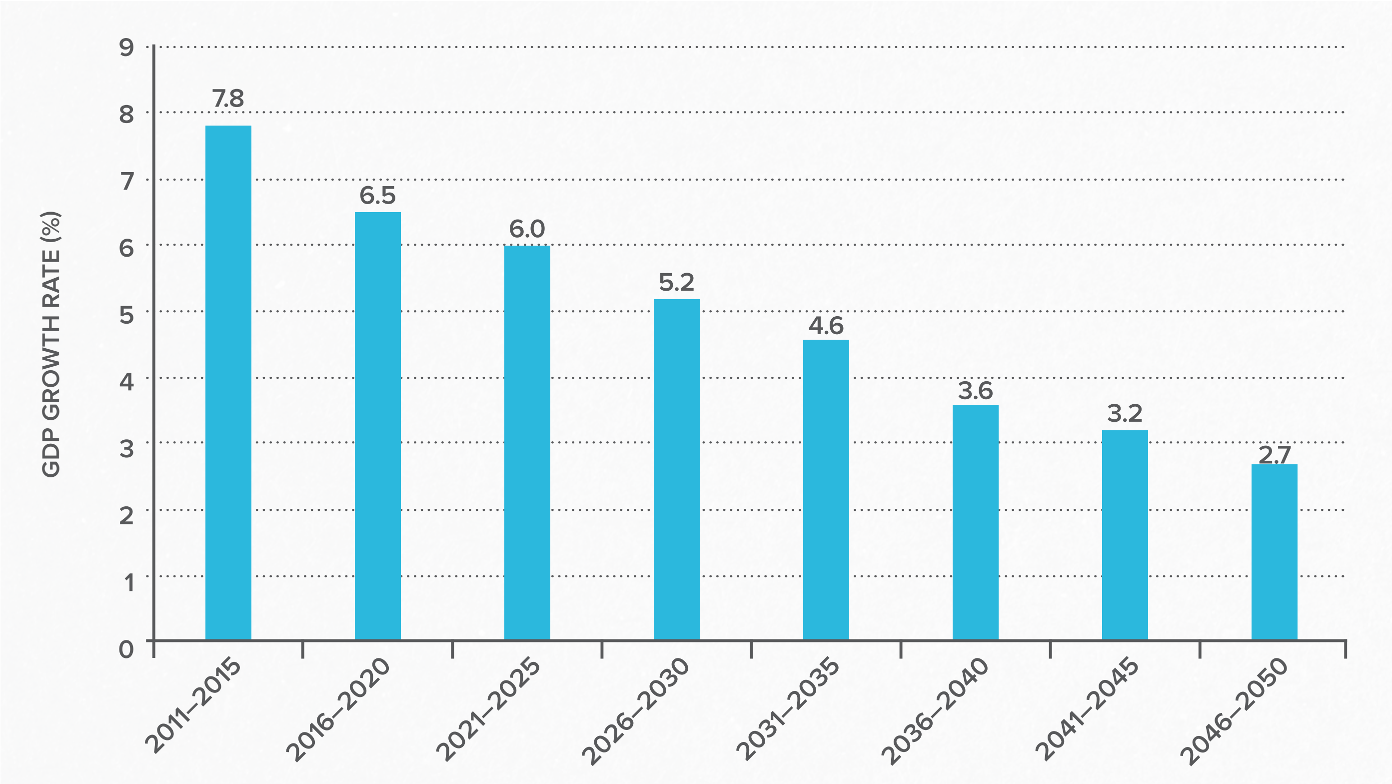


FIGURE 2.3: CHINA'S PROJECTED GDP GROWTH RATE

2010–2050



2.4 DEFINITION OF SCENARIOS

The Reinventing Fire: China analysis developed and assessed two distinct scenarios: a Reference Scenario and a Reinventing Fire Scenario.

Reference Scenario

Under the Reference Scenario, only policies in place in 2010 continue to have effect, and autonomous technological improvement occurs; this scenario does not consider technological breakthroughs or major policy changes. The analysis starts with China's current policies and current development trends, referencing development trends and socio-economic development levels of key industrialized countries. Combined with China's conditions, this scenario describes the energy demand to reach a fully developed country by 2050, but one that still heavily depends upon fossil fuels to support its economy.

Reinventing Fire Scenario

Under the Reinventing Fire Scenario, China meets its energy needs and improves its energy security and environmental quality by deploying the maximum feasible share of cost-effective energy efficiency and renewable supply through 2050. This scenario provides an outlook of the energy demand and structure to reach China's modernization goals by analyzing future activity levels, structural change, technological advancement, and energy requirements of the industry, buildings, transportation, and transformation sectors. The analysis assesses specific pathways that are economically viable and technologically advanced.

In both scenarios, only technologies that are commercialized or piloted at scale as of 2014 are considered. All technologies are considered to have ongoing cost reductions consistent with recent trends. (Appendix A provides the key assumptions for each scenario by sector.)

2.5 SECTOR ANALYSIS

The Reinventing Fire: China analysis focuses on four key end-use energy-consuming sectors of China's economy: buildings, transportation, industry, and transformation (which includes electricity and energy supply). For each sector, extensive research and modeling was conducted to understand the most cost-effective, technologically feasible means for China to meet its overarching development goals, while also meeting individual sector goals in support of the Reinventing Fire: China vision. The sector-level visions that guided this analysis are that by 2050:

- Buildings and communities will be self-sustained and resilient with increased comfort levels.
- Industry will be world-class in terms of energy efficiency and will have moved away from carbon-intensive fuels.
- Transportation systems will provide increased mobility, but more efficiently, with fewer emissions and lower costs.
- Transformation will provide the foundation for a dynamic economy and resilient nation, ensuring the health of the people and the restoration of the ecological environment with a resource supply mix that is secure, flexible, clean, and affordable.

Technical improvement options are considered within each sector that efficiently and cost-effectively reduce demand and environmental impacts.

2.6 MODELING

The Reinventing Fire: China analysis uses two complementary models to assess the future energy-demand pathways of the Reference and Reinventing Fire Scenarios. The primary model is built on the Long-Range Energy Alternatives Planning (LEAP) model platform,[17] and combines ERI's previously constructed 2050 sector analysis modules with LBNL's China 2050 Demand Resource Energy Analysis Model (DREAM) into a single composite model. In addition, the Reinventing Fire: China analysis also uses the Electricity and District Heating Optimization (EDO) modeling platform to analyze China's electricity and thermal networks.[i] Results from the EDO analysis are integrated into the LEAP model to create a final integrated Reinventing Fire: China 2050 model. Additional information on these two modeling platforms and how they have been integrated to create the integrated Reinventing Fire: China model is in Appendix B.

The Reinventing Fire: China 2050 model includes the industry, buildings, transportation, and power sectors and also considers agriculture, construction, mining, oil refining, coking, coal to oil/gas, and other non-power transformation sectors. The industry sector has 21 subsectors and distinguishes energy-intensive sectors from other manufacturing sectors and analyzes product structures based on different production processes. The buildings sector is split by climate zones and has residential, commercial, and public buildings. The buildings sector also includes heating, lighting, cooking, and appliances in existing and new buildings in urban and rural areas. The transportation sector analyzes the demand of freight and passengers, differentiating railway, road, shipping, aviation, and pipelines. Based on different city scales (large, medium, and small), the transportation sector also considers different transportation structures across and within cities and different types and fuels of transport vehicles. The transformation sector covers electricity, combined heat and power, and heat supply modules, and analyzes coal, natural gas, oil, nuclear, hydro, wind, solar, biomass, and geothermal power generation, and assesses power generation units with different energy sources and varying installed capacity levels. The transformation sector also looks at supply potential for emerging resources, such as unconventional gas and oil production, coal-to-gas, coal-to-liquids, and biofuels.

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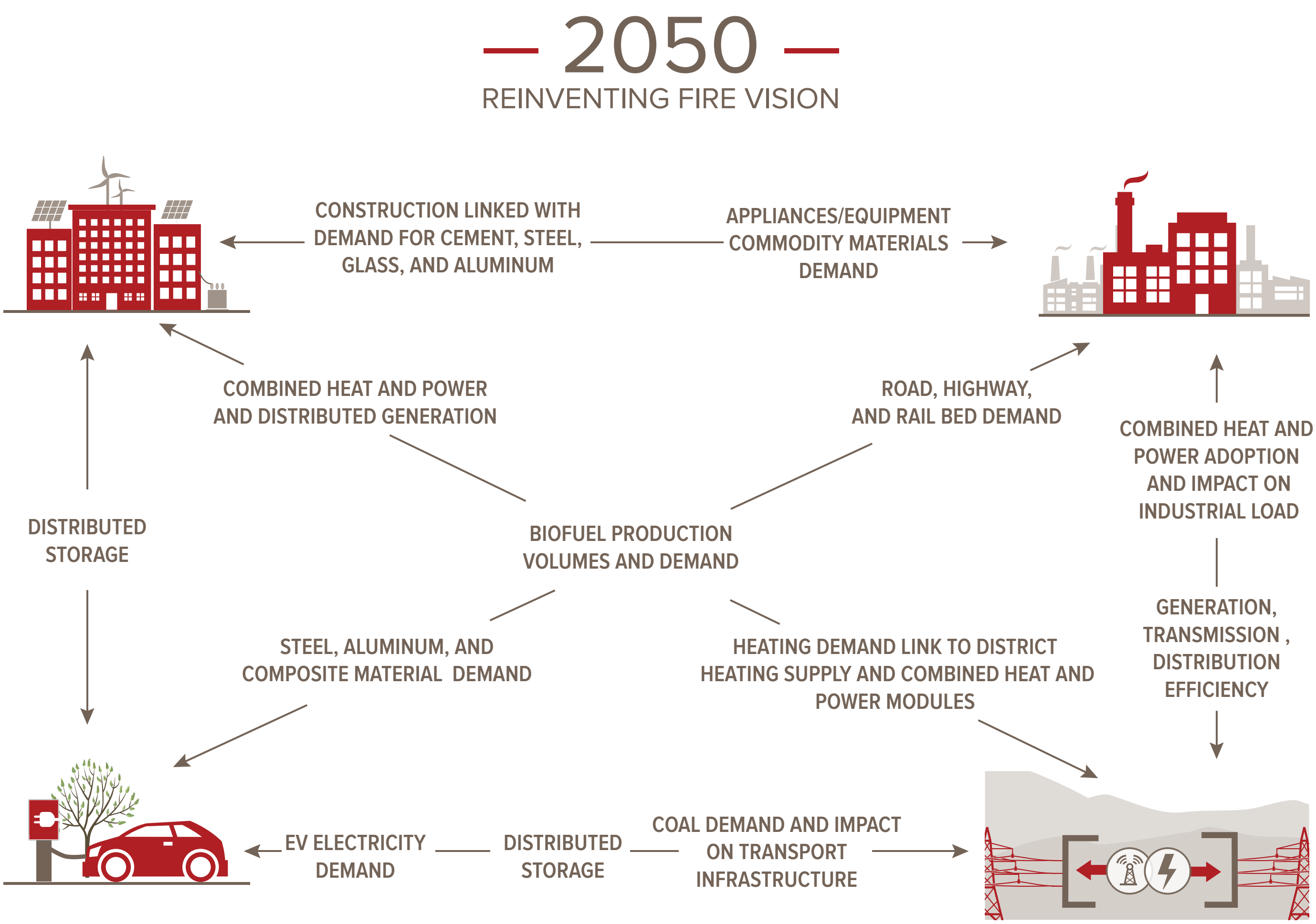
[i] The China Renewable Energy Analysis Model – Electricity and District Heating Optimization (CREAM-EDO, or EDO for short) is a power system planning and policy simulation tool co-developed by ERI, China National Renewable Energy Center, Sino-Danish Renewable Energy Development Program, and the U.S. Department of Energy.

This study establishes comprehensive, systematic quantitative linkages between the macro economy, industrial development, energy demand, subsector activity levels, structure status, technological choices, and the energy structure. The Reinventing Fire: China study uses an integrated sector modeling approach that quantitatively assesses the coupling relationships across various sectors, upstream and downstream industries, and supply and demand relationships. This includes the impact on industrial sectors (such as the demand for iron and steel and cement) by reducing total buildings floor space, the impact on transportation sector (such as the demand for bulk cargo transportation) by optimizing industrial structures and layouts, the impact on the power sector (such as flexible power management through vehicle-to-grid storage) by popularizing electric vehicles in the transportation sector, the impact on energy-intensive products by promoting industrial eco-parks, integrative buildings, and electric vehicles, and the impact on industry, transportation, buildings, and power sector activities from urbanization (Figure 2.4).

FIGURE 2.4: INTEGRATED MODELING APPROACH FOR REINVENTING FIRE: CHINA



A B C D E ES 01 02 03 04 05 06 07 08 09 CHAPTERS APPENDIX A APPENDIX B APPENDIX C APPENDIX D

2.7 COST-EFFECTIVENESS ANALYSIS METHOD

The Reinventing Fire: China analysis describes a pathway for how China can transform its energy economy using existing, cost-effective technologies that have already reached mature levels of commercialization. All improvement measures for each sector are evaluated for cost effectiveness. The Reinventing Fire: China study uses net present value (NPV) calculations to analyze the additional investment costs and net economic benefits of the Reinventing Fire Scenario compared to the Reference Scenario. The study evaluates the cost effectiveness of the proposed technological options using lifecycle and system analysis approaches to ensure the economic feasibility of the Reinventing Fire pathways developed for each sector. For each specific technology, this study calculates the needed investment cost, possible additional operational and maintenance cost, and energy-saving benefits. Based on relevant research, this study uses a 5% real social discount rate.[ii] In the cost estimation, this study does not take into account possible financing and management transaction costs when implementing the technological and policy solutions. When analyzing the cost effectiveness, this study also does not take into account the health or environmental benefits of implementing the Reinventing Fire Scenario. Additional information on the cost-effectiveness calculation methodology is contained in Appendix C.

2.8 PRIMARY ENERGY REPORTING AND EMISSIONS CALCULATIONS

Primary energy refers to the energy contained in natural resources prior to conversion or transformation into other forms such as electricity. Primary energy includes fossil resources such as coal, crude oil, and natural gas, as well as non-fossil resources such as uranium, sunlight, wind, running water, and geothermal heat. In the case of these non-fossil energy sources, however, it is not useful, for purposes of energy systems analysis, to calculate the nuclear, solar, kinetic, or thermal energy of these forms prior to their capture and conversion to electricity. As a result, different conventions have been developed to calculate the energy value of electricity produced by these non-fossil primary energy forms ("primary electricity") when reported in standardized energy units such as joules, British thermal units (Btus), tons of oil equivalent (toe), or tons of coal equivalent (tce) in the case of China.

Internationally, three different methods are used to convert primary electricity into standardized energy units: the Direct Equivalent Method used by the IPCC[18] and the United Nations,[19] the Substitution Method used by the U.S. Energy Information Administration,[20] and the Physical Energy Content Method used by the International Energy Agency, the Organization for Economic Cooperation and Development, and Eurostat.[21]

In addition to these three methods, China has its own unique Power Plant Coal Consumption (PPCC) method[iii] in which non-fossil electricity sources (nuclear, hydropower, solar photovoltaic, solar thermal, wind, and geothermal) are converted to standard units based on the average heat rate (kilograms of coal equivalent per kilowatt-hour, kgce/kWh) of coal-fired power plants each year. For example, the conversion for 2010 is 1 kWh = 0.3197 kgce (9.4 MJ) for these resources.

This report provides primary energy results using the Direct Equivalent Method. For this method, all non-fossil electricity (nuclear, hydropower, solar photovoltaic, solar thermal, wind, and geothermal) is converted assuming 1 kWh = 0.1229 kgce (3.6 MJ).

[ii] There is much discussion on the proper discount rate for developing countries. China's 10-year government bonds, a reasonable proxy for the risk-free social discount rate, have historically ranged between a record low of 2.51% in December 2008 and 4.85% in November 2013. To be conservative, the Reinventing Fire: China analysis uses a discount rate of 5% at the upper end of this range. This is lower than the 8% suggested by Zhuang et al. (2007, Asian Development Bank) for short-term investments. For long-term investments, Zhuang et al. simply recommend "a number lower than 8%."

[iii] For further information about the difference between the IPCC and PPCC methods of conversion, please see the article in Science. 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.

TABLE 2.1: IPCC AND CHINA-SPECIFIC FOSSIL FUEL EMISSIONS FACTORS

Unit: tCO_2/tce	IPCC Recommended Emission Factors	China-specific Emission Factors
COAL	2.79	2.72
PETROLEUM	2.15	2.17
NATURAL GAS	1.64	1.63

Energy-related CO_2 emissions are not calculated in the LEAP model but rather are made as additional calculations using the LEAP model results as inputs. Energy-related CO_2 emissions at the national, sector, and subsector levels were calculated using the primary energy results for all fossil fuels reported by the LEAP model and China-specific CO_2 emissions factors for these fuels. The LEAP model provided the model results for the total primary energy consumption of bituminous coal, natural gas, and crude oil and oil products. The primary energy consumption of each individual fuel is then multiplied by that fuel's CO_2 emissions factor to calculate its energy-related CO_2 emissions.

For example, the energy-related CO_2 emissions from coal consumption are calculated as:

> Energy-related $CO_{2\ coal} = PEC_{coal} \times CO_2\ EF_{coal}$
> where:
> PEC_{coal} is the primary energy consumption of coal, in Mtce, and
> $CO_2\ EF_{coal}$ is the China-specific CO_2 emissions factor for coal, in tCO_2 per tce.

The sum of CO_2 emissions from coal, natural gas, crude oil, and oil products is taken to be the total energy-related CO_2 emissions. The Energy Research Institute provided the China-specific CO_2 emissions factors used in this study, which are similar to the IPCC emission factors (Table 2.1).[22,23]

Energy-related sulfur dioxide (SO_2), nitrous oxide (NO_x), and particulate matter (PM) emissions are calculated using emissions factors and calibrating the actual adoption of emissions control technologies to 2010 in order to project emissions and the penetration of emissions control technologies to 2050.

2.9 CASE STUDIES

The Reinventing Fire: China analysis relies on a number of real-world examples to provide information on technologies and practices used to save energy, reduce demand, fuel-shift, and reduce energy-related emissions. These case studies—which are based on actual implementation of these technologies and practices both in China and other countries—provide information on the commercialization status of each option, barriers to its implementation, capital costs, realized energy savings and energy-related CO_2 emissions reductions, realized cost savings, and any other associated benefits such as reduction of air pollutants, water savings, increased productivity, and health benefits.

In total, 86 case studies provided insights to the Reinventing Fire: China analysis. These case studies are for the buildings (18), industry (32), transportation (14), and transformation (22) sectors.

2.10 EXPERT INPUT AND REVIEW

Experts from a diverse set of fields and disciplines guided the Reinventing Fire: China research, assisting in the calibration of assumptions and offering critical feedback throughout the three years of research. Four distinct processes ensured that the Reinventing Fire analysis is rigorous, accurate, and closely vetted by subject matter experts, policy makers, and leading industry practitioners: convening an Advisory Panel, convening industry roundtables, ad hoc expert engagement, and final report review.

Advisory Panel: The project team established an Advisory Panel of distinguished energy experts, government officials, and international business leaders to steer the analysis from its inception. The Advisory Panel convened 10 times during the 36-month project and helped establish the initial scope of the work, highlighted critical areas of focus, and judiciously assessed interim and final results.

Advisory Panel Members included:

- 刘燕华 Liu Yanhua (Chair): Councilor of the State Council
- 赵家荣 Zhao Jiarong: Deputy Secretary General, National Development and Reform Commission
- 吴 吟 Wu Yin: Deputy Director, National Energy Administration
- 李海燕 Li Haiyan: Deputy Director General of Foreign Affairs Department, National Development and Reform Commission
- 白荣春 Bai Rongchun: Former Director General, Energy Bureau, National Development and Reform Commission
- 何建坤 He Jiankun: Former Executive Vice President, Tsinghua University
- 魏一鸣 Wei Yiming: Dean of the School of Management and Economics, Beijing Institute of Technology
- 张欣欣 Zhang Xinxin: President, University of Science and Technology, Beijing
- 赵忠秀 Zhao Zhongxiu: Vice President, University of International Business and Economics
- 周大地 Zhou Dadi: Director General (emeritus) of the Energy Research Institute, National Development and Reform Commission, currently Vice Chairman of the State Expert Advisory Committee to the National Energy Leading Group of China
- 冯飞 Feng Fei: Director General of Industry, Ministry of Industry and Information Technology
- 武 涌 Wu Yong: Former Deputy Director General, Ministry of Housing and Urban-Rural Development
- Jack Wadsworth: Chairman Emeritus, Morgan Stanley Asia
- Gary Rieschel: Founding Partner, Qiming Ventures
- 陆新明 Lu Xinming: Deputy Director General, Department of Climate Change, National Development and Reform Commission
- 蒋兆理 Jiang Zhaoli: Deputy Director General, Department of Climate Change, National Development and Reform Commission

Ad Hoc Expert Engagement and Sector Roundtables: Numerous experts answered questions and reviewed results on a regular basis. Each sector received generous advice and support from these experts, including the China Development Institute Shenzhen (Transportation) and Regulatory Assistance Project (Transformation). Additionally, the project team conducted a series of in-depth sector and subsector reviews in May 2014, mid-way through the project research. The expert feedback checked assumptions and model results, helped identify new case studies, and provided a critical lens to test the practicality of the solutions identified. These roundtables typically featured 4–6 external experts per sector. The specific organizations represented in these workshops included:

Industry:

- You Yong, Director, Energy Conservation Division, Ministry of Industry and Information Technology
- Li Yongliang, Deputy Director, Industrial Department, China Petroleum and Chemical Industry Association;

Building:

- Wu Yong, Director/Professor, China Association of Building Energy Efficiency
- Zou Yu, Deputy Director/Professor, Institute of Built Environment and Energy Efficiency, China Academy of Building Research

Transportation:

- Wu Wenhua, Deputy Director-General/Professor, Institute of Comprehensive Transportation
- Feng Zhenhua, Associate Professor, Scientific Research Institute, Ministry of Communication

Transformation:

- Pan Li, Director/Professor, Research Center of China Electricity Council
- Liu Yingmei, Associate Professor, China Electric Power Research Institute

Final Report Review: In addition to our Advisory Panel, a group of knowledgeable and respected reviewers were provided the draft manuscript of this report for comment. They included:

Adam Hinge, Sustainable Energy Partnerships

Jeff Logan, National Renewable Energy Laboratory

Jonathan Sinton, World Bank

Mark Levine, Lawrence Berkeley National Laboratory

Ryan Wiser, Lawrence Berkeley National Laboratory

Yunshi Wang, University of California-Davis

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SUMMARY RESULTS

03

SUMMARY RESULTS

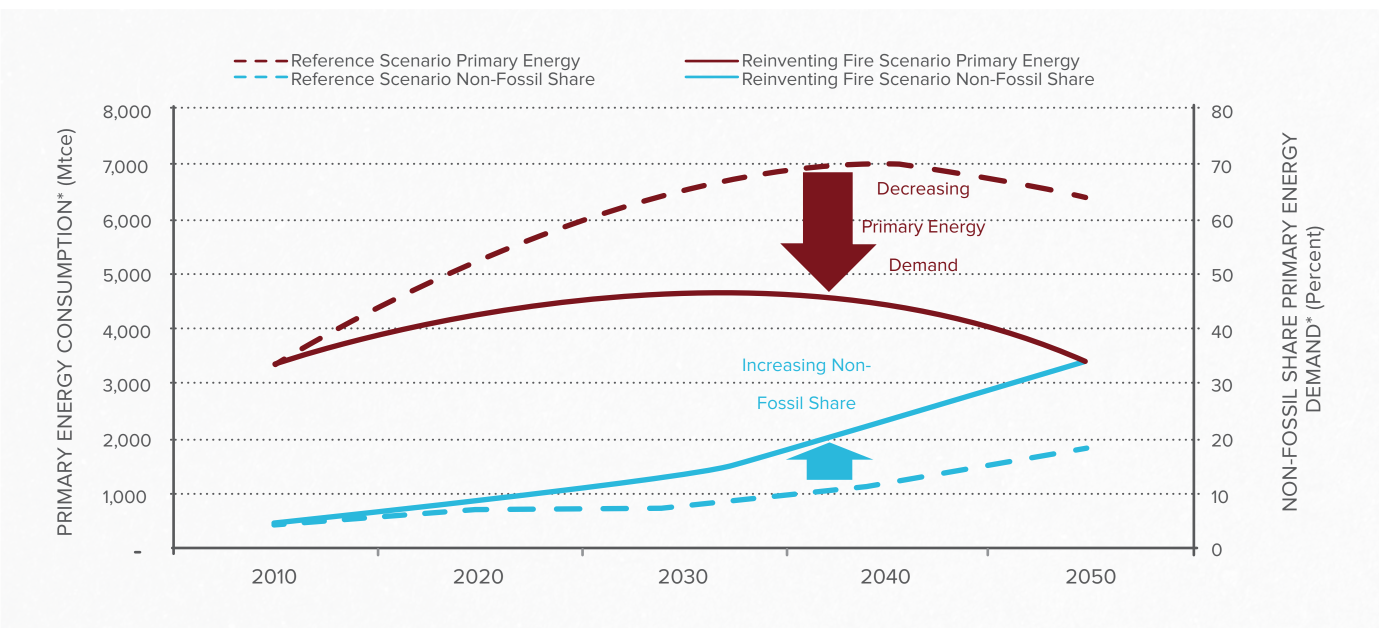
THE REINVENTING FIRE: CHINA analysis found that China could substantially reduce its future energy demand and emissions of energy-related CO_2 and other pollutants through cost-effective actions that reduce demand-side energy consumption in China's buildings, transportation, and industry sectors and through a significant increase in the use of non-fossil energy sources. Under the Reinventing Fire Scenario, China's primary energy demand in 2050 is roughly the same as the country's primary energy demand in 2010 even though China's GDP grows to nearly seven times China's 2010 economy in 2050. The Reinventing Fire Scenario supports China's development goals and achieves China's revolution in energy production and consumption.

3.1 CHINA CAN SIGNIFICANTLY REDUCE ITS PRIMARY ENERGY CONSUMPTION THROUGH CONCERTED, ECONOMY-WIDE, COST-EFFECTIVE ACTIONS

The Reinventing Fire pathway supports China's current growth plan accounting for GDP, population, and urbanization rates under the "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. Primary energy demand peaks in 2034 at 4,670 million tons coal equivalent (Mtce) under the Reinventing Fire pathway. This is a significant improvement over the Reference Scenario, which peaks in 2039 at 6,990 Mtce.

FIGURE 3.1: CHINA'S PRIMARY ENERGY USE PROFILE, GDP, POPULATION, URBANIZATION, AND NON-FOSSIL ENERGY USE IN THE REFERENCE AND REINVENTING FIRE SCENARIOS, 2010 TO 2050 (MTCE)

2010–2050, REINVENTING FIRE SCENARIO

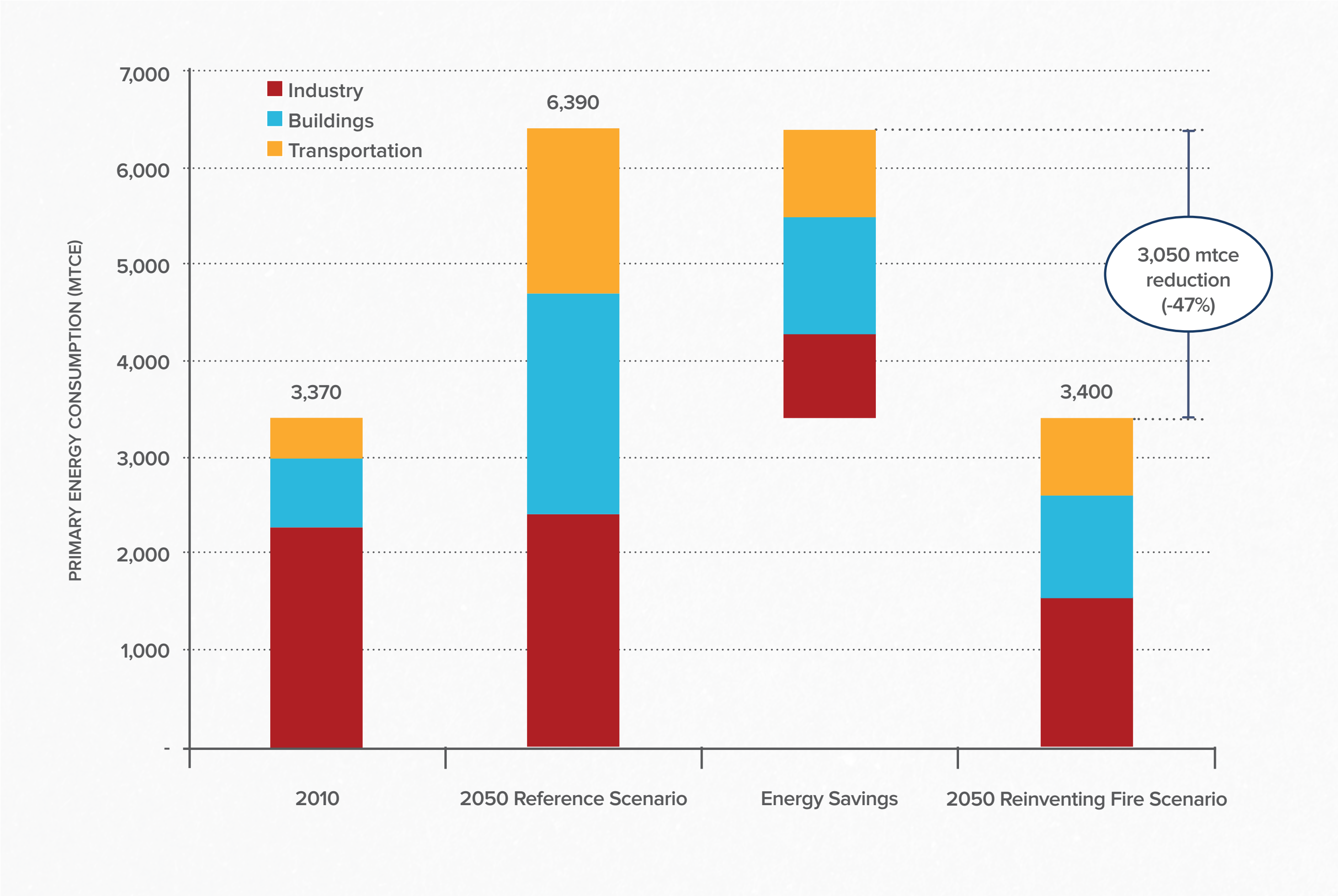


3.2 DEMAND REDUCTION STRATEGIES ACROSS THE INDUSTRY, BUILDING, AND TRANSPORTATION SECTORS CAN SUPPORT A SIGNIFICANTLY LARGER CHINESE ECONOMY THAT USES ABOUT THE SAME ENERGY IN 2050 AS IN 2010

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 3.2: CUMULATIVE SECTORAL CONTRIBUTIONS TO 2050 REINVENTING FIRE PRIMARY ENERGY SAVINGS

2010–2050, REINVENTING FIRE SCENARIO

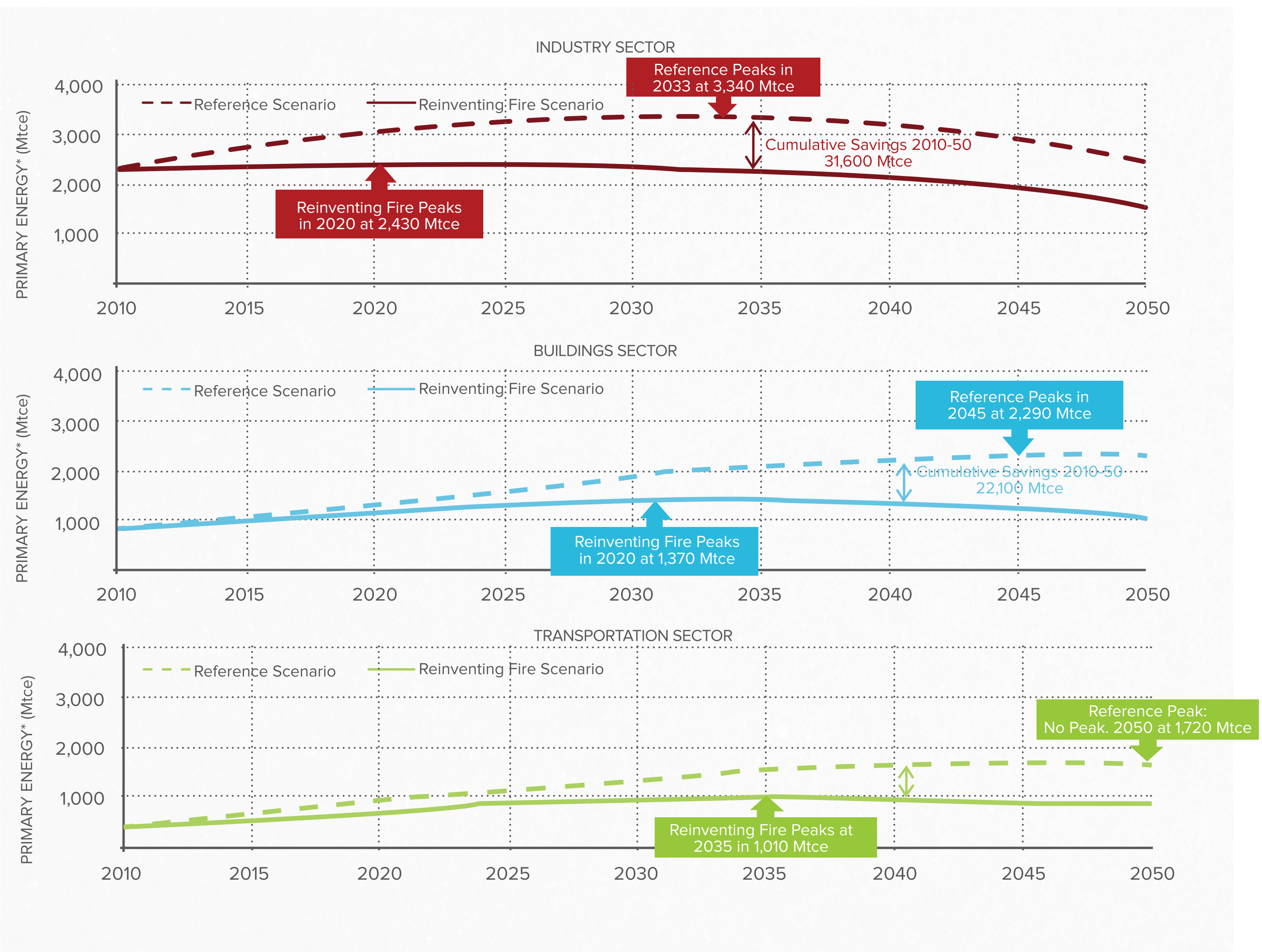


3.3 UNDER THE REINVENTING FIRE SCENARIO, PRIMARY ENERGY CONSUMPTION IN CHINA'S INDUSTRIAL, BUILDING, AND TRANSPORTATION SECTORS ALL PEAK SOONER AND LOWER THAN IN THE REFERENCE SCENARIO, WITH THE GREATEST CUMULATIVE ENERGY SAVINGS IN THE INDUSTRY SECTOR

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. The cumulative energy savings in each sector (the area between the two lines over the 40 years) is 31,600 Mtce for industry, 22,100 Mtce for buildings, and 17,400 Mtce for transportation.

FIGURE 3.3: CHINA'S PRIMARY ENERGY PEAKS BY SECTOR

2010–2050, REINVENTING FIRE SCENARIO

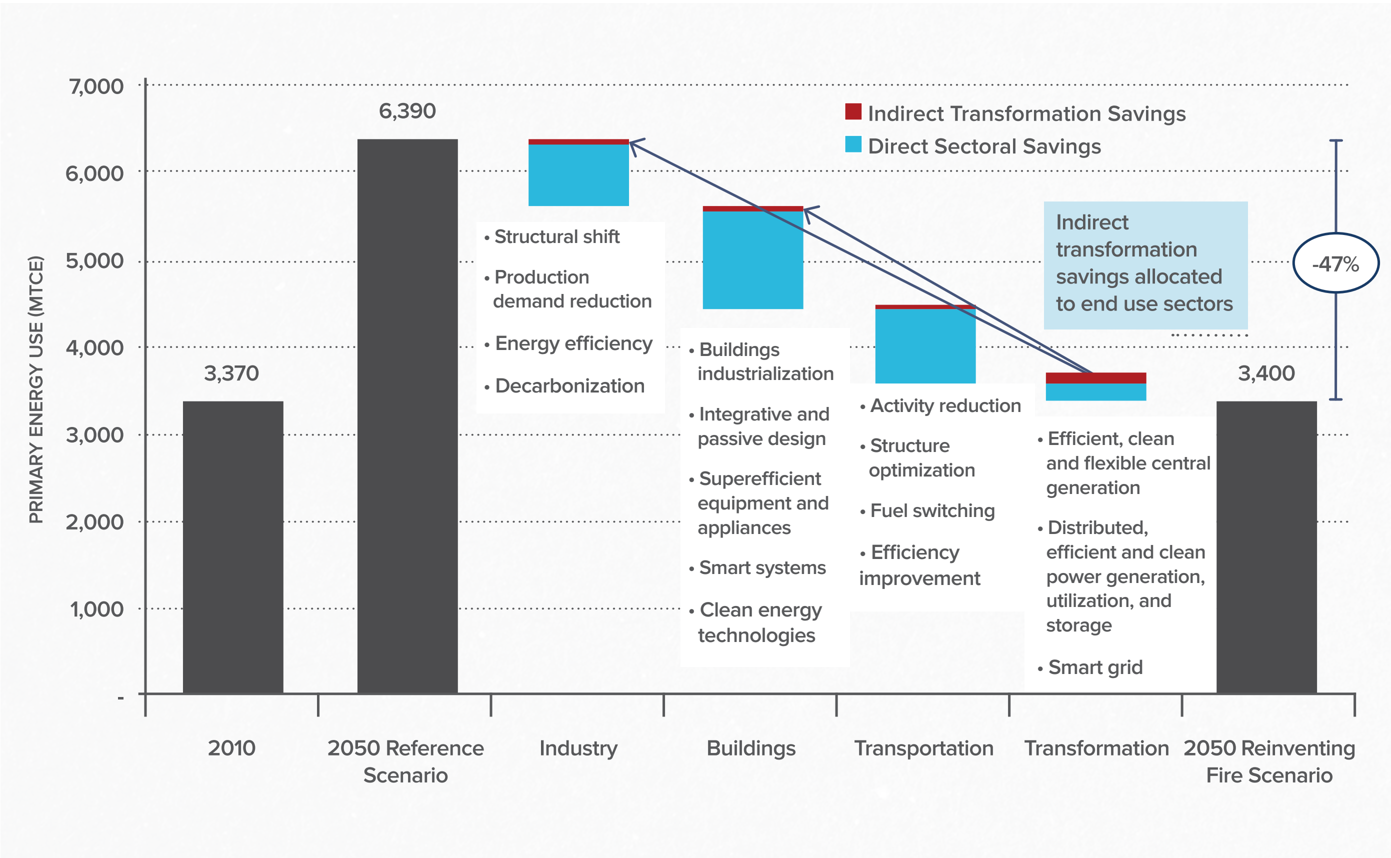


3.4 SECTOR-LEVEL ENERGY SAVINGS ARE CAPTURED BY AGGRESSIVELY PURSUING A RANGE OF EXISTING AND ECONOMIC DEMAND REDUCTION STRATEGIES

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 3.4: 2050 SECTOR ENERGY SAVING POTENTIAL

2010–2050, REINVENTING FIRE SCENARIO



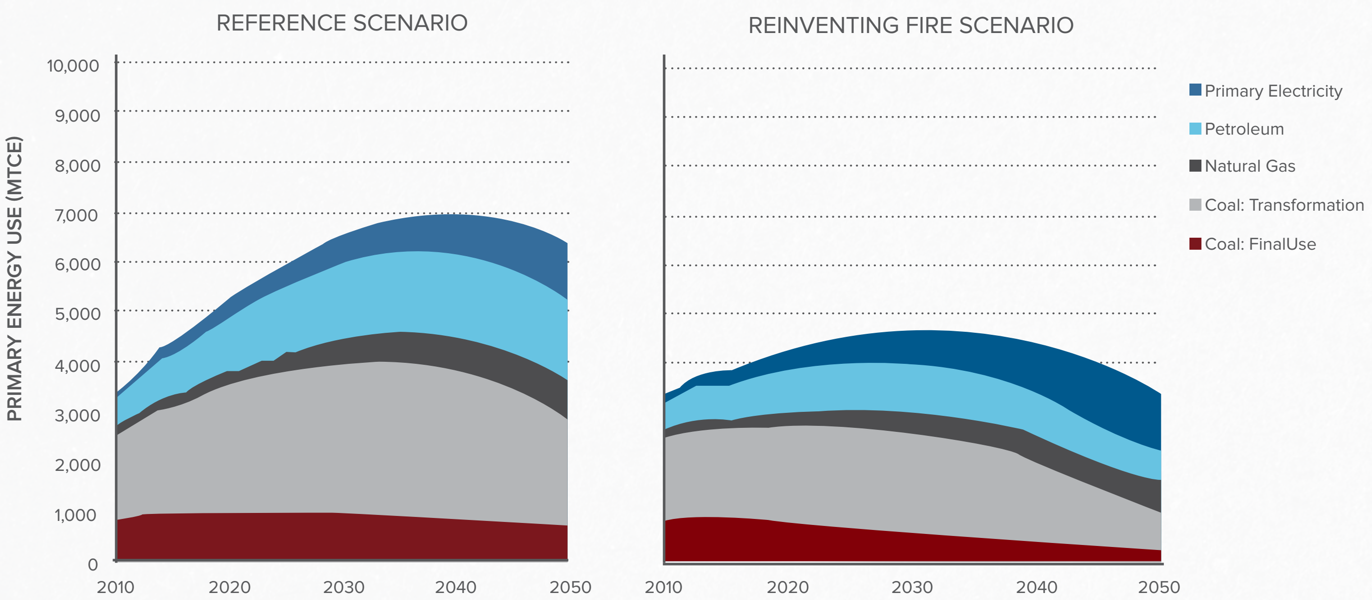
3.5 CHINA'S REDUCED ENERGY DEMAND ALLOWS IT TO DRAMATICALLY INCREASE ITS NON-FOSSIL SHARE OF PRIMARY ENERGY BY 2050

Demand reduction compresses both coal and petroleum consumption over time, reducing fossil energy share from 82% in the Reference Scenario to 66% in the Reinventing Fire Scenario by 2050 (using the direct equivalent method that is consistent with the IPCC). 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 use is 60% lower in 2050 than it was in 2010 in the Reinventing Fire Scenario.

Using the direct equivalent method for conversion of 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%.[i]

FIGURE 3.5: CHINA'S PRIMARY ENERGY FUEL MIX

2010–2050, REINVENTING FIRE SCENARIO



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

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

[i] *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.*

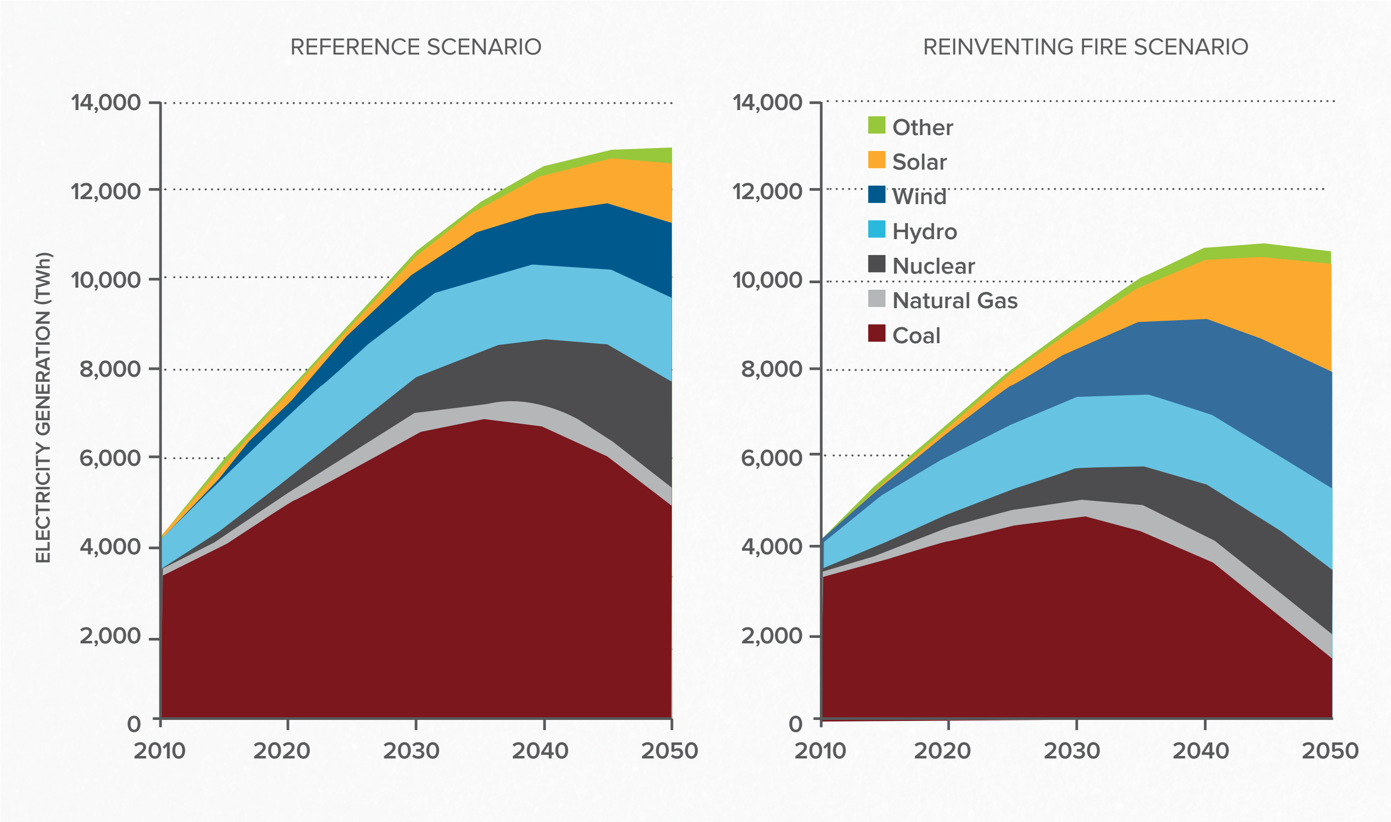
3.6 NON-FOSSIL, NON-EMITTING ELECTRICITY SOURCES CONTRIBUTE 82% OF CHINA'S 2050 ELECTRICITY NEEDS

In the Reinventing Fire Scenario, non-fossil, non-emitting electricity sources generate 82% of China's electricity in 2050; renewable sources alone meet 68% of the demand on an absolute basis. A massive scaling of renewable power generation capacity takes place under both scenarios (2.0 TW in Reference Scenario by 2050, 2.4 TW in Reinventing Fire Scenario by 2050). Under the Reinventing Fire Scenario, the principal differences in power generation are the diminished role of coal and reduced nuclear production, both resulting from demand reductions. The reliable operation of the high-penetration renewable grid is made possible by improving transmission interconnection to allow balancing over broader areas, increasing grid automation to support demand response, increasing the flexbility of the remaining fossil units, and employing a portfolio-based dispatch approach.

With accelerated electrification in the Reinventing Fire Scenario, the electricity share of final energy will rise from 18% in 2010 to 41% in 2050, 12 percentage points higher than the Reference Scenario 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 3.6: CHINA'S ELECTRICITY GENERATION BY SOURCE IN THE REFERENCE AND REINVENTING FIRE SCENARIOS, 2010 TO 2050

2010–2050, REINVENTING FIRE SCENARIO



3.7 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 14 years earlier and 30% lower, CO_2 emissions 11 years earlier and 34% lower, and primary energy five years earlier and 33% lower than the Reference Scenario.

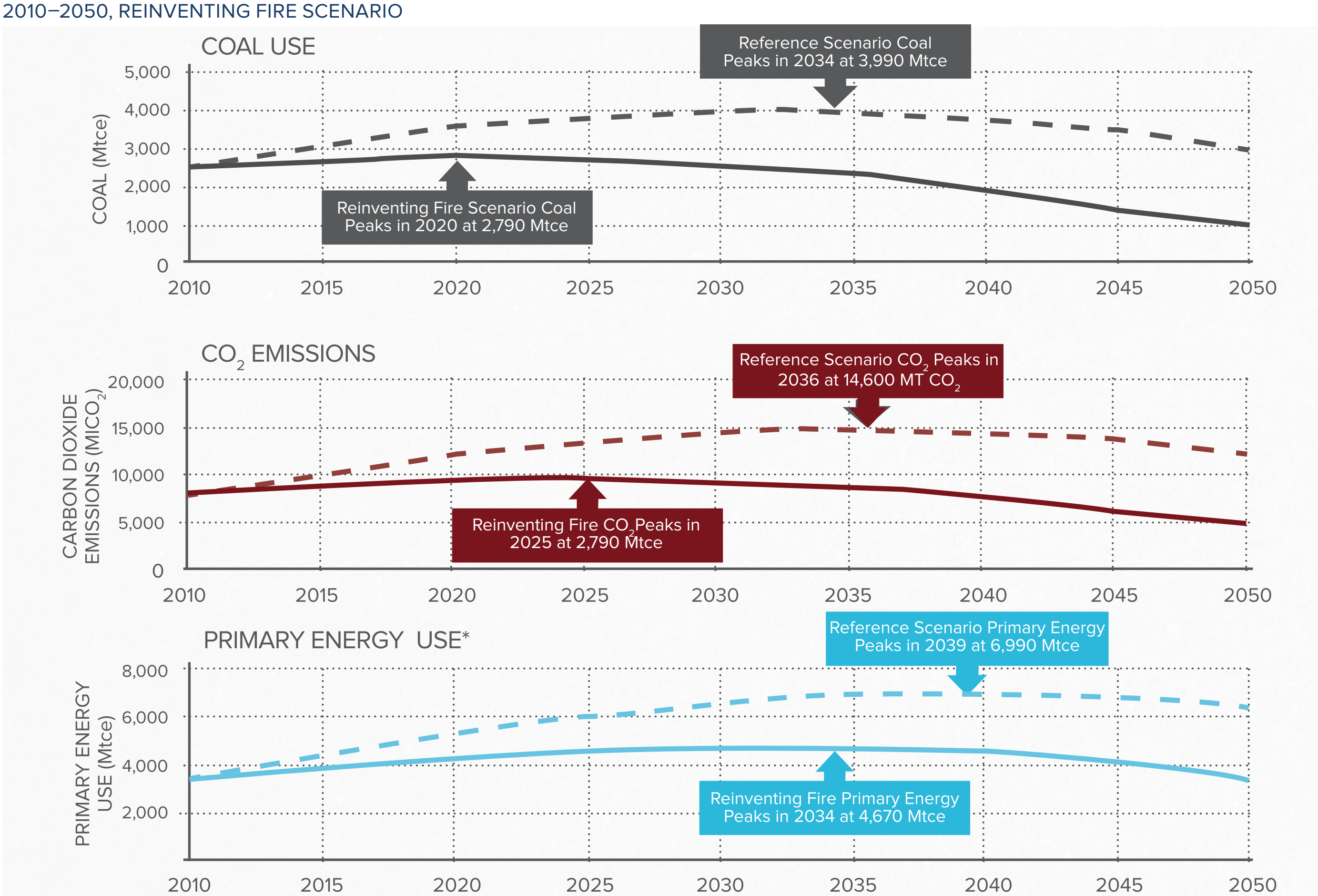
In the Reinventing Fire Scenario, China's coal use will peak around 2020 at 2,880 Mtce. By 2050, China's coal demand further declines to 1,020 Mtce, about 60% lower than 2010 levels.

In the Reinventing Fire Scenario, China's CO_2 emissions begin to level off in 2022, peaking in 2025 at a level of 9,590 $MtCO_2$. By 2050, China's total CO_2 emissions decline to 4,620 $MtCO_2$, about 42% lower than the 2010 levels.

As covered earlier in this chapter, China will peak its Reinventing Fire primary energy consumption around 2034 at 4,670 Mtce. By 2050, China's primary energy demand declines to 3,400 Mtce, less than 1% higher than 2010 levels.

FIGURE 3.7: CHINA'S "THREE PEAKS" IN THE REFERENCE AND REINVENTING FIRE SCENARIOS. ELECTRICITY CONVERTED TO PRIMARY ENERGY USING THE DIRECT EQUIVALENT METHOD

2010–2050, REINVENTING FIRE SCENARIO

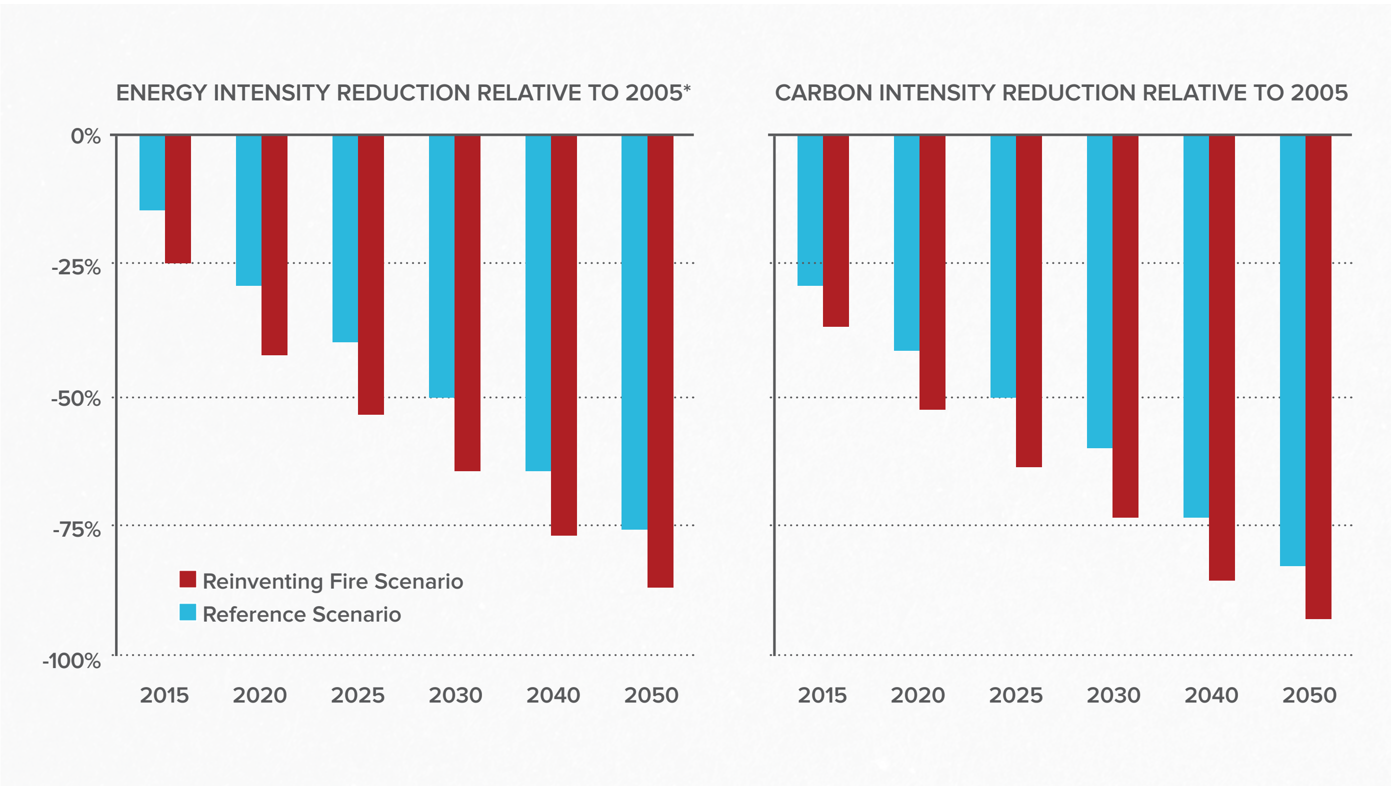


3.8 THROUGH REDUCING ENERGY DEMAND AND SHIFTING TO LOWER CARBON ENERGY SUPPLIES, CHINA LARGELY DECOUPLES ECONOMIC GROWTH AND ENERGY DEMAND UNDER THE REINVENTING FIRE SCENARIO, FREEING THE ECONOMY FROM ENERGY AND ENERGY-RELATED ENVIRONMENTAL CONSTRAINTS

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 3.8: CHINA'S PRIMARY ENERGY INTENSITY REDUCTIONS IN THE REFERENCE AND REINVENTING FIRE SCENARIOS RELATIVE TO 2005 LEVELS

2010–2050, REINVENTING FIRE SCENARIO

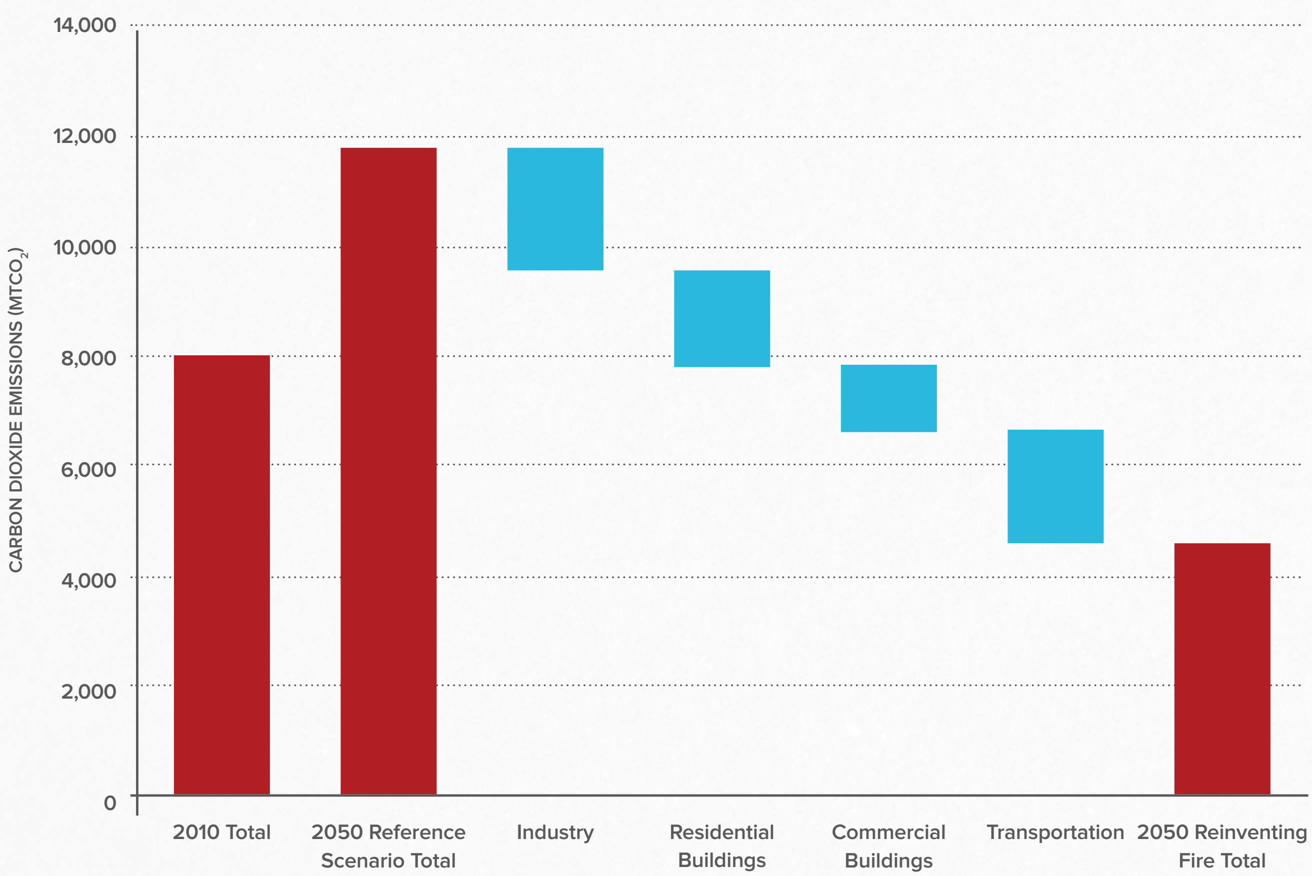


3.9 CHINA'S ENERGY-RELATED CO_2 EMISSIONS DROP 61% BY 2050

By 2050, China's energy-related CO_2 emissions would be 4.5 $GtCO_2$ in the Reinventing Fire Scenario, significantly lower than the 11.4 $GtCO_2$ emissions in the Reference Scenario. The CO_2 emissions reductions are a result of the reduction of direct emissions through demand reduction and fuel switching and the reduction of indirect emissions by reducing demand for electricity and decarbonizing the fuel supply.

FIGURE 3.9: SECTORAL DIRECT AND INDIRECT CONTRIBUTIONS TO 2050 ENERGY-RELATED CO_2 EMISSIONS SAVINGS IN THE REINVENTING FIRE SCENARIO

2010–2050, REINVENTING FIRE SCENARIO

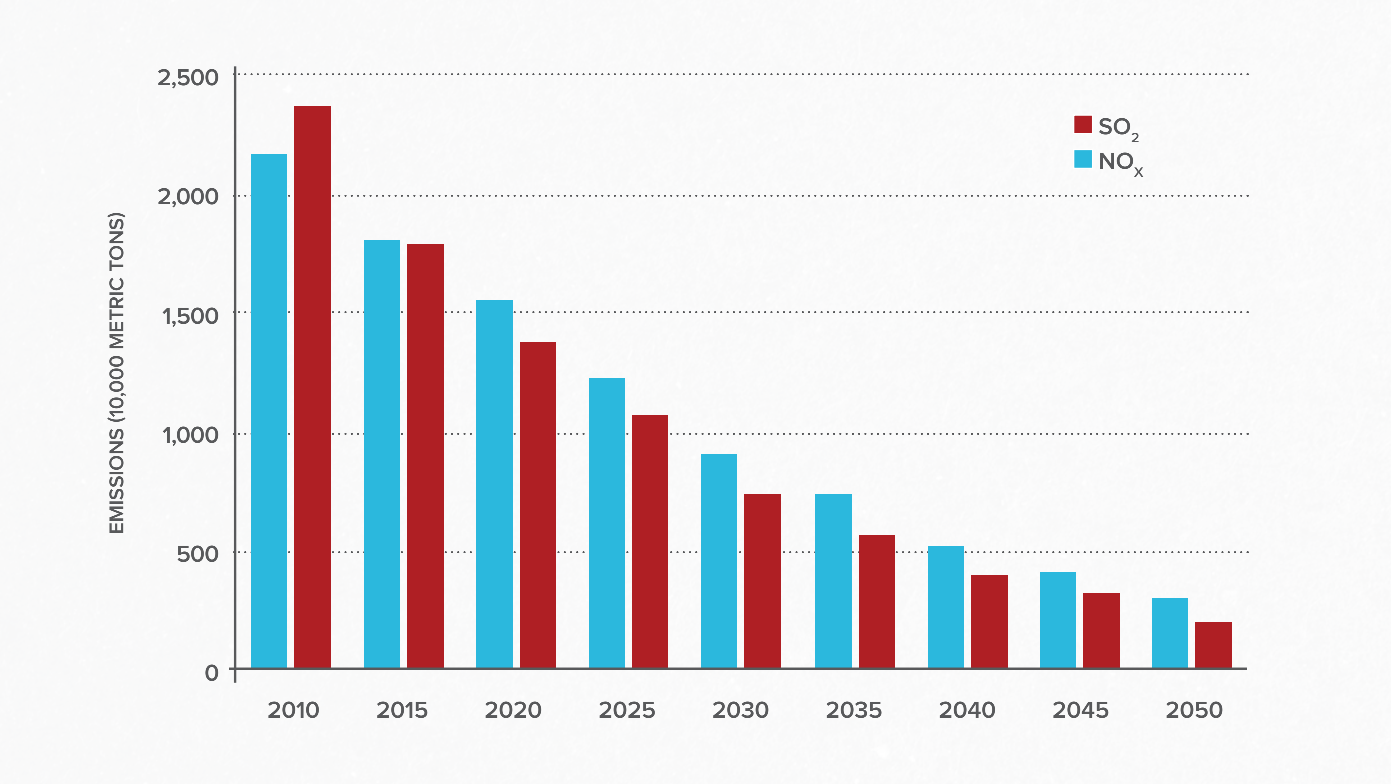


3.10 CHINA'S SO_2 AND NO_X EMISSIONS DROP OVER 85% FROM CURRENT LEVELS BY 2050 IN THE REINVENTING FIRE SCENARIO

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 that are 25–30% below current levels of the U.S. and EU.

FIGURE 3.10: 2010-2050 SO_2 AND NO_X LEVELS IN THE REINVENTING FIRE SCENARIO

2010–2050, REINVENTING FIRE SCENARIO

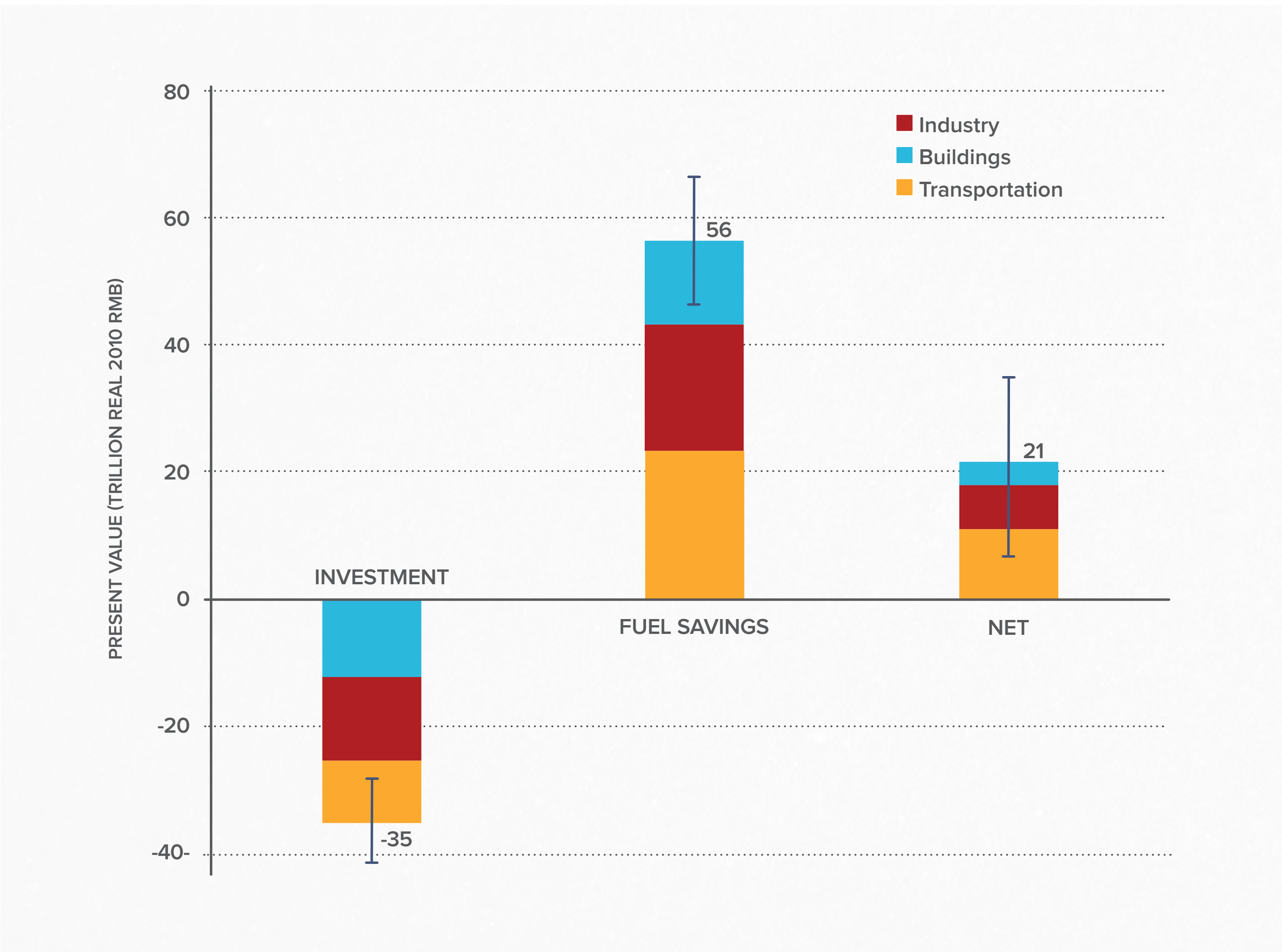


3.11 SINCE THE REINVENTING FIRE SCENARIO RELIES ON COST-EFFECTIVE, COMMERCIALLY-AVAILABLE TECHNOLOGIES, IMPLEMENTATION OF THIS SCENARIO WOULD SAVE CHINA 21 TRILLION RMB IN ENERGY COSTS

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 3.11: INCREMENTAL INVESTMENTS, ENERGY SAVINGS, AND NET PRESENT VALUE SAVINGS OF THE REINVENTING FIRE SCENARIO COMPARED TO THE REFERENCE SCENARIO FOR CHINA, 2010 TO 2050

2010–2050, REINVENTING FIRE SCENARIO



INDUSTRY

04

INDUSTRY

INDUSTRY IS THE CHINESE economy's dominant sector, contributing roughly 40% to overall national gross domestic product (GDP) since the "reform and opening up" in the early 1980s.[i,1] China's industry transforms raw materials into products that build the country's cities and infrastructure, is a key global manufacturing center, and drives domestic and global economic growth.

Despite a recent slowdown in China's GDP growth and industrial activity due to the "New Normal," China continues to be the world leader in industrial output for most industrial products. Furthermore, continued urbanization, the associated increase in domestic commodity consumption, and increased exports are driving demand for energy-intensive raw materials and products. For example:

- Between 2000 and 2010, China's production of energy-intensive commodities such as steel and cement increased 200–500% (Figure 4.1).[2]
- Primary energy consumption of China's industrial sector grew 120% during the period 1995–2010, especially accelerating in 2002, from just under 1,000 million tons of coal equivalent (Mtce) to nearly 2,200 Mtce (Figure 4.2).
- China's energy-intensive manufacturing sectors used roughly 60–65% of total industrial energy annually between 1995 and 2010.[3]

Though China's industrial energy efficiency has improved over the past decade, the energy intensities of China's major industrial subsectors lag behind international levels.[4] As a result, China's industrial sector consumes approximately 70% of the country's primary energy, more energy than the U.S. buildings and transportation sectors combined.[5,6]

China's industrial sector is the country's primary source of energy-related carbon dioxide (CO_2) emissions. In 2012, for example, primary energy consumption from China's industrial sector resulted in 64% of total energy-related emissions[7,8] (5.6 $GtCO_2$), more than the entire energy-related CO_2 emissions of the U.S. or EU.[9] It is also the main source of the country's environmental pollutants, emitting 70–90% of atmospheric emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and total suspended particulate matter in 2010—the primary drivers of air pollution in China's cities (Figure 4.3).[10]

China is in the mid to late stage of industrialization. Personal income and consumption is increasing as the standard of living improves. As a result, expected energy consumption growth in the transportation, buildings, and service sectors will cause severe environmental issues. To realize China's goal to peak CO_2 emissions around 2030, with the intention to try to peak earlier,[11] China has to immediately control energy consumption growth. Even though efforts in other sectors will be important (especially towards the end of the analysis period), the industrial sector is the most critical sector to control the country's overall growth of energy consumption and related CO_2 emissions.[ii]

[i] Industry here refers to the secondary sector of China's economy, which includes mining, manufacturing, and water production and distribution. Within manufacturing, there are 16 main subsectors: food, beverage and tobacco; textiles, chemical fibers, and related products; timber and wood products; paper and paper products; printing and publishing; chemical materials and products; medicines; rubber and plastics; non-metallic mineral products; ferrous metals; non-ferrous metals; metal products; machinery; transport equipment; electric and electronic equipment; and other manufacturing.

[ii] Industry represents the largest cumulative energy savings potential during the study period (2010–2050) and the largest energy savings annually until 2044, at which point, the building sector's energy savings potential becomes larger.

China's slowing economic growth required a revision of the original GDP growth estimates used in this report through 2050. This revision particularly affected the industrial sector, which has historically been a key driving force for GDP in China but which has recently undergone significant downturns under the "New Normal" conditions. This report reflects the most current thinking on the Chinese economy that the industrial sector will decline in economic importance earlier than previously expected in both the Reference and Reinventing Fire Scenarios. Due to this decline, the majority of industrial energy savings occurs between 2020 and 2040. As the service sector grows, industrial activity is expected to decline. This is different than in the buildings and transportation sectors, which see demand growth during the earlier years of the analysis period and a decrease in energy use during later years.

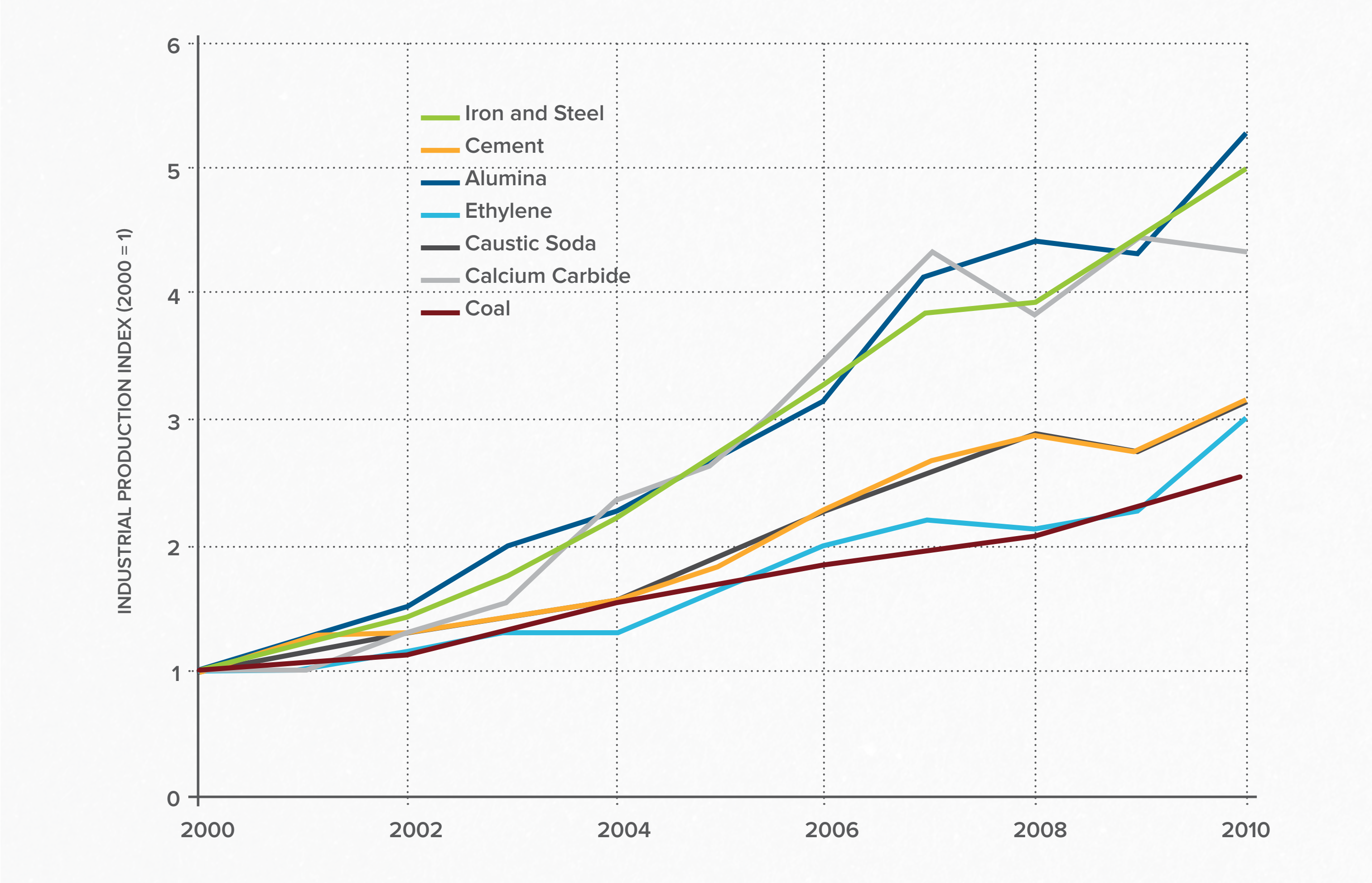
4.1 DEVELOPMENT STATUS AND PROSPECTS FOR THE INDUSTRIAL SECTOR

4.1.1 CHINA'S INDUSTRIAL SECTOR IS KEY TO ACHIEVING CHINA'S OVERARCHING DEVELOPMENT GOALS

Between 2000 and 2010, China's production of energy-intensive commodities such as steel and cement increased three to six times (Figure 4.1),[12] leading to a growing dependence on imported mineral resources. More than 50% of China's key resources such as crude oil, iron ore, bauxite, and copper ore were imported in 2013.[13] If the current industrial development mode and energy use pattern were to continue, China's environmental quality would also continue to degrade and there would be increased risks related to resource scarcity.

FIGURE 4.1: CHINA'S PRODUCTION OF ENERGY-INTENSIVE COMMODITIES

2000–2010 (INDEXED TO 2000 VALUE)[14]



Rapid Chinese industrial production growth (and the associated primary energy consumption) over the past 30 years relied heavily on China's comparative advantages of low energy and environmental costs, low labor costs, and low capital costs. However, this development pattern does not align with China's vision of prosperity, modern industry, and a clean environment. China must simultaneously improve the efficiency of industrial production, switch to cleaner forms of energy, and migrate to higher-value-adding industry in order to meet the country's "Two One-Hundred Years" development goals. These are to double 2010 GDP and per-capita income by the 100th anniversary of the Chinese Communist Party in 2021 and turn China into a modern country that is prosperous, strong, democratic, culturally advanced, and harmonious by the 100th anniversary of the People's Republic of China in 2049.[15]

FIGURE 4.2: CHINA'S PRIMARY ENERGY CONSUMPTION BY INDUSTRY SUBSECTOR

1995–2010[16]

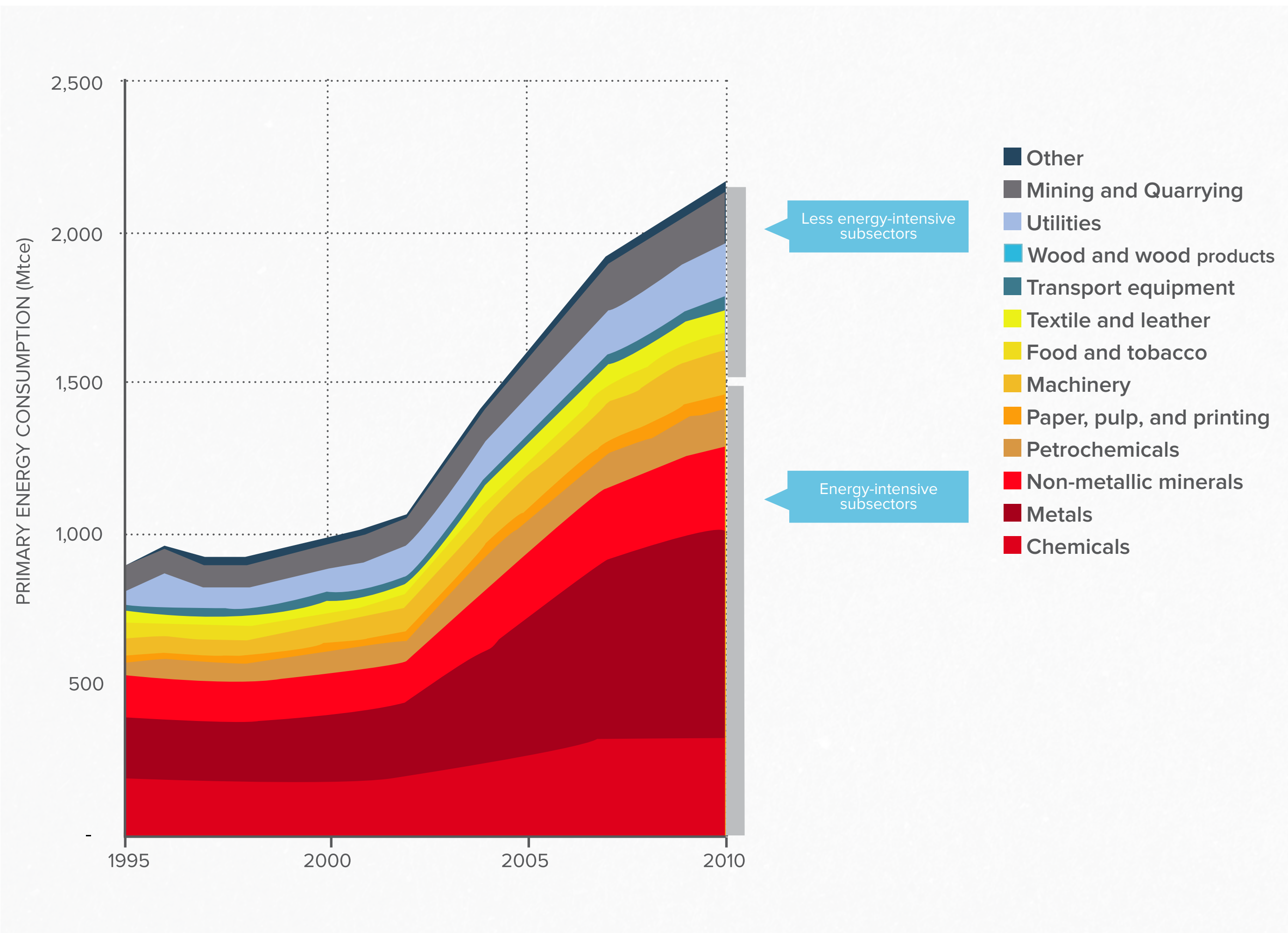
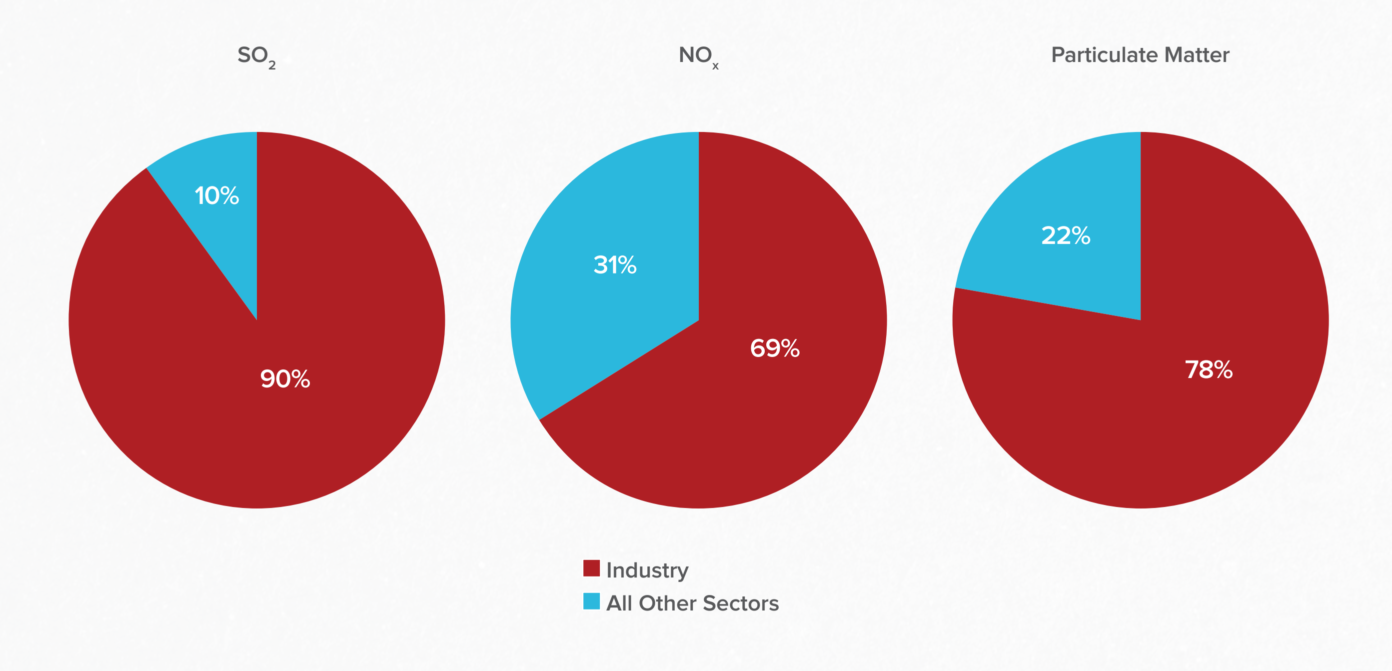


FIGURE 4.3: INDUSTRY SECTOR SHARE OF CHINA'S SO_2, NO_X, AND PM EMISSIONS

2010[17]



4.1.2 ENERGY USE AND ENERGY-RELATED EMISSIONS OF CHINA'S INDUSTRIAL SECTOR CALLS FOR REINVENTING FIRE

The growth in China's industrial energy use was the primary reason that China's energy-related CO_2 emissions surpassed those of the U.S. in 2017.[18] China is now the world's largest emitter of energy-related CO_2; in 2014, China accounted for more than 22% and nearly 30% of the world's total energy use and energy-related CO_2 emissions, respectively.[19] This growth increases the challenge of environmental management.

China's industrial sector is the main source of the country's environmental pollutants, emitting 70%–90% of atmospheric emissions of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and total suspended particulate matter in 2010—the primary drivers of air pollution in China's cities (Figure 4.3).[20]

4.2 VISION AND GOALS OF REINVENTING FIRE FOR THE INDUSTRIAL SECTOR

In the Reinventing Fire Scenario, 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 supplies through 2050. An industrial sector that is world class in terms of energy efficiency and which has moved away from carbon-intensive fuels and toward higher-value-added subsectors is critical for realizing the overall Reinventing Fire vision for China. Pursuing this vision can achieve four key goals for the industrial sector:

1. **Strategically transform China's industry**
   Industry is the main component of China's national economy and the base of prosperity. Yet China has a large share of energy-intensive and highly polluting industries, an unbalanced industrial structure, and surplus production capacity.[21]

The combined effects of low energy prices, low energy efficiency, low levels of industrial competition, and excessive investment in industry to grow income (which in turn leads to surplus production capacity), further increases the risk of maintaining low levels of technology in China. The essence of the Reinventing Fire Scenario is to improve the quality and efficiency of industrial production, optimize the industrial structure, complete the transformation to a country with advanced industries, and to be a force for long-term sustainable economic development and the foundation for improved standards of living.

2. **Establish a world-leading green and efficient industrial organization and production system**
   With decades of rapid development, China's manufacturing industry was the global leader in manufacturing value added in 2013.[22] The Reinventing Fire Scenario would establish China as a global leader in green and efficient industrial organization and production systems, powered by large shares of low-carbon energy, positively contributing to the global economy and environment.

3. **Provide high-quality materials and products**
   In addition to improving production processes through improved resource and energy productivity, China's industry will also provide long-lasting, high-quality materials and products for the buildings and transportation sectors, laying the foundation for energy savings and emissions reductions in those sectors.

4. **Peak industrial energy consumption and CO_2 emissions early to allow for expected increases in other sectors**
   With increasing GDP per capita and improving living standards, energy consumption and CO_2 emissions from the buildings and transportation sectors will continue to grow. The industrial sector must peak its energy consumption and CO_2 emissions early. This allows for increasing energy consumption and CO_2 emissions from other sectors while China meets its 2030 goals, including improving environmental quality and standards of living.

4.3 RESULTS OF REINVENTING FIRE IN THE INDUSTRIAL SECTOR

4.3.1 CHINA'S INDUSTRIAL SECTOR ENERGY INTENSITY DECREASES

In the Reinventing Fire Scenario, the GDP of the industrial sector *increases* from 15.3 trillion RMB in 2010 to 75.2 trillion RMB in 2050 (Figure 4.4). Meanwhile, energy consumption *decreases* during that same period, with 2050 energy consumption of China's industrial sector 32% lower than the 2010 value, decoupling energy consumption from economic growth.[iii] Under this scenario, in 2050 the industrial sector energy intensity (energy consumption per unit of industrial GDP) is 86% lower than the 2010 level, falling more than 4.8% per year on average over 40 years.

4.3.2 CHINA'S INDUSTRIAL SECTOR ENERGY CONSUMPTION PEAKS 11 YEARS EARLIER

In the Reinventing Fire Scenario, China's industrial sector total primary energy consumption peaks around 2020, 11 years earlier than in the Reference Scenario. Primary energy consumption peaks at 2,300 Mtce or 816 Mtce less (26%) than the peak under the Reference Scenario (Figure 4.5). Primary energy consumption of China's industrial sector peaks a decade earlier than the other demand sectors and is critical for supporting China's goal to peak national CO_2 emissions by 2030.

[iii] The decline in energy consumption is not continuous over the study period. In the Reinventing Fire Scenario, industrial energy use grows to 2020 and then begins a steady decline. This decline becomes more pronounced after 2035. Note that these values are presented in primary energy terms using the direct equivalent conversion methodology. This methodology overstates the decoupling effect because shifting from coal-based electricity to renewable electricity makes it appear that energy use declines at a greater rate because of primary energy conversion assumptions. This analysis was therefore also conducted using final energy savings to eliminate this effect. In the final energy analyses the result is similar though slightly less pronounced.

FIGURE 4.4: INDUSTRY SECTOR CHANGES IN GDP, PRIMARY ENERGY, AND ENERGY INTENSITY

2010 VS. 2050, REINVENTING FIRE SCENARIO

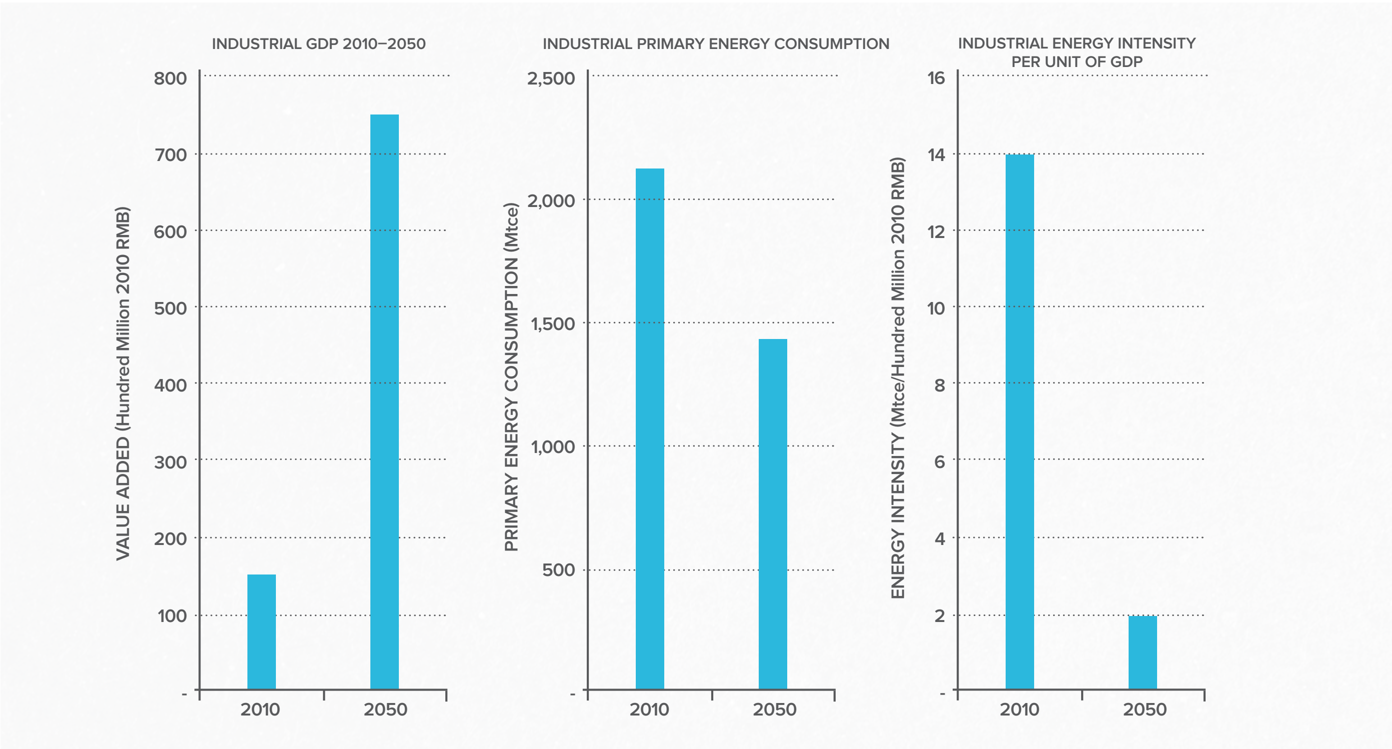
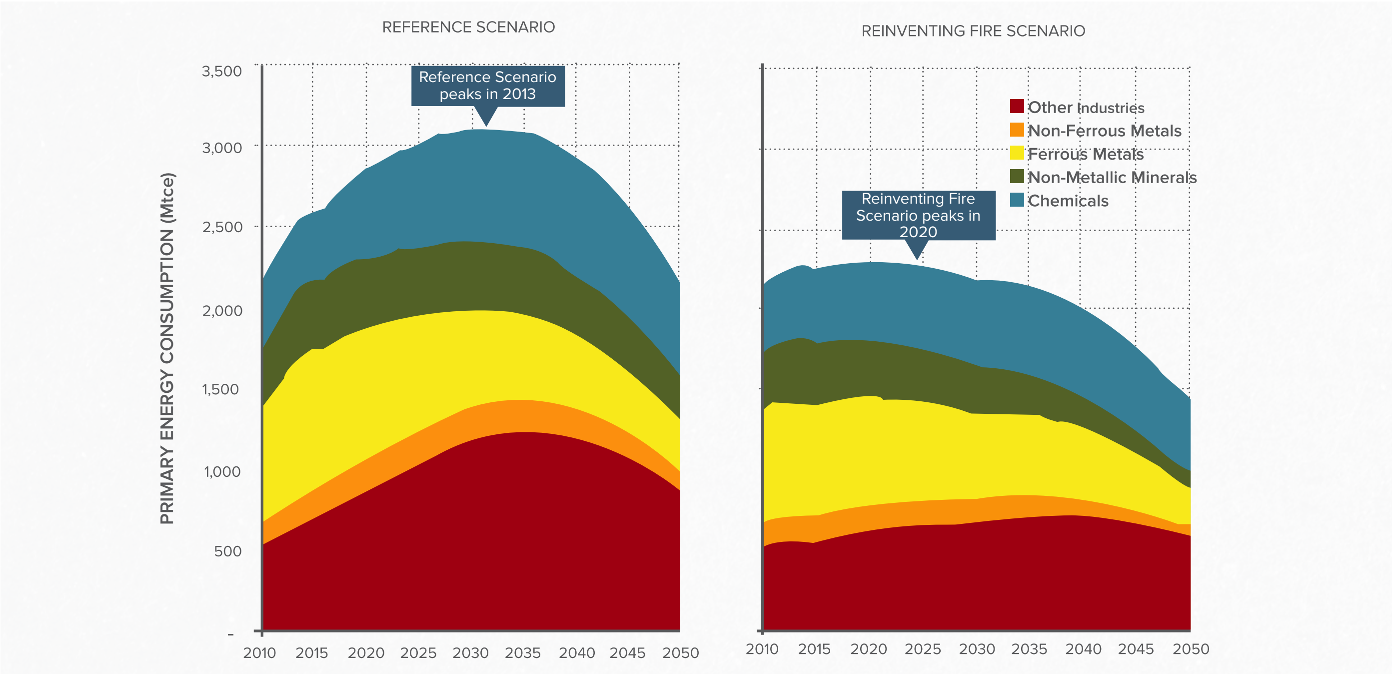


FIGURE 4.5: INDUSTRY SECTOR PRIMARY ENERGY TRENDS

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

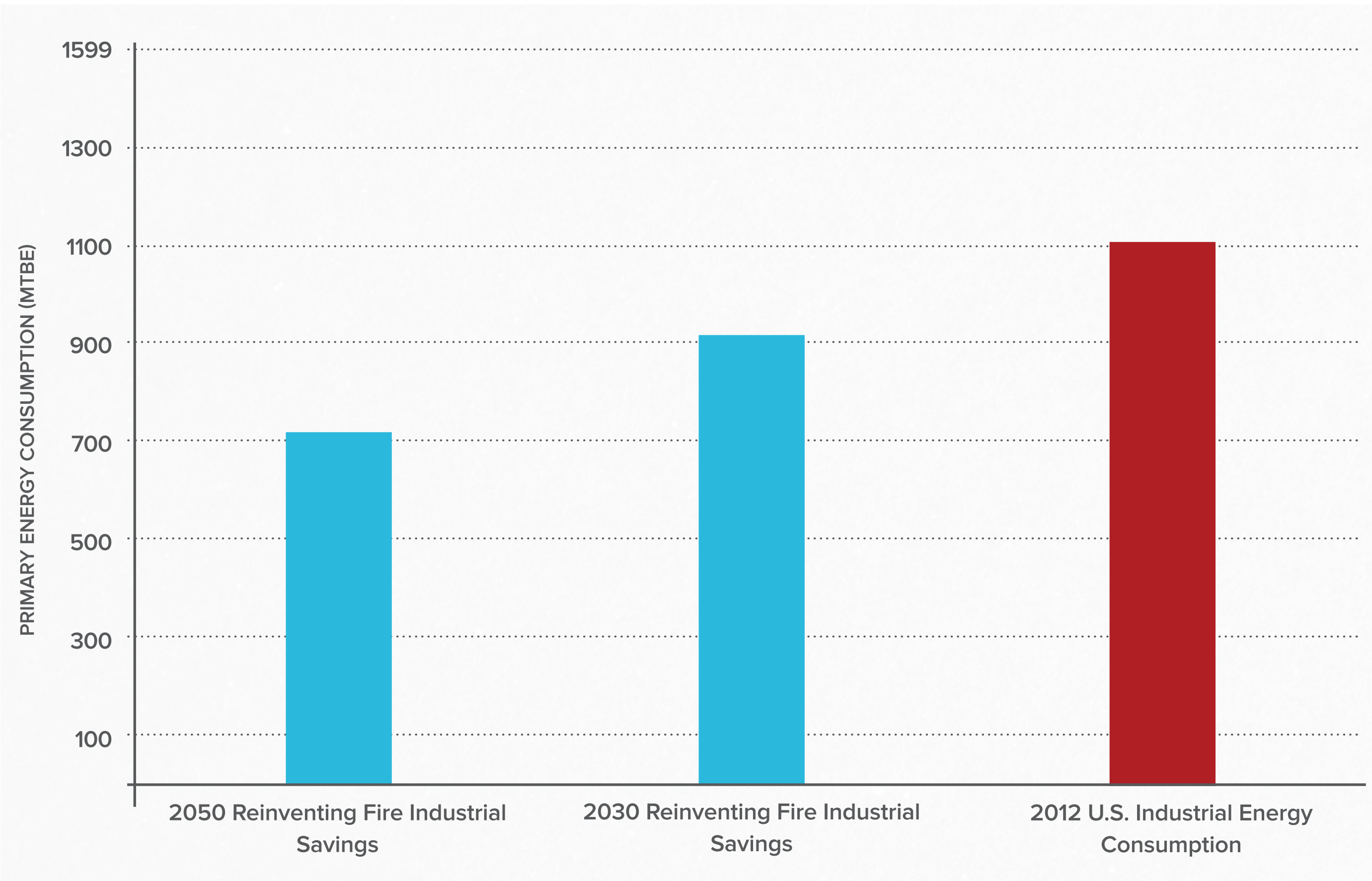


4.3.3 CHINA'S INDUSTRIAL SECTOR ENERGY CONSUMPTION IS SIGNIFICANTLY LOWER IN 2050 THAN IN THE REFERENCE SCENARIO

In the Reinventing Fire Scenario, industrial primary energy consumption is 720 Mtce lower (33%) by 2050 than the Reference Scenario. These savings are even more significant in 2030. In the Reinventing Fire Scenario, industrial primary energy consumption is 920 Mtce lower (30%) than the Reference Scenario, almost as large as the entire U.S. industrial sector in 2012 (Figure 4.6).[23]

FIGURE 4.6: CHINA'S INDUSTRY SECTOR ENERGY SAVINGS VS. U.S. INDUSTRY

2012 VS. 2050, REINVENTING FIRE SCENARIO[24]



4.3.4 CHINA'S INDUSTRIAL SECTOR ENERGY SUPPLY SHIFTS TOWARD LOW-CARBON OPTIONS

In the Reinventing Fire Scenario, China's industrial sector shifts away from a coal-dominated energy supply. In 2050 the share of coal in final energy use in the industrial sector drops to 25%, decreasing by more than half compared with 2010 levels. Compared with the Reference Scenario, coal's share in the Reinventing Fire Scenario in 2050 is 15% lower (Figure 4.7).

In the Reinventing Fire Scenario, the share of electricity in final energy consumption increases from 19% in 2010 to 38% in 2050, 6% higher than in the Reference Scenario. This electrification generates CO_2 savings because the power sector utilizes an increasing share of low-carbon generation resources in the Reinventing Fire Scenario (see the electric power chapter of this report for additional information). Natural gas also plays a key role in the reduction and substitution of coal in the industrial sector, with the proportion of natural gas in total final consumption increasing from 3% in 2010 to around 11% in 2050.

FIGURE 4.7: INDUSTRY SECTOR FINAL ENERGY FUEL MIX

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

4.3.5 CHINA'S INDUSTRIAL SECTOR SIGNIFICANTLY REDUCES ITS ENVIRONMENTAL IMPACT

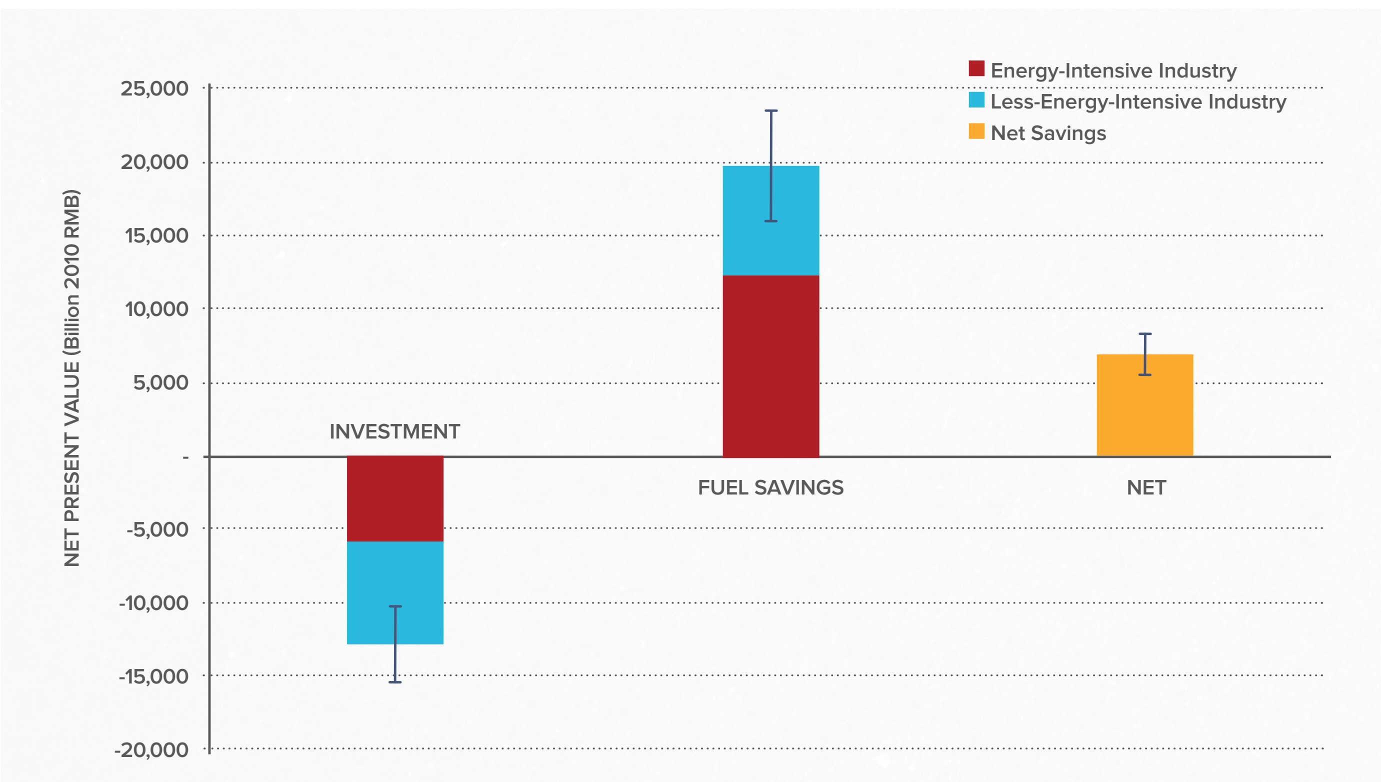
In the Reinventing Fire Scenario, industrial sector emissions of energy-related CO_2 and local pollutants will be effectively controlled by 2050. Industrial energy-related CO_2 emissions decrease at least 2,970 $MtCO_2$ (58%) by 2050 compared to 2010; the Reinventing Fire Scenario reduces emissions by more than 2,000 $MtCO_2$ (48%) relative to the Reference Scenario in 2050. Sulfur dioxide, nitrogen oxides, particulate matter, and other pollution emissions will also decrease 70–80% relative to 2010 levels.

4.3.6 THE REINVENTING FIRE SCENARIO FOR CHINA'S INDUSTRY CAN BE REALIZED AT NO NET COST

Achieving the Reinventing Fire Scenario vision requires that industry invest 10–15 trillion RMB (2010) more than in the Reference Scenario; this reflects a range of costs for industrial efficiency technologies and measures for various industries.[25,26,27,28] These costs are largely borne by the energy-intensive industries in China,[iv] which will need to invest 5.8 trillion RMB, or 45% of the total capital investment required during the 2010–2050 time frame. This investment will generate savings of 15–25 trillion RMB from reduced energy consumption for a net savings of 5.5–8.2 trillion RMB using commercially available energy-efficiency technologies and measures. This does not include additional savings that are possible through full application of integrative design concepts, which were not calculated in this analysis. Energy-intensive industries will realize the majority of these savings—an average of 12.5 trillion RMB, or nearly 63% (Figure 4.8).

FIGURE 4.8: INDUSTRY SECTOR REINVENTING FIRE SCENARIO NET PRESENT VALUE

2010–2050, INCREMENTAL TO REFERENCE SCENARIO



[iv] *Chemicals, nonmetallic minerals, nonferrous metals, ferrous metals, mining, paper, and water production.*

4.4 PATHS FOR REINVENTING FIRE FOR CHINA'S INDUSTRIAL SECTOR

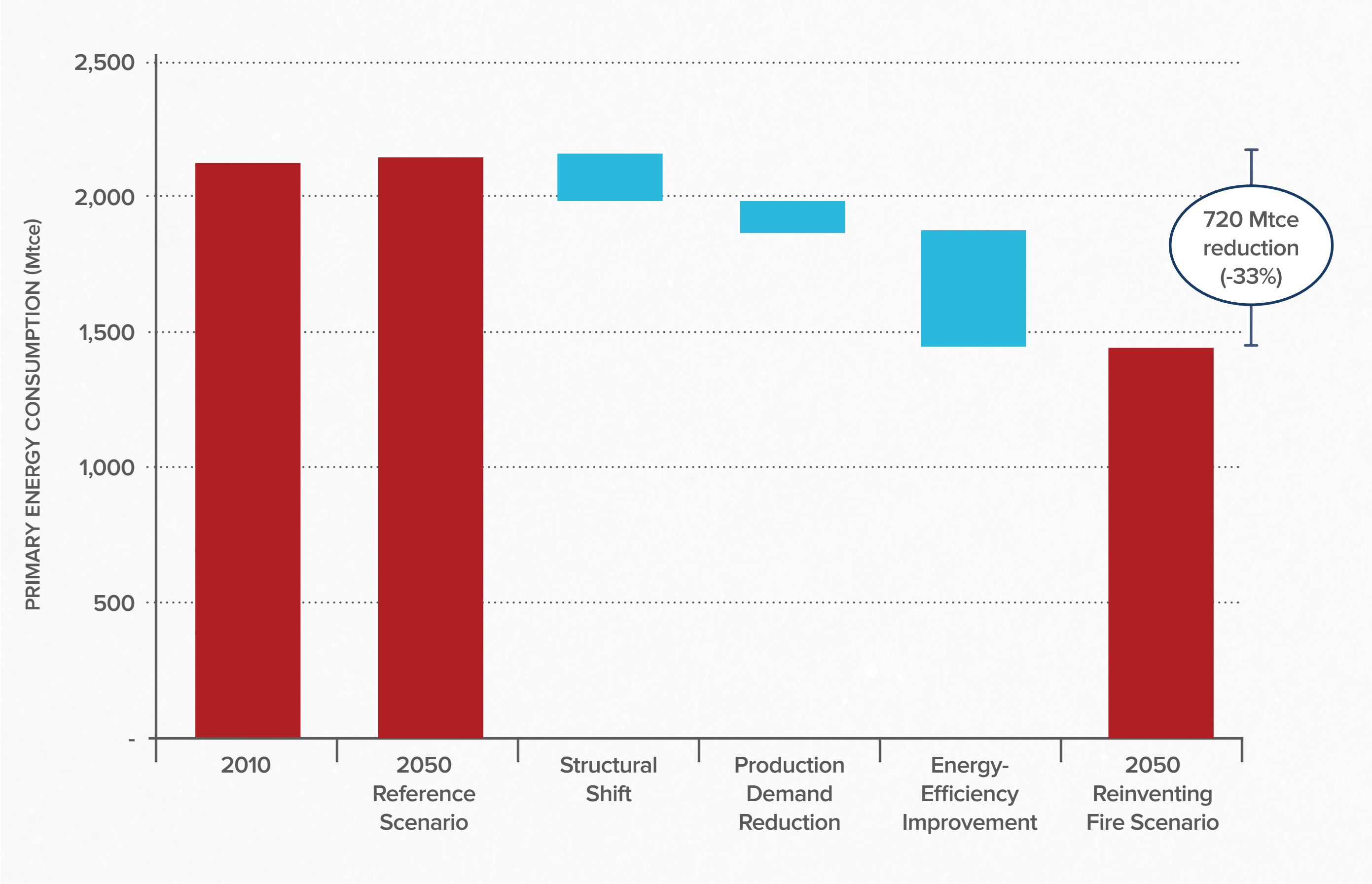
There are four pathways that achieve the Reinventing Fire vision and goals for China's industrial sector:

- Structural shift
- Production demand reduction
- Energy-efficiency improvement
- Decarbonization

In the Reinventing Fire Scenario, 2050 primary energy savings are found in three areas: structural shift (178 Mtce), production demand reduction (107 Mtce), and energy-efficiency improvement (429 Mtce) (Figure 4.9). The Reinventing Fire Scenario also saves energy in the near term. By 2020 and 2030, industrial energy use is 2,300 and 2,180 Mtce, respectively, reducing use by 550 Mtce (19%) and 920 Mtce (30%), respectively, relative to the Reference Scenario.

FIGURE 4.9: INDUSTRY SECTOR PRIMARY ENERGY SAVINGS AND PATHWAYS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

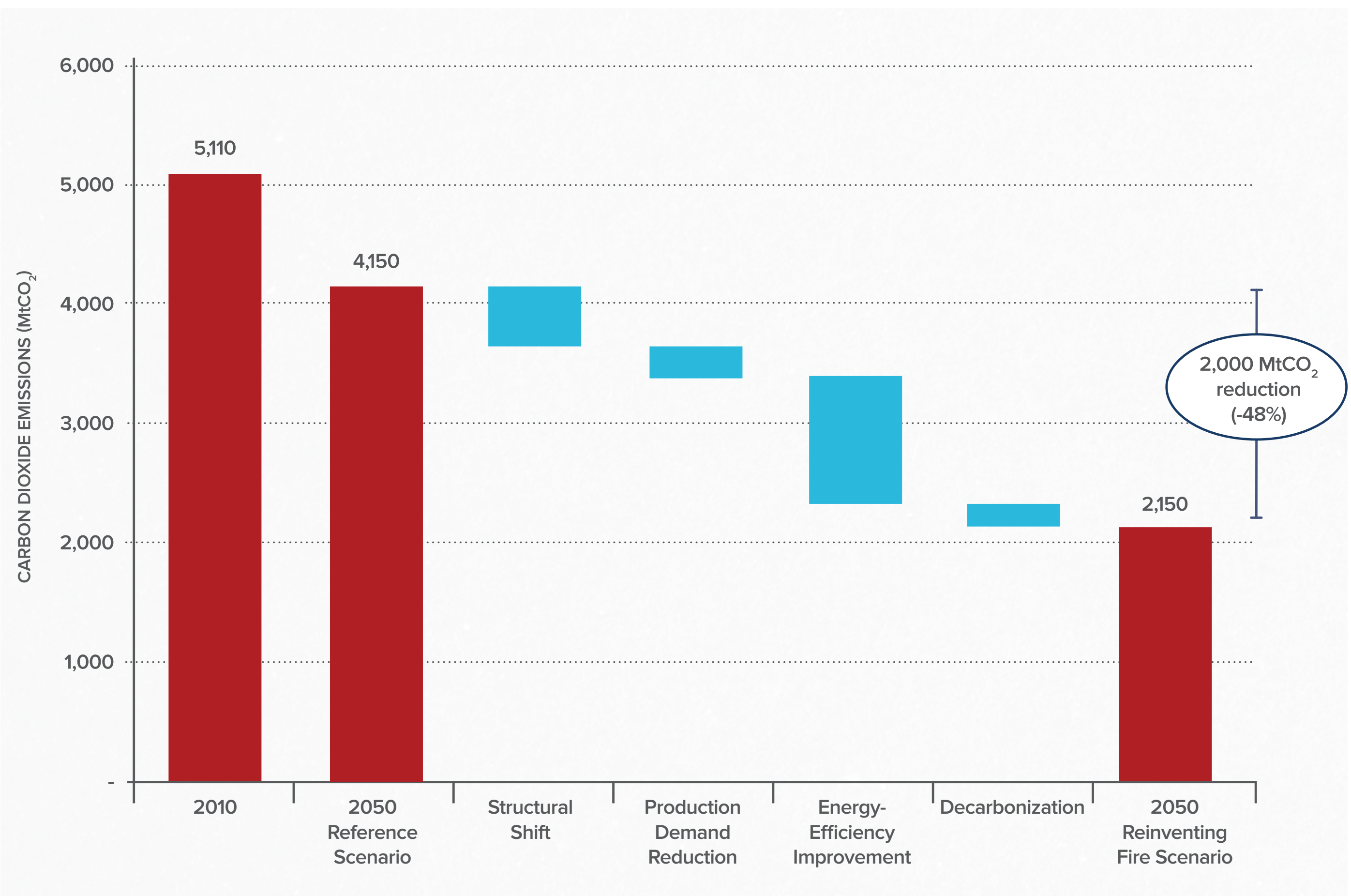


Similar reductions in energy-related CO_2 emissions are realized through structural shift, production demand reduction, and energy-efficiency improvement. Additional CO_2 emissions reductions are gained by fuel switching to lower-CO_2-emitting fuels and electrification, following the decarbonization of the electric grid. In the Reinventing Fire Scenario, 2050 CO_2 savings are found in structural shift (500 $MtCO_2$), production demand reduction (260 $MtCO_2$), energy-efficiency improvement (1,080 $MtCO_2$), and decarbonization (160 $MtCO_2$) relative to the Reference Scenario (Figure 4.10).

As with primary energy consumption, the Reinventing Fire Scenario also lowers the CO_2 emissions trajectory over the next two decades. In 2020 and 2030, industrial sector energy-related CO_2 emissions in the Reinventing Fire Scenario are 5,500 and 4,830 $MtCO_2$, respectively, reducing emissions by 1,430 $MtCO_2$ (21%) and 3,900 $MtCO_2$ (33%), respectively, relative to the Reference Scenario.

FIGURE 4.10: INDUSTRY SECTOR ENERGY-RELATED CO_2 EMISSIONS REDUCTIONS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



4.4.1 PATHWAY #1: STRUCTURAL SHIFT

Industry transformation and upgrade through rebalancing industrial structure and reshaping growth

In the Reinventing Fire Scenario, China begins to transform from the world's factory—producing manufactured goods for both domestic and export markets—to a more service-oriented economy. Urbanization stabilizes by 2050, leading to a larger role for the service economy. Since service sector activities typically consume less energy per unit of value added than industrial sector activities, such structural change from industry to services can reduce energy consumption while maintaining economic growth. For example, structural change in California was as important as the improvement of energy intensity in reducing overall energy consumption between 1997 and 2008.[29] The Reinventing Fire Scenario savings associated with structural shift are distributed across all industries.

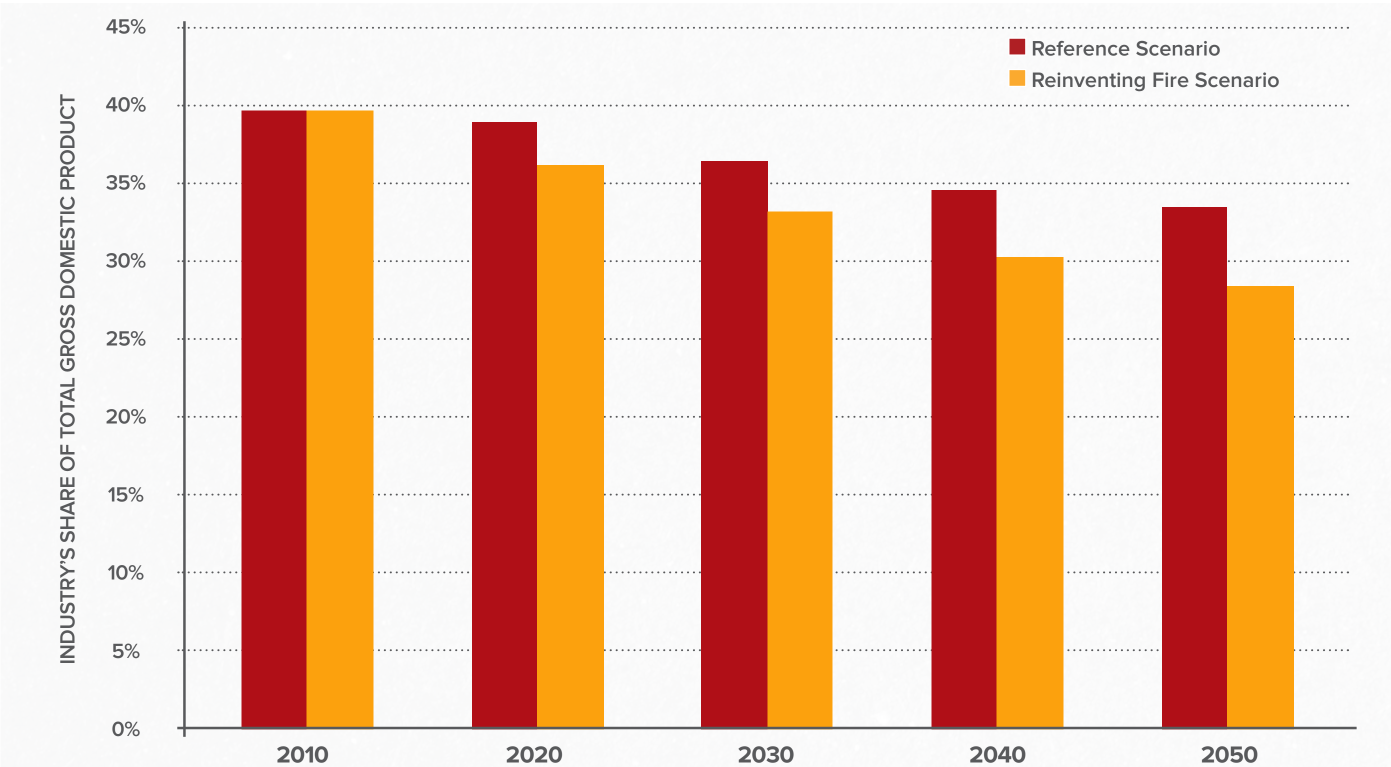
Two types of structural shift will occur in China's industrial sector.

(1) Structural shift from the industrial sector to the service sector

China's current GDP per capita, urbanization rate, ratio of industrial added value to total GDP, and ratio of less-energy-intensive to energy-intensive industry output show that China is now in the mid to late stage of industrialization. Given this, it is assumed that the ratio of industrial added value to total GDP in China will fall from 40% in 2010 to 28% in 2050 in the Reinventing Fire Scenario (Figure 4.11), compared to 33% in the Reference Scenario.[30] An example of a government successfully promoting a shift to the service sector can be found in the UK's Tech City initiative, which was designed to grow the technology cluster in East London. This program established London as the third-largest technology startup cluster in the world after

FIGURE 4.11: INDUSTRIAL SECTOR PORTION OF OVERALL CHINESE GROSS DOMESTIC PRODUCT

2010–2050



Source: ERI Economic Model, 2015.

San Francisco and New York City. Vodafone, Google, Facebook, and Intel committed to invest in the Tech City.[31]

China's urbanization will stabilize by mid-century. Until then, demand for basic materials such as cement and steel and basic industrial products will remain high and the industrial sector will be a long-term driving force for development.

From the historical experience of developed countries, the ratio of industry value added to GDP stabilizes (with a slight tendency to decline) as countries become more developed. Considering the integration of industrialization and information, the large development potential for finance and technology, and research and development derived from the internet economy, China's service sector is expected to take advantage of industry's transformation and further develop. From the 13th Five-Year Plan period on, the industry ratio of industrial value added to total GDP in China is expected to stabilize or drop. Even so, industry will continue to play a significant role in China's economy, contributing 33% and 28% to overall GDP in the 2050 Reference and Reinventing Fire Scenarios, respectively.[32]

(2) Structural shift within industry from low-value-added, energy-intensive industry to high-value-added, less-energy-intensive industry

With industrialization, there will be structural changes within industry, from resource- and labor-intensive to value- and technology-intensive. The rise of new industries and the transformation of traditional industries will promote rapid economic structural change and a new round of economic growth. Generally, emerging industries are higher value-added and less energy-intensive than traditional industries. Industrial modernization will play a role in improving the economic output per unit of energy consumption. Thoughtful policies can increase the role that green industries play in this transition.

In the future, within industrial subsectors, development trends between traditional high-energy-consuming industries and emerging less-energy-intensive industries will diverge. The role of resource- and capital-intensive industries—such as mining, steel, and cement—will decline due to cost and other market pressures, and the proportion of their added value will decline. Labor-intensive industries such as the food, printing and dyeing, and textiles industries will continue to increase in added value, but the ultimate proportion of added value of these industries relative to overall industry added value will remain unchanged or even fall slightly. The high-value-added industries such as machinery, transportation equipment, electrical equipment, and chemical products manufacturing will play a much larger role. In Japan, Germany, South Korea, and the U.S., these industries make up half of the entire added value of the industrial sector,[33] which is significantly higher than China's current level of 27%.[34] Overall, the share of high-value-added, less-energy-intensive industries is expected to increase in China.

The Reinventing Fire Scenario reflects this expectation—growth rates of China's transportation equipment manufacturing and electrical and electronic equipment manufacturing industry are significantly higher than in the Reference Scenario. The added value of these and other high-value-added industries in the Reinventing Fire Scenario in 2050 will be nearly 12% higher than that of the Reference Scenario (Figure 4.12 and Figure 4.13).

FIGURE 4.12: INDUSTRY SECTOR ENERGY INTENSITY STRUCTURAL CHANGES

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

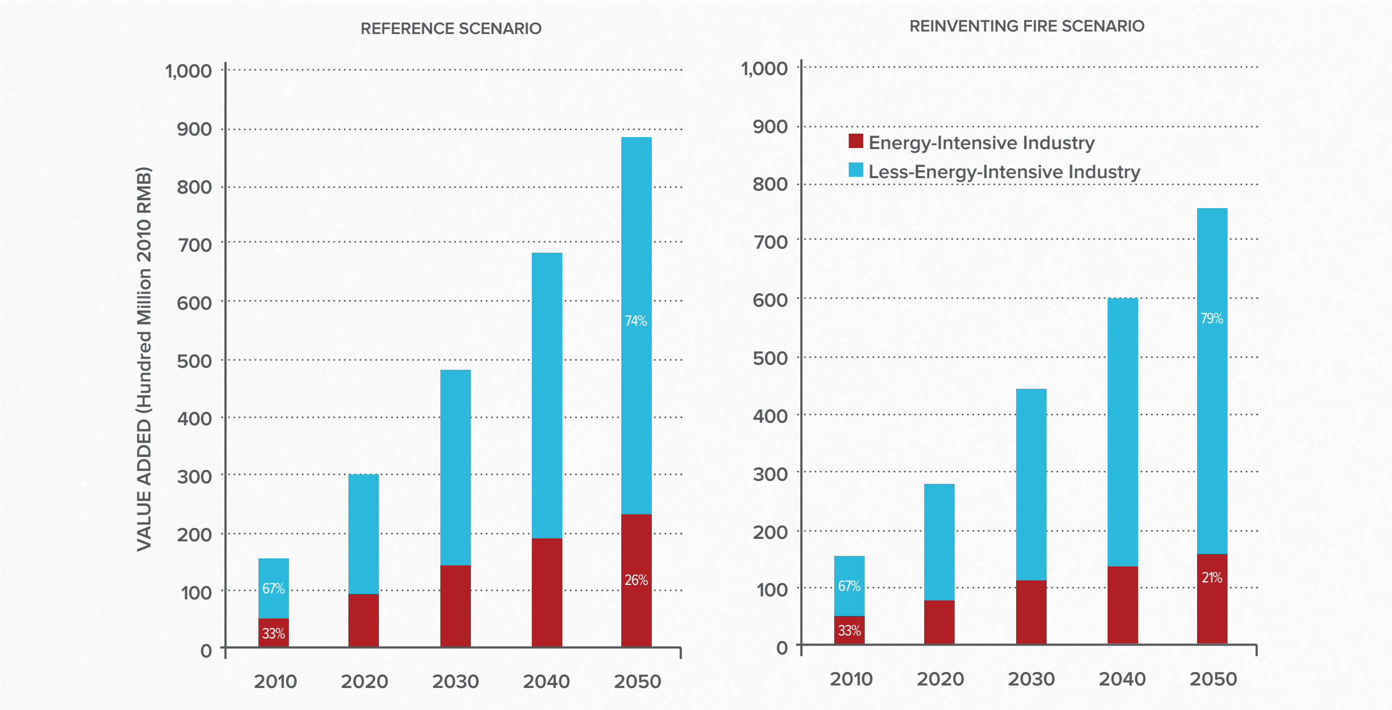
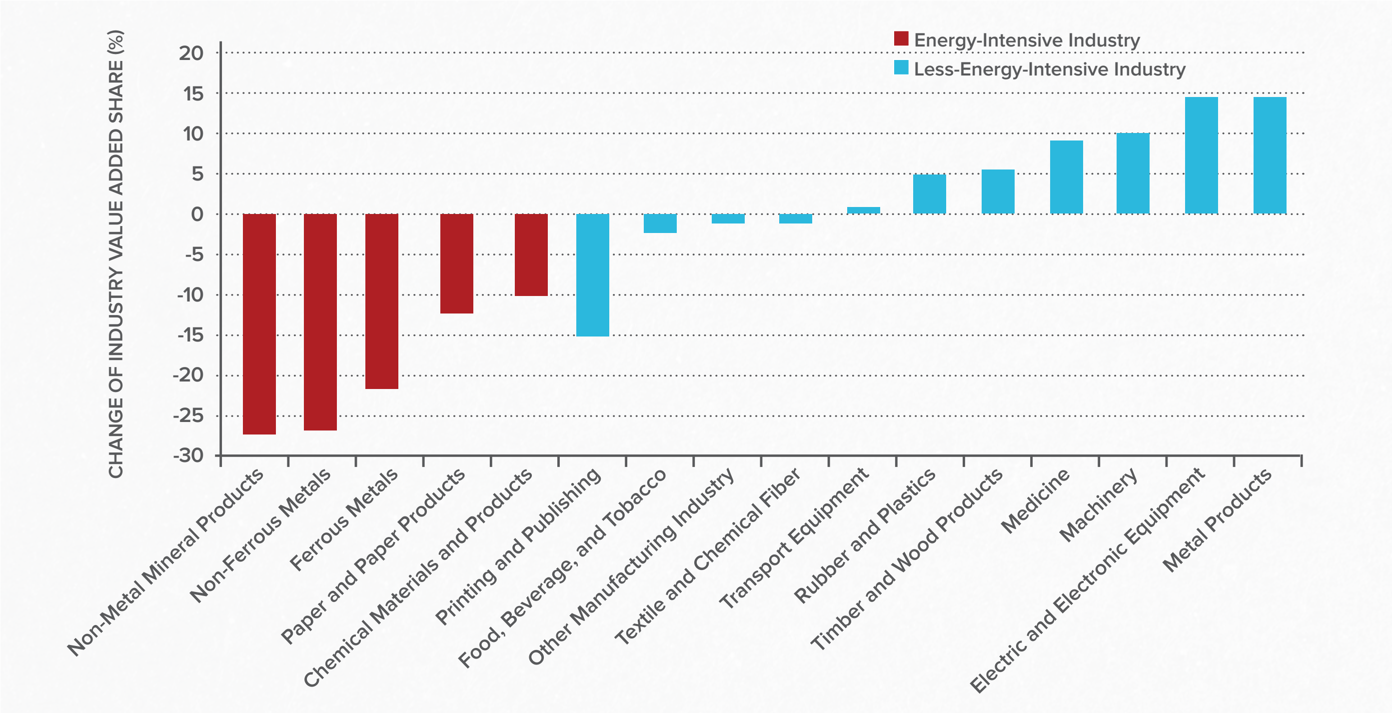


FIGURE 4.13: INDUSTRY SECTOR VALUE-ADDED CHANGE FOR SELECT SUBSECTORS

2050, REINVENTING FIRE SCENARIO, INCREMENTAL TO REFERENCE SCENARIO



In most countries that entered the late stage of industrialization or have completed it, high-energy-consuming industries did not shrink rapidly and production did not decrease significantly, but plateaued for a long time, and the added value of these industries continued to grow. This feature was particularly evident in Japan, Germany, and South Korea (although the steel and cement production of the U.S. and UK declined, it only fell by about 20–30% from the peak level).[35] Accordingly, China's energy-intensive industries will likely embark on an intensive development path and increase the added value per unit. Therefore, while the absolute production of energy-intensive products will remain relatively high, it will decrease relative to 2010 production, and the value added per unit of product will increase due to the increased production in high-value-added industries, achieving decoupling of production and added value.

Barriers

While there are significant opportunities for energy savings and CO_2 emissions reductions associated with structural shift of China's industrial sector, there are also barriers for realizing such shifts. First, fundamental trends in population growth coupled with continued urbanization mean energy-intensive commodities such as steel, cement, and glass (needed to build buildings and infrastructure) are required to meet the demand for housing, offices, hospitals, schools, roadways, and other urban needs. This continued demand makes it difficult for China's industrial sector to significantly shift away from the production of energy-intensive basic commodities. While the forecasts of industrial commodity production generally peak between 2020 and 2030, total production remains high relative to other industrialized countries.

Additionally, provincial GDP growth targets can currently be achieved more easily through large investments in capital-intensive industries rather than through relatively small capital investments in the service sector.[36] However, overcapacity in some energy-intensive sectors leave the potential for significant stranded assets in the form of newly constructed, energy-intensive facilities.[37] The service sector often has higher tax rates and higher financing costs than the industrial sector, making investments in services less attractive. As demand for labor shifts, the need for changing skills will affect those employed in certain heavy industries and more training or education for service sector jobs will be required.

Solutions

- Restrict the growth of energy-intensive industries by expanding energy-efficiency appraisals and integrating those with environmental appraisals for new large industrial facilities.
- Increase the restrictions on the export of energy-intensive products and cancel the energy-intensive products export tax rebates.
- Continue to close small, inefficient facilities as has been done since the 11th Five-Year Plan.
- Stimulate structural change by providing incentives such as tax rebates or easier permitting for high-value-added and low-energy-consuming industries.
- Reduce unnecessary burdens and costs for the service sector while incentivizing higher-value-added industry, thus allowing market forces to drive additional investment in the service sector.
- Encourage high-value-product R&D and protect intellectual property.
- Allow the market to eliminate inefficient production capacity (remove subsidies for unneeded production).

4.4.2 PATHWAY #2: PRODUCTION DEMAND REDUCTION

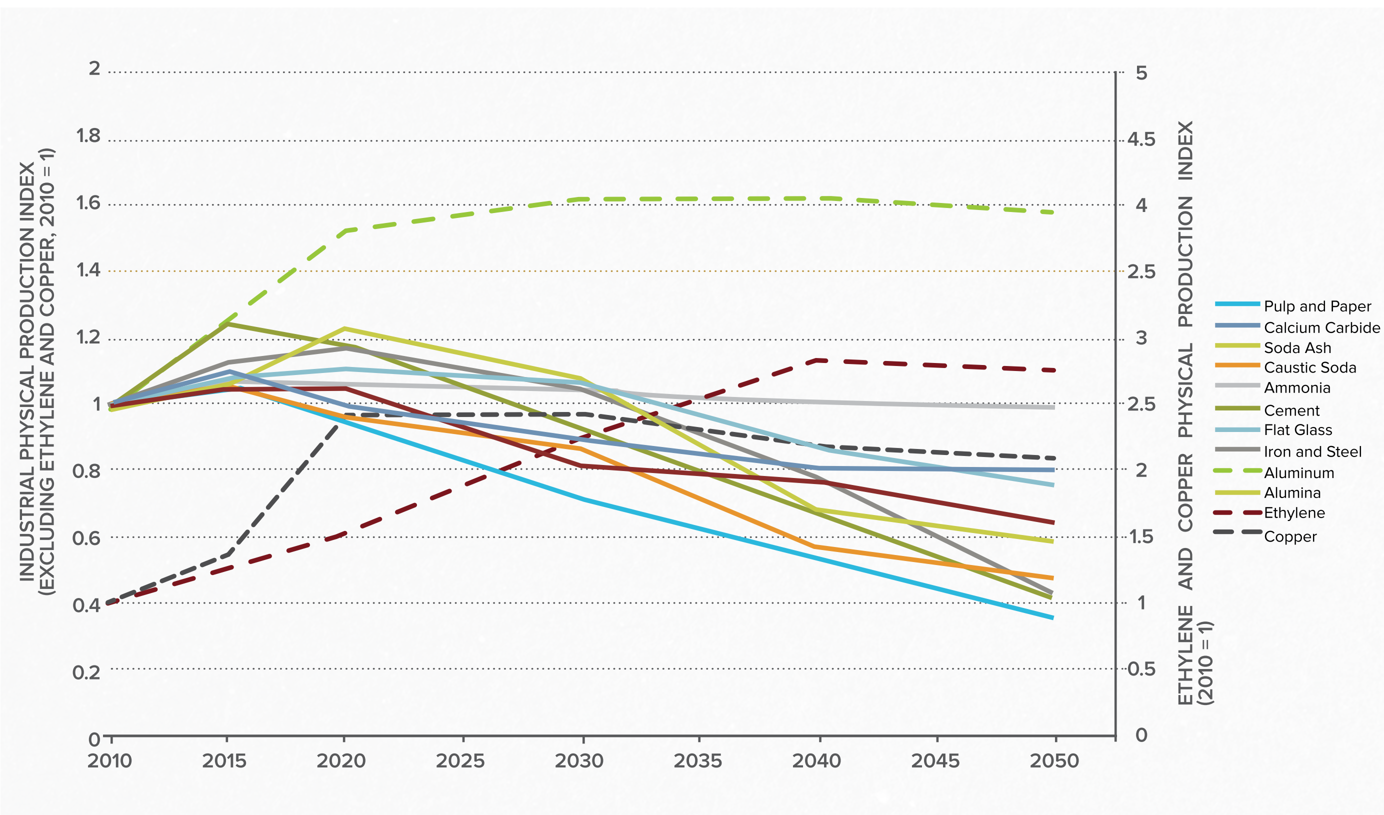
Decrease manufacturing of energy-intensive products through demand reduction and resource recycling

In 2013, energy consumption of energy-intensive industries such as iron and steel, building materials, chemicals, and nonferrous metals accounted for more than 70% of the total energy consumption of China's industrial sector.[38] In the Reinventing Fire Scenario, reduced demand for energy-intensive industrial products results from increased material strength (e.g., in the steel and concrete used to construct buildings), smart development that maximizes building and infrastructure lifetime, and intelligent designs that require less material. Reduced production from raw materials in turn lowers energy consumption and related CO_2 emissions. Recycling and remanufacturing materials, rather than using raw materials to create new materials, reduces industrial energy consumption and moves China toward a circular economy where products are continually reused.

In 2050, production demand reduction decreases annual energy consumption by more than 107 Mtce relative to the Reference Scenario, avoiding emissions of more than 260 $MtCO_2$ each year. These savings are concentrated in the ferrous metals (iron and steel) and non-metal mineral products (cement) sectors—largely as a result of increasing building and infrastructure lifetime. In the Reinventing Fire Scenario, production of all major energy-intensive commodities is projected to peak between 2015 and 2020 (roughly 10 years earlier than in the Reference Scenario) and decline more rapidly than the Reference Scenario (Figure 4.14).[v]

FIGURE 4.14: INDUSTRY SECTOR PRODUCTION TRENDS

2010–2050, REINVENTING FIRE SCENARIO



[v] *Industrial production activity forecasts were developed in consultation with various Chinese industry experts as described in Chapter 2.*

(1) End "major demolition and construction" practices and reduce irrational demand for materials

In 2014, 4.2 billion m^2 of buildings and infrastructure were under construction in China,[39] more than the sum of construction in all developed countries.[40] The average lifetime of Chinese buildings in urban areas is 25–30 years;[41] in rural areas it is 15 years or less.[42] This is an artifact of low-quality building materials and continual rebuilding as China strives to recast its cities in new forms and urbanization continues.[43] These building lifetimes are significantly lower than the average building lifetime of 60 years in the U.S.[44] Premature demolition or demolition and construction of buildings with poor-quality materials results in enormous waste of energy and resources, and contributes to environmental pollution through both construction dust and energy-related pollution emissions associated with the production of building materials such as steel, cement, and glass.

To realize the Reinventing Fire vision, China needs high-quality, well-designed cities built with long-lasting buildings and infrastructure. High-quality buildings can be both resilient and flexible in their design to allow for changing uses over time. An example is the new 121,000 m^2 parking structure at the Massachusetts Convention Center Authority in Boston; while it is currently a parking garage, its universal design structure allows changes to support a variety of denser, higher-value uses. This ensures that the materials used to construct the structure can be adapted to changing requirements for the entire building lifetime.[45]

By reducing unnecessary major demolition and construction, material demand can be cut by 20% by 2050 relative to 2010 while providing the same service.[46] Accordingly, the production demand of steel, cement, non-ferrous metals, and other energy consuming products can be reduced by 10%.[vi]

(2) Improve material quality and reduce material-use intensity

Low-quality materials make up a large share of production of steel and concrete in China. Using low-quality construction materials not only decreases the strength and lifetime of buildings, infrastructure, and other products, it also increases the need for materials and reduces utilization efficiency, resulting in significant waste of resources and energy. Therefore, improving material quality, reducing material usage intensity, and decreasing material consumption are vital ways to reduce energy-intensive material production.

An example of a process for reducing material usage is near-net shape casting, which integrates casting and hot rolling of steel into one process step, reducing machining at the finishing step because the steel is casted at or near its final thickness, and saving energy and reducing emissions. Nucor Corporation utilized near-net shape casting in a U.S. facility to reduce CO_2 emissions by 70% relative to other finished metal production facilities.[47]

China uses predominately lower-quality cement for concrete construction relative to developed countries. In 2011, high-quality cement production represented only about 26% of total production.[48] Replacing low-quality cement with high-quality cement can reduce cement demand by 15–40%. If the proportion of high-index cement to total cement production increased to 50% or more, it would be possible to save 20 Mtce per year.[49]

Smarter use of materials also reduces energy consumption. For example, in traditional construction, rebar of the same diameter, spaced at the same distance, is used across large surface areas in order to make detailing, identifying, laying, and checking installation easier—but this uses 15–30% more rebar than needed to meet performance and code requirements.[50] In Australia, BAMTEC® technology is used to produce a pre-fabricated "rolled carpet" steel reinforcement system consisting of smaller-diameter rebar that optimizes the sizing and placement of rebar. This avoids overuse and expedites installation by 30–40%.[51] Currently, the technology can only be applied to slab reinforcement, although using it in other applications, such as shear walls, is under development.[52]

[vi] *This is based on an assumption from the buildings chapter that approximately 50% of the production demand for these products comes from the building sector.*

CASE STUDY 4.1: USING LESS CEMENT IN ONE WORLD TRADE CENTER

By using BASF's water-reducing admixtures to substantially replace Portland cement with cement made with supplementary cementitious materials, One World Trade Center in New York City improved the compressive strength of its concrete from 8,000 to 14,000 pounds per square inch. This stronger concrete has better thermal performance and reduced the heating, ventilating, and air conditioning needs of the building, leading to both short-term construction and long-term in-use energy savings. Overall, the building required 40% less cement for construction compared to conventional designs, saving 33,000 tCO_2.[53] Key challenges of using high-strength concrete include the impact of heat from concrete curing and finding the right concrete mixture proportions. One World Trade Center adopted night pours and introduced high levels of ice into the mix. The project monitored the in-place concrete temperatures to make sure specific requirements were met. An all-level quality assurance and quality control was implemented to ensure the high-strength concrete mixture had the right consistency throughout the project.

These approaches aren't limited to heavy industry—they also play a role in the manufacturing of commercial and consumer goods. In the U.S., General Electric's (GE's) full-scale additive-manufacturing facility in Cincinnati, Ohio, significantly reduced material waste by cutting the material losses typically associated with tooling materials into final shapes. GE Aviation is exploring the use of 3D printing on titanium, aluminum, and nickel-chromium alloys and planned to use 3D-printed fuel nozzles on its newest aircraft engine in 2016. This technology has the potential to reduce material needs by up to 90%, equally reducing energy use in associated raw material production.[54] Cost effectiveness and product "resilience" are two of the biggest concerns of industrial-level 3D printing. Other concerns of 3D printing at a smaller scale (e.g., commercial or personal-use 3D printing) include quality control, safety standards, and intellectual property rights.[55]

(3) Develop a recycling economy to make the best use of resources and maximize resource use efficiency

The use of recycled materials is a related and equally important factor in production demand reduction. For example, producing recycled steel from scrap steel requires only one-third the energy required to produce steel from iron ore and other raw materials. The proportion of electric arc-furnace (EAF) steel, which predominately uses scrap steel as a raw material,[56] in China has been only about 10%, far below the level of 30–50% in many industrialized countries.[57] In recent years, due to the rapid growth of China's crude steel output, EAF steel production growth has not increased proportionally (Figure 4.15). In 2012, China's total consumption of scrap in the iron and steel industry was about 80 million tons.[58] The main reason for this is China's relative lack of scrap, resulting in scrap supply shortages and high prices. In addition, unlike many developed countries, electricity prices for the industrial sector in China are higher than those for the residential sector.[59] This leads to higher EAF production costs and low competitive capacity, which limits the increase of EAF steel production. Scrap steel availability is forecast to increase to more than 300 million tons per year in 2030 vs. 200 million tons per year in 2014, indicating significant potential for greater use of EAF in the future.[60]

Additional energy savings can be achieved by recycling other resources. There are significant opportunities to increase recycling of aluminum, copper, and other resources such as paper and glass in China (Figure 4.16).

FIGURE 4.15: ELECTRIC ARC FURNACE SHARE OF TOTAL STEEL PRODUCTION

2010–2014[61]

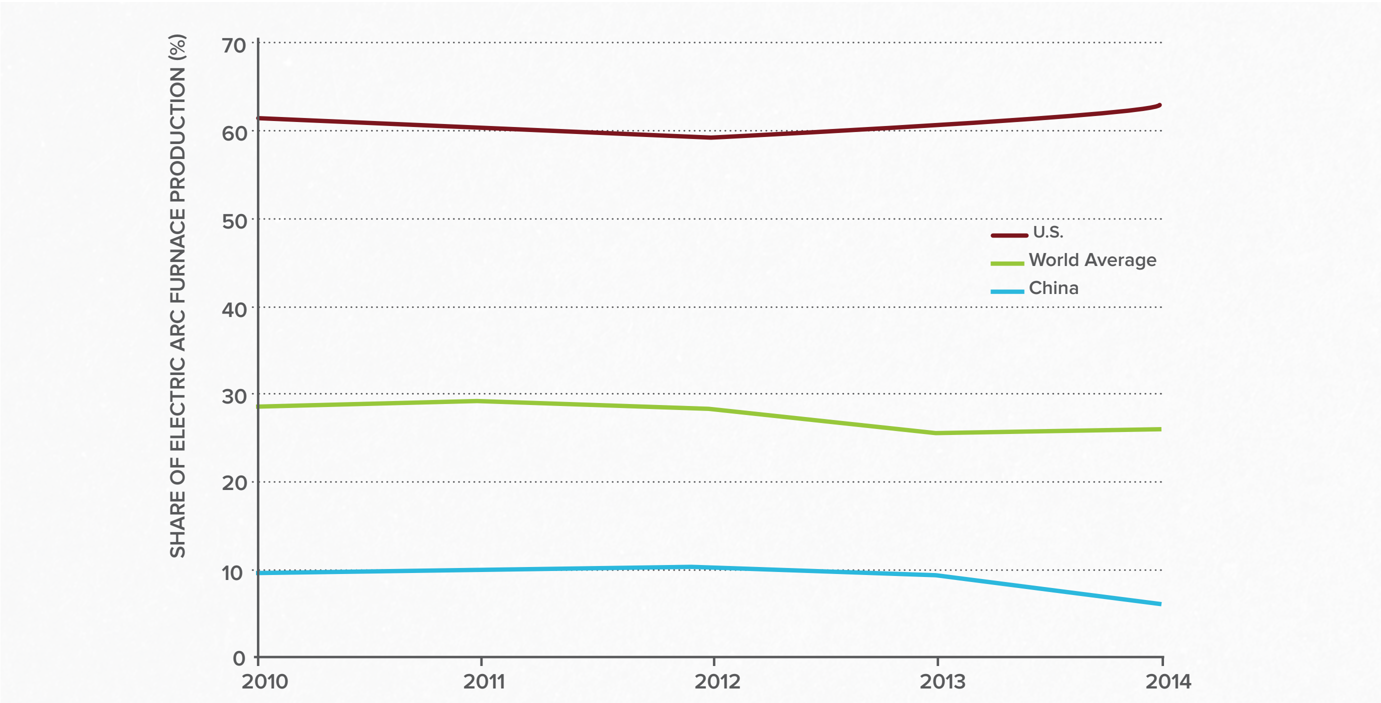
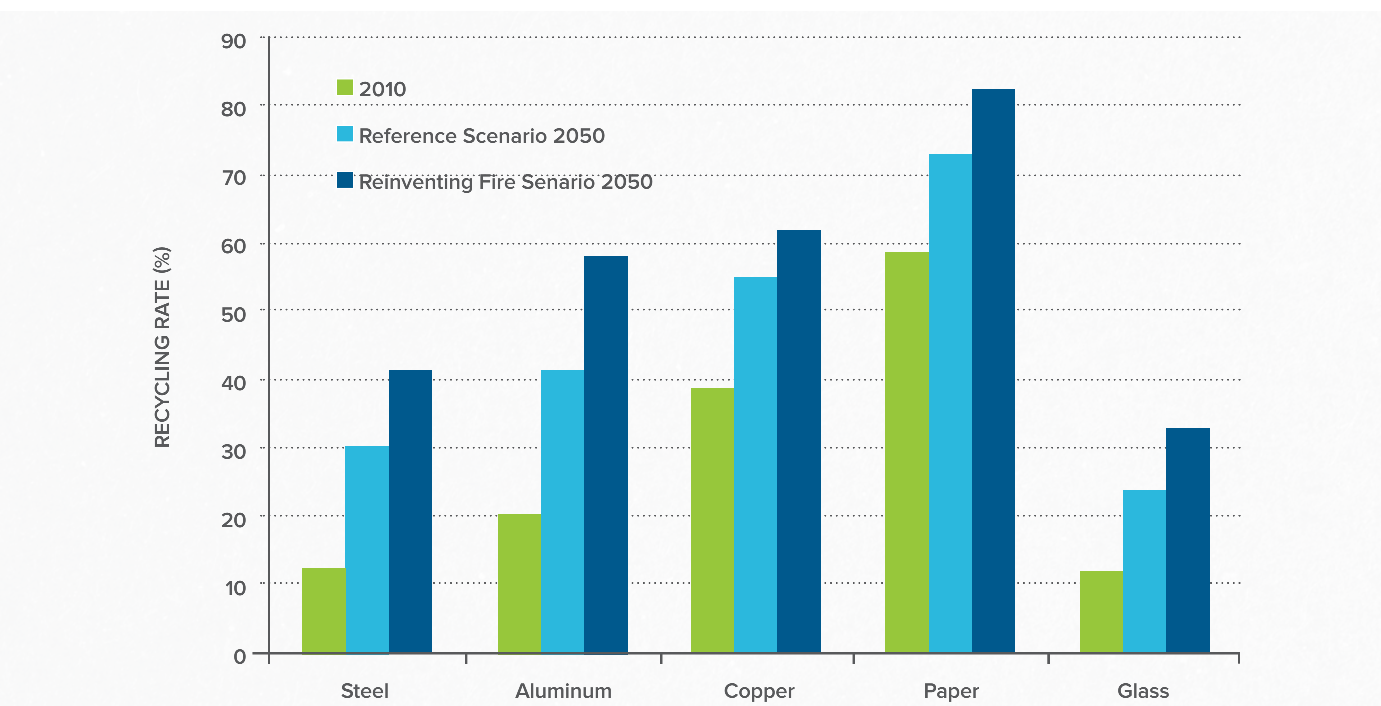


FIGURE 4.16: INDUSTRY SECTOR PRIMARY PRODUCT RECYCLING RATE ASSUMPTIONS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



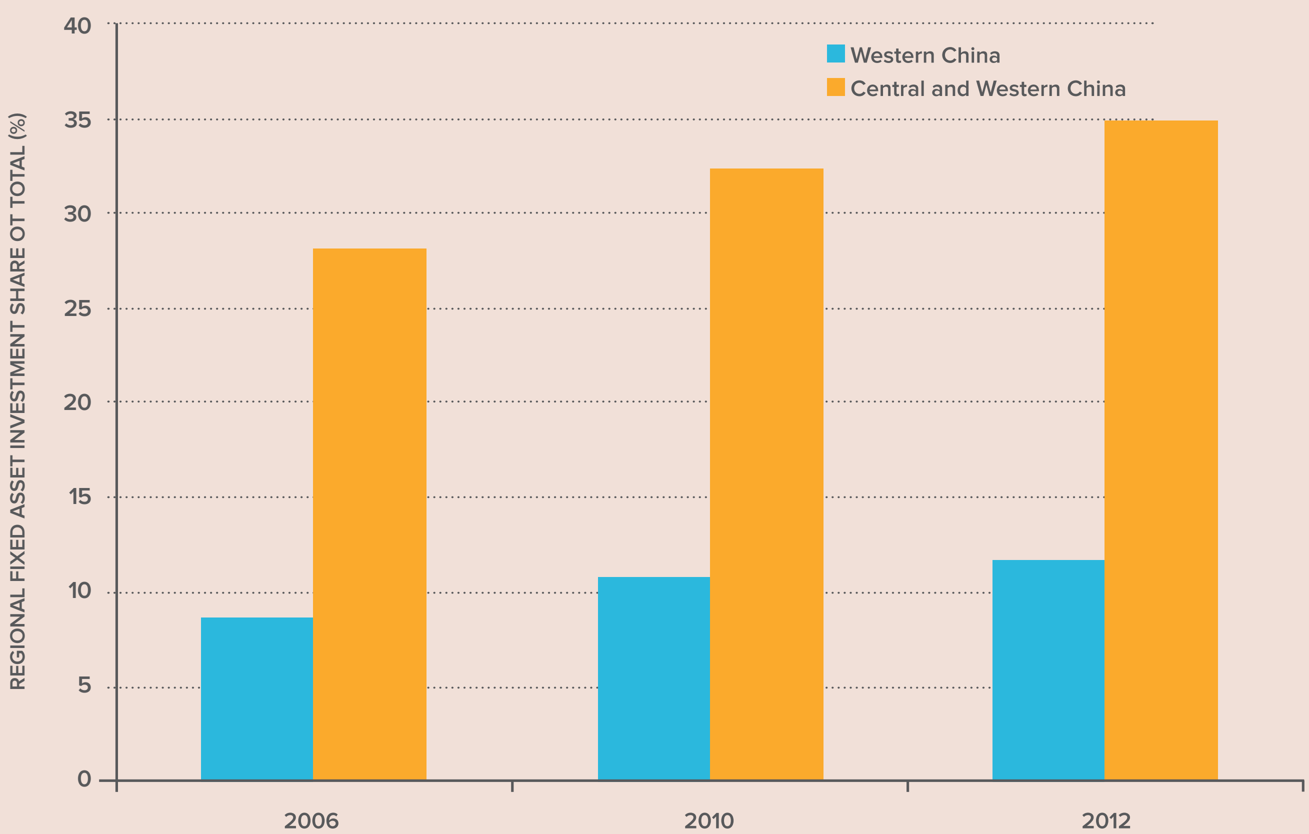
CASE STUDY 4.2: THE IMPORTANCE OF WESTERN AND CENTRAL CHINA

Nationally, China is in the mid and late stage of industrialization, where the overall share of industry in the economy begins to decline. However, because of significant regional differences, the share of industry in some relatively less-developed regions may continue to increase. Infrastructure construction in China's central region will boost local demand for energy-intensive materials. As a result, industrial development of the central and western regions will accelerate and play an increasingly important role in industrial production.

Industrial relocation provides an ideal opportunity to improve the overall level of China's industrial energy intensity, but only if the central and western regions ensure that energy savings and environmental protection are important criteria for investment. At the same time, new construction, renovation, and expansion of industrial enterprises also provides the opportunity to promote advanced energy-saving technologies, equipment, production technologies, and the application of integrative design (Figure 4.17).

FIGURE 4.17: WESTERN AND CENTRAL CHINA FIXED ASSET INVESTMENT RATIOS

2006–2012[62]



Eco-industrial parks also have significant potential to reduce energy consumption, improve material and energy efficiency, minimize waste, reduce greenhouse gas emissions, and provide co-benefits such as reduced water consumption and improved air quality. The Kalundborg Eco-Industrial Park in Denmark reduced the import of natural gypsum by recycling 150,000 metric tons of gypsum from desulphurization of flue gas, avoided 240,000 metric tons of CO_2 emissions per year, and saved 3 million m^3 water per year.[63,64] There are about 20 byproduct synergy projects in the U.S. and it is estimated that in 20 years, these projects could save $560 million in cost, reduce 38 trillion British thermal units (BTUs) (1.4 Mtce) in energy consumption, and decrease CO_2 emissions by 9 million metric tons.[65] South Korea's Ulsan Eco-Industrial Park began operation in 2005, with a total investment of about $53 million, and achieved a profit level of $58 million per year. The park reduced waste by 37,000 metric tons per year, and avoided CO_2 emissions by 300,000 metric tons per year.[66,67]

There are technical challenges for eco-industrial parks, such as ensuring technical feasibility of symbiotic relationships, reducing technical risks and improving stability, and ensuring technologies have sound economic viability.[68] In addition, other challenges include the risks of being too big and expecting too much due to demands and coordination among various project stakeholders, lack of funding, lack of suitable financing mechanisms, burdensome permitting and bureaucratic processes, lack of motivation from local community and private sectors, and lack of effective management and operation.[69]

Barriers

Despite the significant energy- and cost-saving potential, there are barriers to achieving large reductions through production demand reduction. Key barriers include rapid urbanization in China (which results in quick and often poor-quality construction), a lack of standards and enforcement for high-quality products and low-material-intensity products, the absence of a comprehensive and integrated waste-management system across many industries, and an artificially low (or zero) cost for waste treatment and disposal.

Solutions

- Promote long-term urban planning regulations that require high-quality construction practices to reduce demand for construction materials over time.
- Develop standards and incentives, coupled with strong enforcement, to promote higher-quality products and material efficiency in production.

- Conduct pilots to demonstrate and spread high-performance, high-quality buildings.
- Promote market-based approaches to encourage production demand reduction. For example, performance labeling schemes such as the Leadership in Environmental and Energy Design (LEED) green building rating scheme awards points for the use of recycled materials such as fly ash as a clinker substitute in cement/concrete production, and the use of higher-strength steel and cement in construction provides economic benefits by reducing construction costs (see the One World Trade Center case study).
- Transform existing industrial parks and key enterprises with the concept of eco-design circular economy.
- Establish municipal waste, sewage, and waste recycling systems.
- Develop a reasonable price for industrial waste disposal.

4.4.3 PATHWAY #3: ENERGY EFFICIENCY IMPROVEMENTS

Use integrative design and efficient technologies to improve energy efficiency

In the Reference Scenario, the energy intensity of Chinese industry improves to reach 2010 advanced levels by 2050. In the Reinventing Fire Scenario, the energy efficiency of Chinese industry surpasses 2010 world best practice values by 2050. To achieve this, industrial facilities fully adopt currently available commercialized technologies—including sophisticated management and control systems—to ensure that energy is used efficiently and losses are minimized. Integrative design provides additional opportunities for savings by applying whole-system optimization techniques and industrial ecology wherein waste, input, and energy streams are coordinated across multiple co-located industries and non-industrial facilities to improve overall system efficiency.

(1) Build and retrofit plants with energy-efficient technologies and integrative design

There are hundreds of commercialized energy-efficient technologies and measures that can be used in the design and construction of new industry-specific facilities or to retrofit existing industrial plants (depending on their age, layout, and existing processes) and in the operation of both new and existing facilities. These options include sector-wide options (e.g., efficient electric motors, high-efficiency boilers and process heaters, fuel switching), process-specific options (e.g., bio energy contained in food and pulp and paper industry wastes, turbines used to recover energy from pressurized blast furnace gas), and operating procedure changes (e.g., control of steam and compressed air leaks, use of insulation).[70]

Between 2010 and 2050 in the Reference Scenario, every industrial subsector in China shows significant autonomous energy-intensity improvements as new efficient facilities are built and existing facilities implement available energy-efficiency measures. Energy-intensity improvement in the Reference Scenario ranges from a high of 78% for the other non-metallic mineral products sector (e.g., gypsum) to a low of 22% for the other paper and paper products sector (e.g., cardboard) over the 40-year study period. In the Reinventing Fire Scenario, energy intensity improvement in China's industrial sector exceed the Reference Scenario by 13–27%, depending on the subsector, as additional savings are realized through integrative design and further adoption of energy-efficiency technologies and measures (Figure 4.18).

Integrative design and system optimization generate large savings by first optimizing end-use demand. For example, server virtualization offers a way to consolidate servers by allowing multiple different workloads to run on one physical host server. A "virtual server" is a software implementation that executes programs like a real server. Multiple virtual servers can work simultaneously on one physical host server. Therefore, instead of operating many servers at low utilization, virtualization combines the processing power onto fewer servers that operate at higher total utilization. This is a vast improvement over the old system of running one physical server per application at 6–12% capacity.[71] By reducing the number of servers, this in turn may allow installation of smaller, more-efficient cooling systems. Investing in on-site, combined cooling, heat, and power (CCHP) for electricity and cooling minimizes losses in the power generation, transmission, and distribution system.

Economic theory generally assumes diminishing returns: the more energy-efficient technologies or measures adopted, the more steeply the marginal cost of the next increment of savings rises, until it becomes too costly (the left half of Figure 4.19). Integrative design and system optimization often yield expanding returns if the engineering is done unconventionally but properly; large savings can cost less than small or no savings by optimizing whole systems for multiple benefits (the right half of Figure 4.19) instead of components for single benefits.

GM's vehicle assembly plant in Lansing, Michigan, was built with the goal of adopting energy efficiency measures within a two-year simple payback period. In the facility, modeling software separated the space into zones and ensured maximum reuse of waste energy, minimized loss of throughput, and effective production design. Compared to similarly designed new plants using only cost-effective technology, the Lansing facility uses 45% less energy and saves $1 million per year in energy costs. With efficiency of design, the 223,000 m^2 (2.4 million ft^2) facility cost $800 million in 2006.[72] Overall, GM's focus on incorporating technologies and practices with a payback period of less than two years saved the company $90 million per year in operational costs by 2012.[73]

FIGURE 4.18: INDUSTRY SECTOR ENERGY INTENSITY IMPROVEMENT

2010–2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

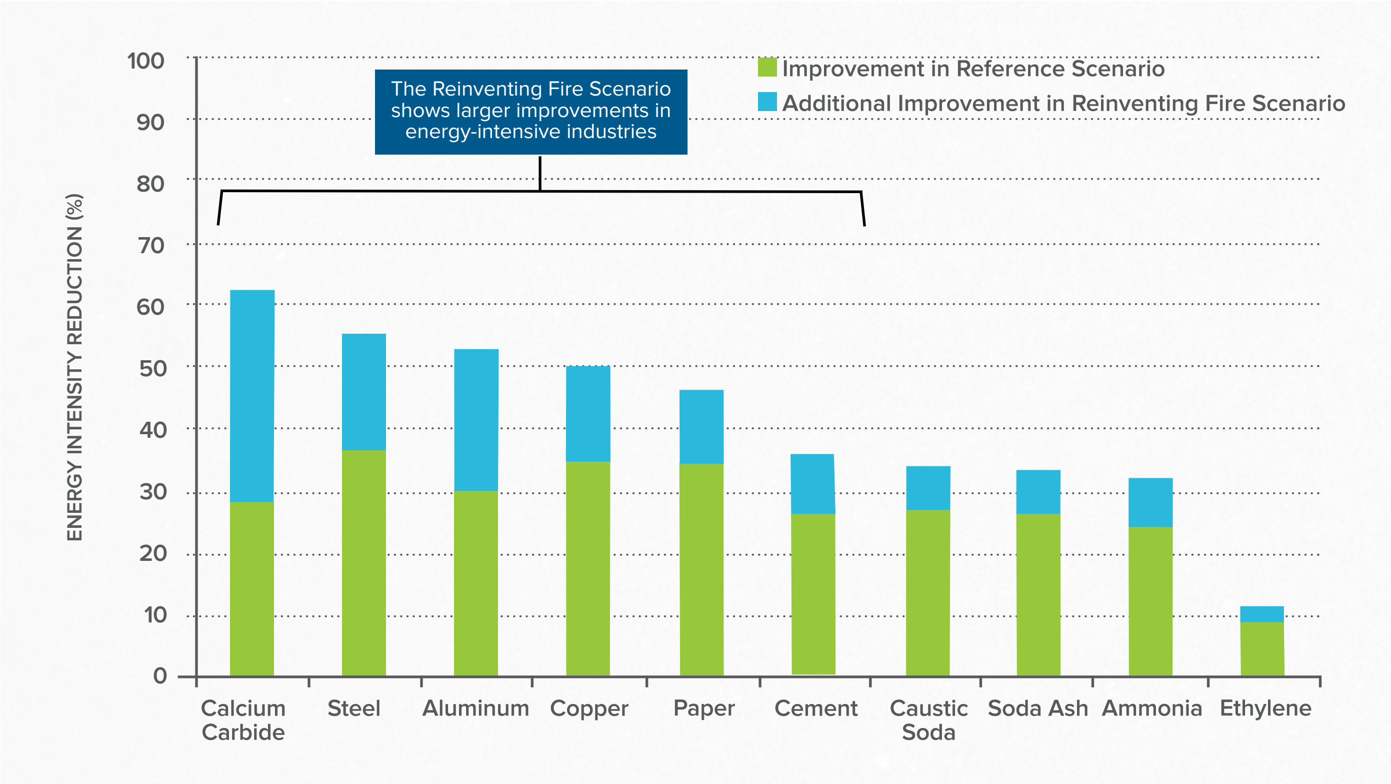
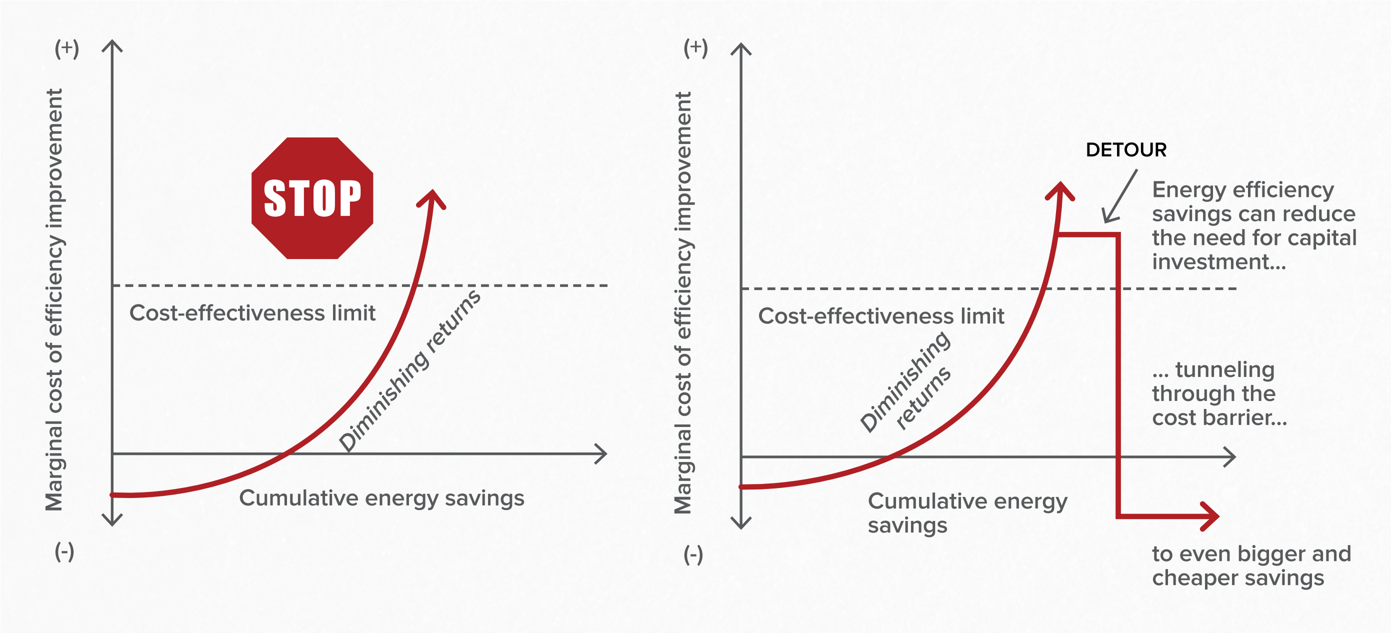


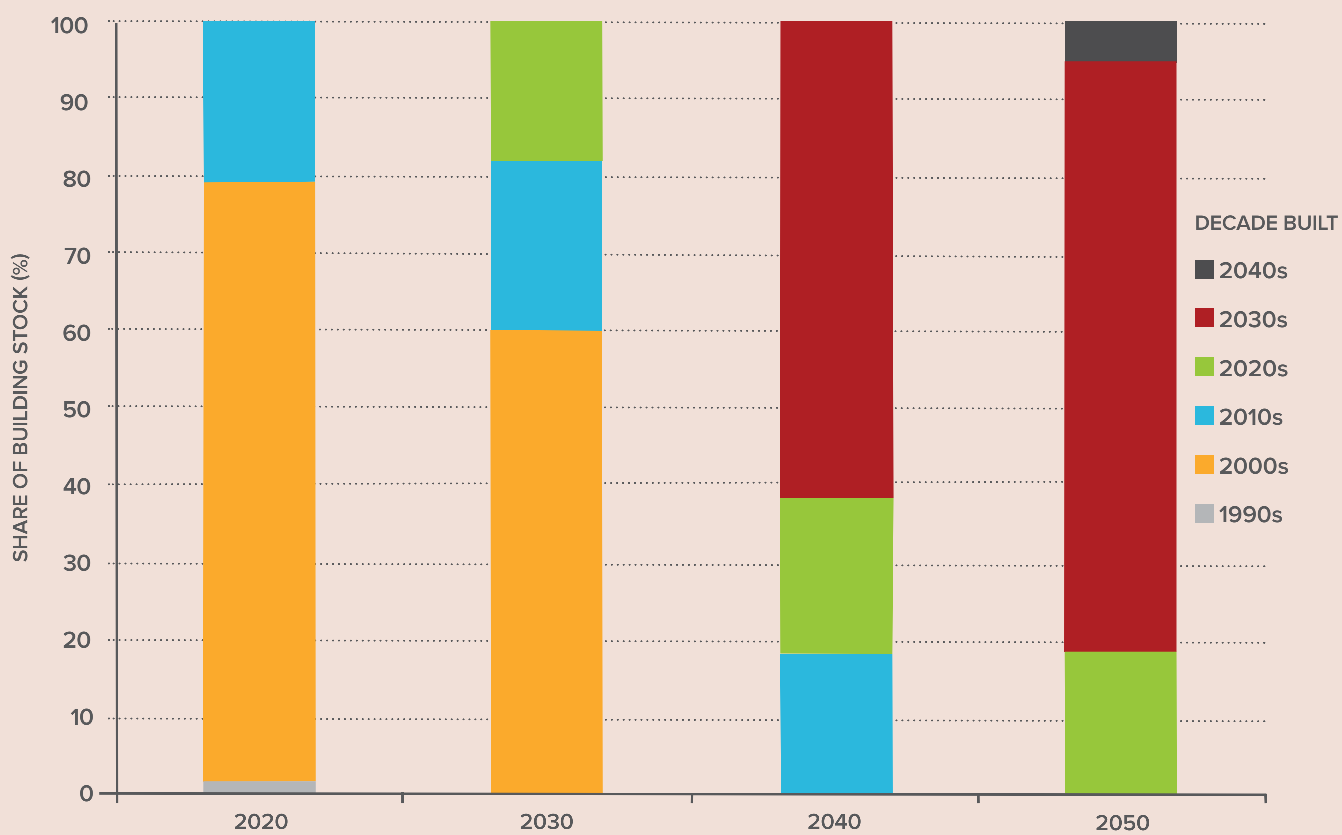
FIGURE 4.19: TUNNELING THROUGH THE COST BARRIER WITH INTEGRATIVE DESIGN



CASE STUDY 4.3: ANALYSIS OF IRON AND STEEL INDUSTRY PRODUCTION CAPACITY STOCK TURNOVER

An analysis of the Chinese stock turnover of the iron and steel industries and future production capacity mix revealed that over the next 30 years, most existing production capacity will retire. This capacity will be replaced by production capacity built after 2020 (Figure 4.20). This analysis was based on the multi-year composition of the existing production capacity and considered certain lifecycle conditions. Therefore, China's iron and steel industries have the opportunity to build factories based on energy-efficient integrative design with highly efficient production capacity.

FIGURE 4.20: AGE OF STEEL MILLS IN PRODUCTION BY DECADE



(2) Use advanced sensing and control technology to increase efficiency

Accelerating development of technologies that support information technology is a key enabler for greater efficiency in Chinese industry, especially for improving production of automobiles, aircraft, ships, machinery, and household electric appliances. Establishing industry software research and development programs and production and service systems will provide strong support for digital networks and smart manufacturing.

The accelerated development of advanced sensing and controls will speed the development of smart energy systems. Smart energy means real-time monitoring and analysis by next-generation information technologies, such the Internet of Things (IoT), to manage production, storage, transmission, and use of energy. Such technology allows real-time monitoring, reporting, and optimization on the basis of real-time data and cloud computation, thereby promoting scientific, reasonable, and sustainable energy production and consumption.

The U.S. Department of Energy (DOE) estimates that adopting proven energy management best practices can save roughly 7% of total U.S. industrial energy consumption.[74] To capture this opportunity, the DOE and the U.S. Council for Energy-Efficient Manufacturing (U.S. CEEM) created the Superior Energy Performance Program (SEP) to improve industrial energy efficiency at industrial facilities; the program implements the ISO 50001 energy management systems. Facilities meeting the standard have improved their performance up to 30% over a three-year period.[75]

Canadian-based Guelph Glass provides an example of smart energy savings. The company installed a series of adjustable-speed-drive (ASD) motors in their facility in Ontario, Canada, while simultaneously installing a closed-loop sensor and monitoring system to run them. The sensor system allowed the fans in the facility to adjust their speed based on production volume. The equipment combined with the sensor system (ASDs would have had little value without control systems) resulted in a 50% energy-efficiency improvement and a 10-month return on investment.[76]

Barriers

There are a number of barriers to capturing significant levels of energy efficiency, including a lack of financial resources to invest in efficient technologies and measures especially in small and medium enterprises, risk of production disruptions, and general lack of information and knowledge of energy-efficiency options in companies, including top management. This is complicated because efficiency measures may not be directly tied to production, which management correlates with profit, even though reducing energy costs directly improves a company's economic bottom line. On a larger scale, a lack of enforcement of government regulations and a lack of coordination between government agencies makes it easier for enterprises to ignore energy efficiency, especially when environmental externalities are not internalized through energy pricing.

Solutions

- Establish a nationwide energy-efficiency benchmarking program for enterprises to identify and reward the most efficient industrial facilities and provide appropriate incentives for less efficient facilities to reduce their energy intensity. The Suzhou Province Energy Efficiency Star or the U.S. Superior Energy Performance programs are examples of such benchmarking approaches. Enterprises can use the benchmarking information to assess the competitiveness of their own operations and set targets to improve their energy efficiency. There are also proven market-driven benchmarks, such as the Solomon Energy Intensity Index in the refining and petrochemical industries, that private enterprises voluntarily participate in to gauge their relative energy performance and competitiveness.

- Develop proven financial mechanisms for energy efficiency in China. Loan guarantee programs such as the U.S. Department of Energy's Renewable Energy and Energy Efficiency Loan Guarantee Program (with more than $32 billion in loans guaranteed)[77] and the Australian Clean Energy Finance Corporation are examples of market-based solutions that encourage the deployment of energy efficiency by reducing perceived financial risk of investment.

- Improve China's support of energy performance contracting and energy service company (ESCO) business models to increase access to capital and energy-efficiency services for enterprises.[78,79]
- Promote demonstration of best practices in energy efficiency and integrative design and focus on capacity building in the field of energy efficiency. Examples include energy management systems that enable continuous improvement and thermal integration of processes at industrial facilities.
- Encourage research, development, and investment in intelligent manufacturing through pilot projects.
- Develop grid-integration standards in utilizing complex industrial waste heat and electricity, and emission standards in co-processing wastes.

4.4.4 PATHWAY #4: DECARBONIZATION

Focus on reducing coal use, increasing the use of low-carbon and renewable energy sources, and increase electrification as China's electric grid decarbonizes

Replacing coal with alternative fuels such as natural gas while increasing the use of renewable energy sources and electrification (coupled with a low-carbon grid) in key industries are important means to optimize the industrial sector's energy consumption structure and address environmental pollution.[v] For example, the CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50 initiative in Japan is evaluating the use of chemical and physical absorption technologies to reduce blast-furnace CO_2 emissions by 30%.[80]

[v] Industrial carbon capture, utilization, and storage was not explicitly modeled in the Reinventing Fire analysis, but pilot projects are testing its viability.

1) Reduce direct coal consumption

Coal is the dominant fuel that provides power and thermal energy for Chinese industrial production and is an important industrial production material, especially in the production of steel and chemicals. In 2010 direct consumption of coal and coke in China exceeded 400 Mtce and 330 Mtce, respectively, on a final energy basis—accounting for more than 45% of final non-electricity coal consumption in industry.[81]

Direct coal use can often be replaced with natural gas and with other low-carbon fuels. In China, the Guangzhou Heidelberg Yuexiu Cement Company retrofitted its production line to co-fire sewage sludge and reduced annual energy consumption by nearly 14,000 tce.[82] To use sewage sludge as an alternative fuel in the cement industry requires effective governance and enforcement of environmental regulations to ensure that co-firing sewage sludge delivers the expected energy benefits while also minimizing harmful environmental impacts.[83] In Cairo, Egypt, the El-Shorbagy textile factory created low-temperature heat (85°C) using a solar thermal collector to offset fossil-fired steam boilers.[84]

(2) Electrification

Decarbonization through electrification (coupled with a low-carbon grid) is also possible in many industries. The two primary mechanisms for saving energy and reducing CO_2 emissions with electric end-use technologies are: 1) upgrading existing electric technologies, processes, and energy systems and 2) expanding end-use applications of electricity in industry.

There is a huge potential for electrification in China's industrial sector. For example, in the steel industry, highly-energy-intensive steel production using blast furnaces and basic oxygen furnaces can be replaced by less-energy-intensive electric arc furnaces, if there is adequate availability of steel scrap. Many fossil-fuel-based process heating and drying systems in Chinese industries can also be replaced with commercially available electric heating and drying systems. For example in Belgium, ABB worked with Stora Enso's Langerbrugge paper mill to electrify processes. By focusing on electrification of drive systems, ventilation, and HVAC systems, the mill gained increased automation and productivity while decreasing energy use. As electrification increased, greater control over the papermaking process allowed additional investments and work in quality control.[85]

The timing of electrification is important. If China electrifies parts of the industrial sector too early, before the power sector has added significant additional low-carbon generation resources, CO_2 emissions will increase. Electrification of the industrial sector needs to be pursued in parallel and in coordination with low-carbon supply investments in the power sector to generate CO_2 emissions reductions.

Barriers

There are a number of barriers to decarbonization, including the high cost and lack of domestic low-carbon fuels and the fact that fossil-fuel prices do not reflect their full costs. Other barriers include the relatively high upfront capital costs associated with combined heat and power and the difficulty of selling electricity generated from distributed resources to the grid in China. Finally, carbon capture, utilization, and storage (CCUS), while not included in our analysis, requires significant research and development before it can be applied to the industrial sector.

Solutions

- Establish a nationwide CO_2 cap-and-trade program or carbon/fuel tax. This can stimulate a shift from coal to low-carbon fuels. Cap-and-trade programs in the EU and elsewhere are piloting the efficacy of this approach for CO_2, and in the case of the EU, generating significant insights such as the importance of appropriately allocating emission allowances.
- Develop comprehensive policies to promote CCHP and distributed generation in the industrial sector in China. For example, the Public Utilities Regulatory Policies Act (PURPA) in the U.S. has successfully promoted CCHP and other distributed generation by requiring utilities to buy power from such resources if they can provide power at costs lower than the utility's marginal cost of generating power.[86]
- Accelerate the infrastructure construction of oil and gas pipelines and ultra-high-voltage electricity transmission.

China has numerous successful strategies and policies to address industrial energy use and emissions in place today. These range from the Top 10,000 Energy Consuming Enterprises Program to a national Boiler Action Plan to promote high-efficiency boilers in industry. For a summary of Chinese industrial sector policies, see the Lawrence Berkeley National Laboratory China Energy Group Policy Tracker.[87]

To achieve the Reinventing Fire Scenario vision for Chinese industry, the strategies and policies discussed earlier in this chapter are needed to overcome the barriers to achieving the four key elements of the vision: structural change, production demand reduction, energy efficiency, and decarbonization.

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BUILDINGS

05

BUILDINGS

BUILDINGS USE MORE primary energy than any other sector globally and account for a third of energy-related global CO_2 emissions.[1] China's building energy consumption accounts for about 20% of total primary energy.[2] In 2010, the end-use energy consumption of China's buildings sector was about 770 Mtce of primary energy.[3] Although China's buildings sector consumes a large and growing amount of energy, the energy use per unit of floor space and energy use per capita are far less than in many developed countries.[4]

Dwarfed by the industrial sector's energy consumption, the share of China's building energy consumption is lower than the 40% typical of developed countries.[5] China's building energy use per capita in 2012 was only about 83% of the global average, and about 20% and 33% of the average levels in the U.S. and OECD countries, respectively.[6] Energy use per unit of floor space in 2005 for urban buildings was only about 40% of the level of that of the U.S. due to different usage patterns and uncomfortable Chinese indoor temperatures.[7]

5.1 DEVELOPMENT STATUS AND PROSPECTS FOR THE BUILDING SECTOR

5.1.1 BUILDINGS ARE A KEY SOURCE OF FUTURE ENERGY DEMAND GROWTH

Due to rapid economic growth over the last several decades, China is the world's largest market for new construction, adding 1.8–2.0 billion m^2 of floor space annually (Figure 5.1).[8] Among end uses, heating energy use in the northern China increased most rapidly, as heated areas of buildings increased 200% from 2000 to 2010.[9]

The composition of China's buildings is diverse and complex. Across its vast landmass, China's climatic zones encompass cold northern winters, hot and humid southern summers, and mixed seasons in transition areas. Across regions, the availability of natural resources, level of economic development, and standard of living varies widely. For example, China's urban residential buildings in the cold northern region have central heating that meets internationally accepted standards for thermal comfort, but the hundreds of millions of people in the Yangtze River Valley must rely on individual heating devices that may only provide marginal thermal comfort.

Buildings and HVAC systems in most of China historically have been manually operated. The operation in different buildings varies over time (hours, days, and seasons) and with differing fractions of total floor space conditioned. Manual operation—especially in buildings with low levels of comfort—causes many buildings to exhibit low energy consumption.[i] But this does not mean that a typical building meeting Chinese building codes and standards is efficient.[10] Envelope thermal integrity and infiltration are key problems in Chinese buildings and appliance and equipment efficiency lag behind international levels. Many buildings are not metered or properly controlled and few buildings are commissioned—resulting in higher energy consumption than designed.

As a developing country, China's urbanization rate will increase, driving growth in household incomes and leading to larger household size, increased use of energy-consuming appliances, and growth in residential energy consumption. Urban households consume more energy than rural households, particularly of non-biofuels. And as China's economic development shifts away from heavy industry towards a service-oriented economy, industrial sector growth is slowing while energy consumption in the buildings sector is increasing. This is driven by an increase in total commercial building floor area, as well as energy use intensity (kWh/m^2). Floor area per employee is expected to rise from 30 to 45 m^2 per person between 2010 and 2050—a level consistent with current international levels.[11]

5.1.2 AN UNSUSTAINABLE DEVELOPMENT MODEL

Low-quality construction, short lifetime, and extensive

[i] An exception is in Northern China, where centralized heating is provided continuously during the winter heating season.

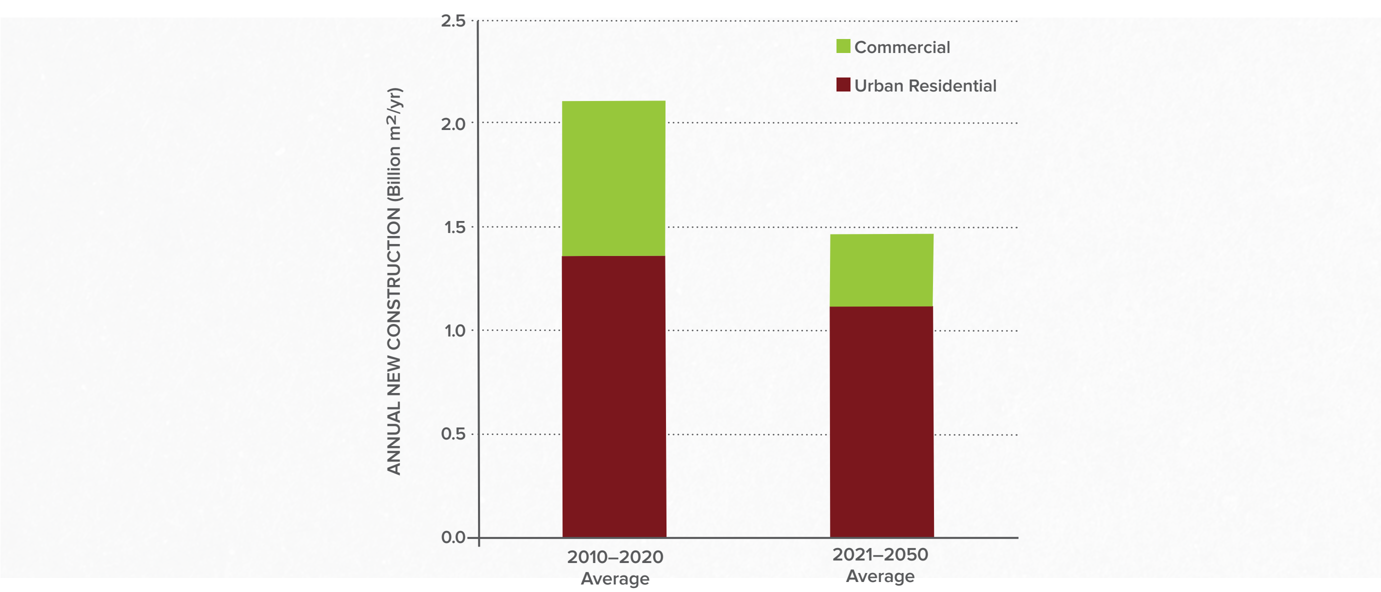
development are significant issues for China's buildings sector. Many local governments pursue high-yield urban construction and development of the real estate industry, leading to excessive demolition and rapid construction. The average lifetime of Chinese buildings in urban areas is 25–30 years[12] and in rural areas 15 years or less.[13] Energy-saving retrofits of existing buildings are mostly non-existent, as there is little point in retrofitting a building that will be demolished before the investment has shown profit. This results in a large amount of unoccupied buildings and waste due to stock turnover. Building construction is a resource-intensive, high-energy-consumption process that also requires building materials with significant embedded energy such as cement, steel, aluminum, and glass. Steel and cement consumption for buildings in China in 2011 was 398 million ton (Mt) and 1,706 Mt respectively, representing about 12% of the year's national energy use.[14]

Increasing energy consumption from buildings is also a key factor contributing to pressure on the ecological environment. The air pollutants emitted by heating—both by large centralized plants as well as low-efficiency, decentralized individual small coal boilers—are a major contributor to poor air quality. In 2010, total building-related $PM_{2.5}$ emissions were 1.55 Mt, with 62% as direct $PM_{2.5}$ emissions from heating and 38% as indirect $PM_{2.5}$ emissions from building electricity use.[15] Coal combustion emits pollutants such as particulates and SO_2. Since medium-size coal-fired boilers in China do not have emission control measures,[16] per unit of heat supplied, coal boilers generate as much as four times the particulate matter, 100 times the SO_2, and 2.5 times the NO_x emissions as natural gas boilers.[17] Many local governments meet urbanization goals by expanding alongside existing cities; this causes extensive urban sprawl and low utilization efficiency of land.

5.1.3 RAPID URBANIZATION'S EFFECT ON BUILDING SECTOR ENERGY USE

Driven by national population growth, urbanization, and unprecedented economic development, China's building sector is growing rapidly. The urban population will increase from 50% of total population in 2010 to 68% in 2030, adding 280 million people to cities.[18] In 2010, China constructed over 2 billion m² of new buildings. This annual rate of construction is expected to continue through 2020, averaging 2.1 billion m² yearly over the 10-year timeframe. New urban residential buildings will average 1.4 billion m² per year of this total, as China's urban population increases (Figure 5.1).

FIGURE 5.1: BUILDINGS SECTOR ANNUAL NEW CONSTRUCTION
2010–2050



By actively exploring new types of urbanization pathways, promoting integrative and efficient urban-rural development, and guiding the transition of residential lifestyle, China can reinvent the development of the buildings sector. Such an approach can help ease the growth of building energy consumption and ensure continued improvement of building floor space and building service level. Incorporating efficiency into the design of new buildings is most cost effective. Not considering efficiency as part of China's rapid urbanization will have lasting implications for decades. Constructing the most energ-efficient buildings now will serve to compound energy savings in the future.

5.1.4 DESIGN AND TECHNOLOGICAL INNOVATION

Internationally, from low-energy buildings to passive houses, zero-energy buildings, and net-positive-energy buildings, energy-saving technologies are improving quickly. International and domestic case studies indicate that through the integration and optimization of technologies and application of commercialized and new emerging technologies, building energy consumption can be significantly reduced with little, if any, increase in construction costs.[19]

Energy-efficient building technologies are constantly brought to market. Current best-in-class technologies include smart windows, high-performance insulation, solar PV roofs, phase-change insulating materials, LED lights, ground- and air-source heat pumps, and high-efficiency appliances. These super-efficient components provide a strong technological base for achieving the Reinventing Fire vision for the buildings sector.

5.2 VISION AND GOALS OF REINVENTING FIRE FOR THE BUILDINGS SECTOR

In the Reinventing Fire Scenario, China's buildings are resilient and use the maximum technically-feasible, cost-effective, energy-efficient technologies and renewable energy supplies. The best technologies and design approaches available today are widely deployed in China by 2050, producing higher quality buildings with improved comfort, health, and productivity for occupants. Pursuing this vision can achieve four key goals for the building sector.

1. **Provide thermal comfort**
   Among China's urban residential buildings, only regions with district heating in China's northern cold climates meet internationally recognized indoor thermal comfort criteria. In the future, the shift over time to meet international comfort standards could cause a two-fold and three-fold increase in urban residential heating loads and cooling loads, respectively.[ii] In the Reinventing Fire Scenario, with improved designs that incorporate passive strategies, thermal comfort is achieved with no load increase.

2. **Incorporate urban planning, integrative design, and quality construction**
   By 2050, Chinese per capita income increases to roughly $29,900, equivalent to the current lower levels in Europe and Japan.[20] The floor space per capita increases to reach the current lower level of developed countries. These factors, along with improved thermal comfort, increase building energy use in the Reference Scenario. In the Reinventing Fire Scenario, controlling building energy demand through planning, design, and construction reduces growth in energy use. This includes incorporating a high-performance envelope, optimizing energy-using systems, manufacturing prefabricated buildings, and performing energy-saving retrofits on existing buildings. The total building floor area is the same in both scenarios. However, the Reinventing Fire Scenario requires less new construction as building lifetimes increase due to improved construction quality.

[ii] *Average load increases are urban residential load assumptions in Reinventing Fire: China building sector model; actual value depends on climate zone and building type.*

3. **Employ smart management of super-efficient equipment**
   By 2050 in the Reinventing Fire Scenario, 100% of Chinese households and commercial buildings will use today's super-efficient appliances and equipment. The Reinventing Fire Scenario employs smart building systems using sensor controls and analytics to increase access to performance data and improve building intelligence. Using smart systems improves overall building energy efficiency, lowering operating costs and increasing reliability.

4. **Utilize clean energy sources and infrastructure**
   To peak carbon early and improve air quality, the Reinventing Fire Scenario promotes clean energy sources and infrastructure, including replacing distributed coal systems for heating with growing shares of electric heat pumps and renewable energy sources, such as biomass and solar thermal. It also includes the complete phase out of coal-based cooking, accelerating the decline of LPG cookers, and increasing the use of electric and natural gas cookers (as well as biomass in rural areas). In addition, the Reinventing Fire Scenario includes the installation of on-site solar photovoltaic systems on buildings, which support a distributed electric grid, making buildings not only energy consumers but also energy producers.

While the immense size and rapid growth of China's buildings sector is a challenge, it also presents opportunities for new business initiatives to drive innovation and to realize social benefits such as job creation, pollution reduction, and increased living standards. The biggest opportunities lie in designing and constructing new buildings properly as well as retrofitting the most inefficient existing buildings.

5.3 RESULTS OF REINVENTING FIRE IN THE BUILDINGS SECTOR

5.3.1 BUILDING ENERGY CONSUMPTION AND CO_2 EMISSIONS DECREASE

If all opportunities are successfully captured, the primary energy savings potential of the Reinventing Fire Scenario exceeds 50% of the 2050 consumption of the Reference Scenario (Figure 5.2). By 2050 under the Reinventing Fire Scenario, annual residential and commercial primary energy consumption are reduced to 620 Mtce and 380 Mtce, respectively, a 30% increase from the 2010 base year level. For both sectors, the energy savings result in additional benefits in terms of improved thermal comfort and air quality.

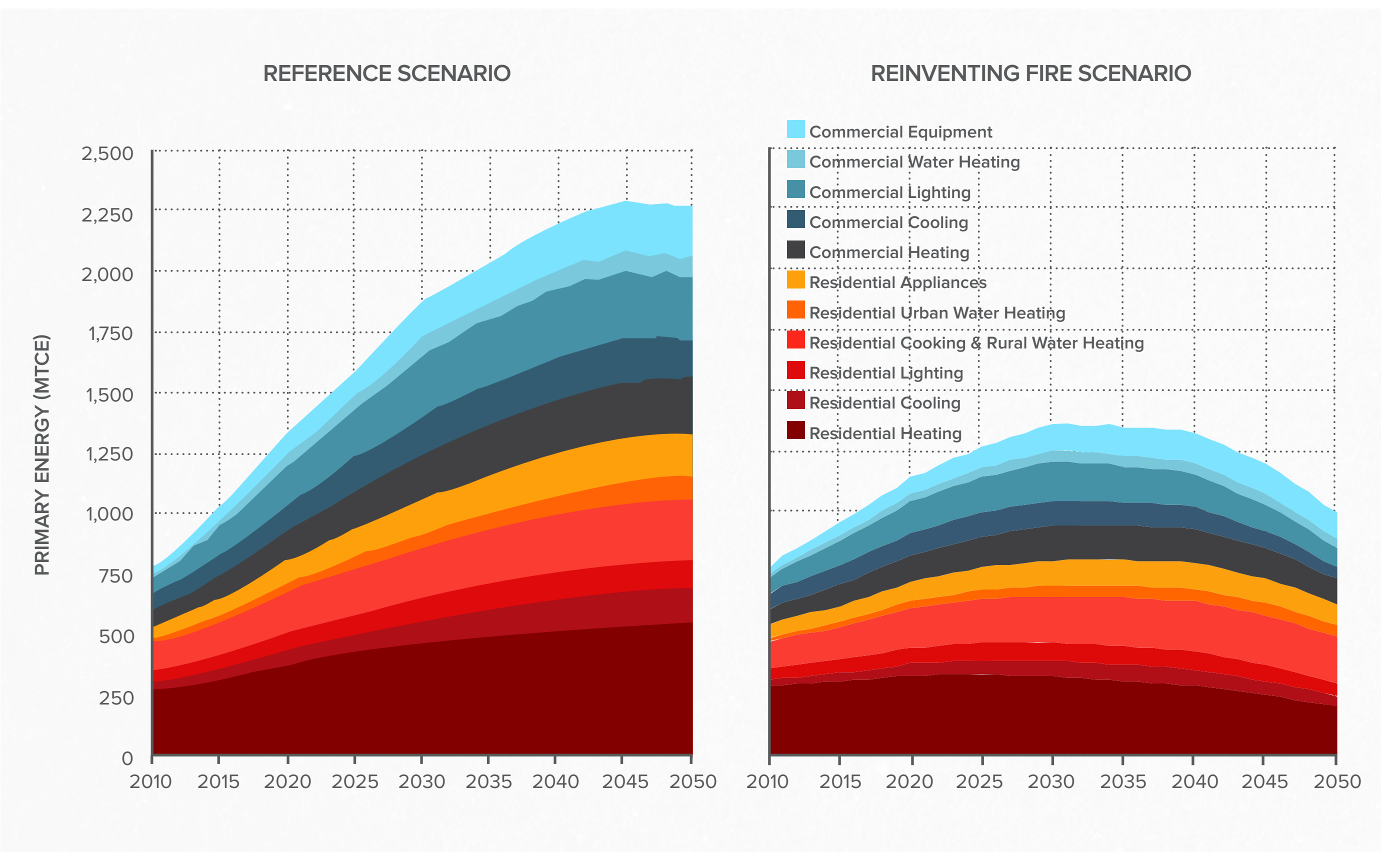
5.3.2 THERMAL COMFORT AND ENERGY EFFICIENCY IMPROVE

Efficiency improvements for residential appliances and commercial equipment (plug loads) reduce total electricity demand by 500 TWh final energy annually in 2050 compared with the Reference Scenario—equivalent to the annual output of five Three Gorges Dams.

Space heating and cooling represent the largest energy uses in residential and commercial buildings in the Reference Scenario (Figure 5.2). Growth in floor area and increased thermal comfort in residential buildings increase heating and cooling primary energy use two- and six-fold, respectively, under the Reference Scenario from 2010 to 2050. The same

FIGURE 5.2: BUILDINGS SECTOR PRIMARY ENERGY DEMAND BY SUBSECTOR AND END USE

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS



improved comfort for heating and cooling is achieved under the Reinventing Fire Scenario with lower energy consumption through improvements in design and construction. Over the same time period, this results in decreased annual residential heating energy consumption and only a two-fold increase in annual residential cooling energy consumption.

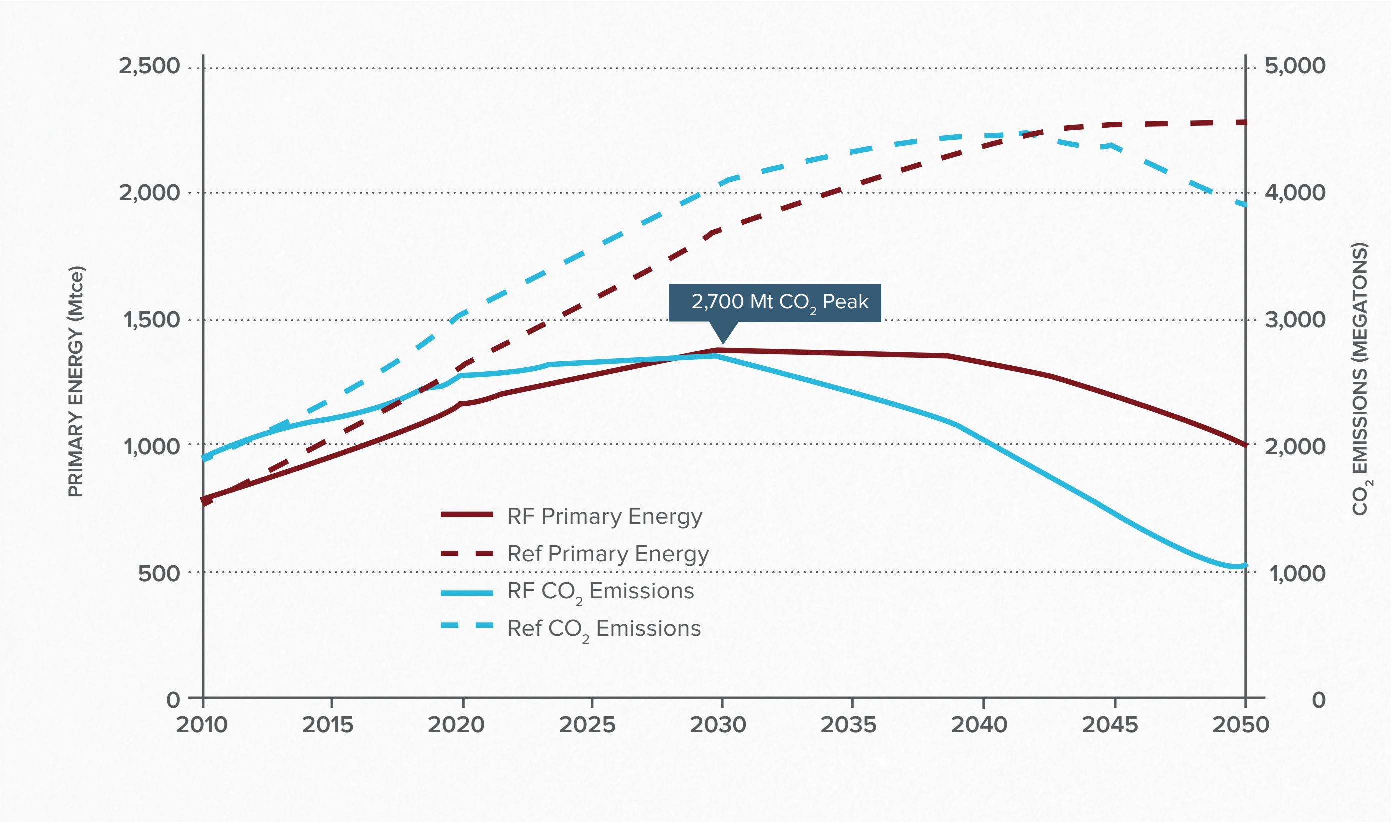
In commercial buildings, increases in the amount of floor area cooled result in a 150% increase in primary energy use for cooling in the Reference Scenario. The Reinventing Fire Scenario is able to achieve increased comfort with slightly lower primary energy use for cooling due to the faster penetration of efficient air conditioners and the prevalence of load-reducing strategies. This results in a savings of 110 Mtce in 2050 compared to the Reference Scenario.

5.3.3 BUILDINGS SECTOR ENERGY SOURCES ARE CLEAN AND LOW-CARBON

In the Reinventing Fire Scenario, both CO_2 emissions and primary energy peak early. Emissions increase slowly from 2010, peaking by 2029 at a level of 2.7 billion tons. CO_2 emissions decrease thereafter. In 2050, CO_2 emissions drop by 46% compared to 2010 emissions (Figure 5.3). Primary energy use peaks at 1,370 Mtce just after 2030, at a level 78% higher than the 770 Mtce 2010 level. Energy consumption in the buildings sector decreases slowly after that.

FIGURE 5.3: BUILDINGS SECTOR PRIMARY ENERGY AND CO_2 EMISSIONS TRENDS

2010–2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



Increased electrification in both urban and rural areas in the Reference Scenario results in growth in the percentage of electricity in final energy use, from 22% in 2010 to 50% in 2050 (Figure 5.4). In the Reinventing Fire Scenario, the share is even larger (66%), but the quantity of final energy associated with the electricity is much lower due to high end-use efficiency. Lower pollutant emissions are attributed to increases in renewable electricity in the power sector.

In the Reinventing Fire Scenario, switching from dirty coal to cleaner, more-modern energy technologies results in an almost complete phase-out of direct coal consumption in the buildings sector. Increased adoption of renewable technologies such as air-source heat pumps, geothermal (ground-source) heat pumps, and solar water heaters reduces fossil-fuel use, including 250 Mtce of coal and 140 Mtce of natural gas annually by 2050. Rural cooking sees the elimination of coal stoves and a major reduction in LPG cookers, which are replaced primarily by electric cookers.

5.4.4 THE REINVENTING FIRE SCENARIO FOR THE BUILDING SECTOR IS COST EFFECTIVE

Under the Reinventing Fire Scenario, China's buildings sector has an energy-savings potential of 13.0 trillion RMB (2010 price, 5% discount rate). Between 2010 and 2050, China requires an investment of 9.5 trillion RMB to improve design, use more-efficient equipment, retrofit

FIGURE 5.4: BUILDINGS SECTOR FINAL ENERGY FUEL MIX

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

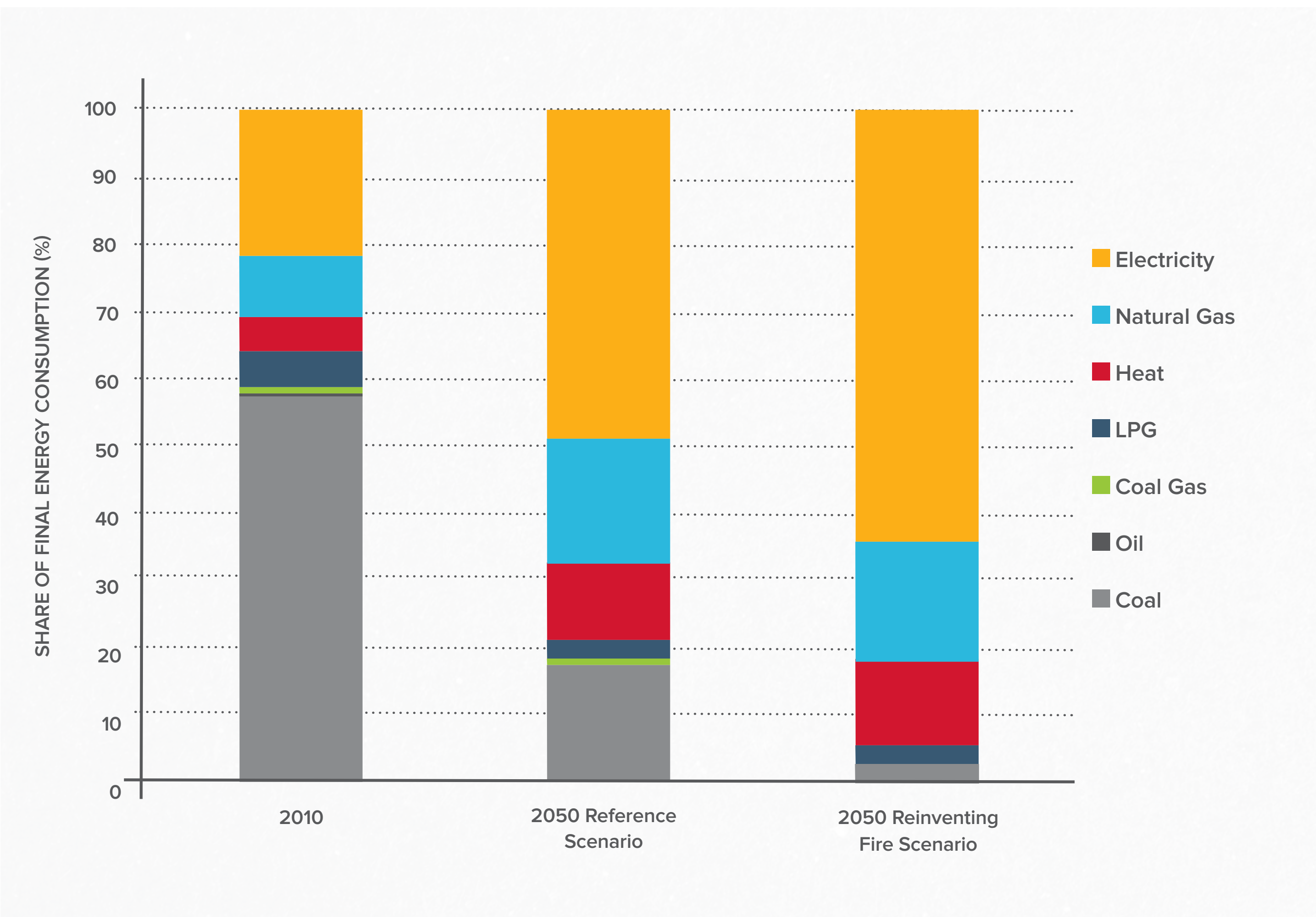
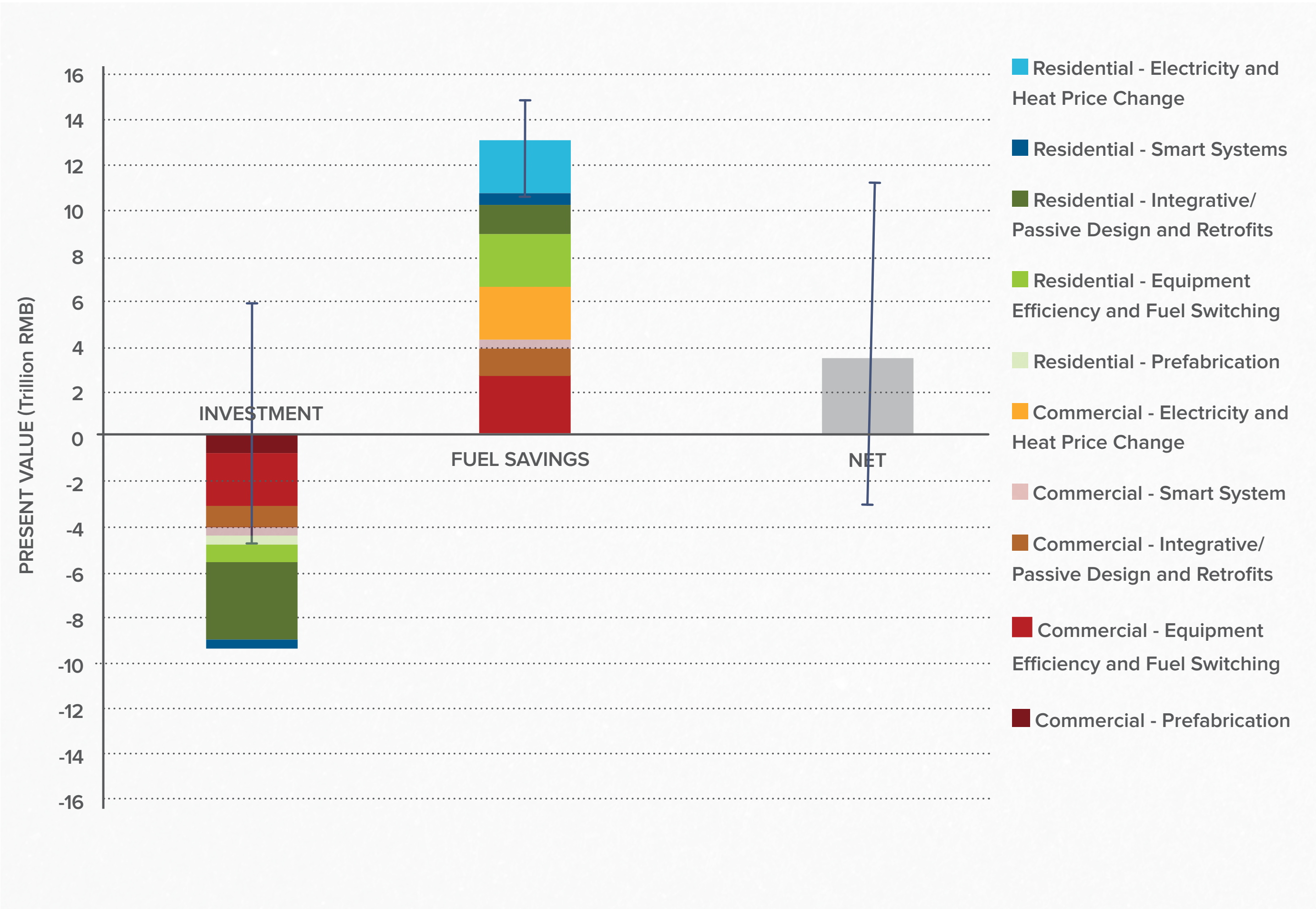


FIGURE 5.5: BUILDINGS SECTOR REINVENTING FIRE SCENARIO NET PRESENT VALUE

2010–2050



existing buildings, implement smart control systems, and realize other such measures. As a result, the Reinventing Fire Scenario yields 3.5 trillion RMB in net benefits in the building sector (Figure 5.5). Large energy-saving (or load-saving) strategies are found in integrative and passive design, reducing loads for heating, cooling, and electric lighting. But these strategies also need the largest capital investments for better envelope assemblies and higher-quality construction. The second biggest investment goes toward improving equipment efficiency, which produces the largest energy cost savings. (Additional detail on methodology is contained in Appendix C.)

5.4 PATHS FOR REINVENTING FIRE FOR CHINA'S BUILDINGS SECTOR

There are five pathways that together achieve the Reinventing Fire vision and goals:

- Advanced construction practices,
- Integrative design, passive strategies, and retrofits,
- Super-efficient equipment,
- Smart systems, and
- Clean energy sources.

Under the Reference Scenario, 2050 primary energy use increases 195% to 2,270 Mtce (Figure 5.6). In the Reinventing Fire Scenario, the annual primary energy use increases 30% to 1,000 Mtce by 2050 compared to the actual 2010 value of 770 Mtce. The total Reinventing Fire primary energy savings for the buildings sector is 1,270 Mtce. The largest savings result from integrative and passive design (410 Mtce) and super-efficient equipment and appliances (370 Mtce). Retrofit buildings (150 Mtce), smart systems (130 Mtce), and building prefabrication (120 Mtce) (including savings from less material waste) also contribute. Switching to clean energy sources for on-site equipment (90 Mtce) and power generation (70 Mtce) also account for a portion of the primary energy savings.

The impact on annual CO_2 emissions is even more pronounced than that for primary energy (Figure 5.7). In the Reinventing Fire Scenario, annual CO_2 emissions related to energy use in buildings is 1,010 $MtCO_2$ by 2050, or 46% lower than the 2010 CO_2 emissions of 1,880 $MtCO_2$. The projected emissions for the Reinventing Fire Scenario are 2,890 $MtCO_2$ lower (74%) than the Reference Scenario, which totals 3,900 $MtCO_2$. Reducing building loads, fuel switching for building end uses, and a heavily decarbonized power sector all contribute to emissions reductions. The largest savings come from integrative/passive design (690 $MtCO_2$), super-efficient equipment/appliances (670 $MtCO_2$), and clean energy sources for on-site equipment (600 $MtCO_2$). The rest of the savings come from clean energy sources for power generation (320 $MtCO_2$), building retrofits (270 $MtCO_2$), and smart systems (250 $MtCO_2$). Prefabrication accounts for 230 $MtCO_2$, when less construction material waste is included. As with primary energy savings, integrative/passive design and super-efficient equipment/appliances are the largest CO_2 emissions-reduction opportunities, with 47% of the overall reduction potential. Clean energy sources for on-site equipment and power generation also contribute substantially, accounting for 32% of the annual emissions savings.

FIGURE 5.6: BUILDINGS SECTOR PRIMARY ENERGY SAVINGS AND PATHWAYS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

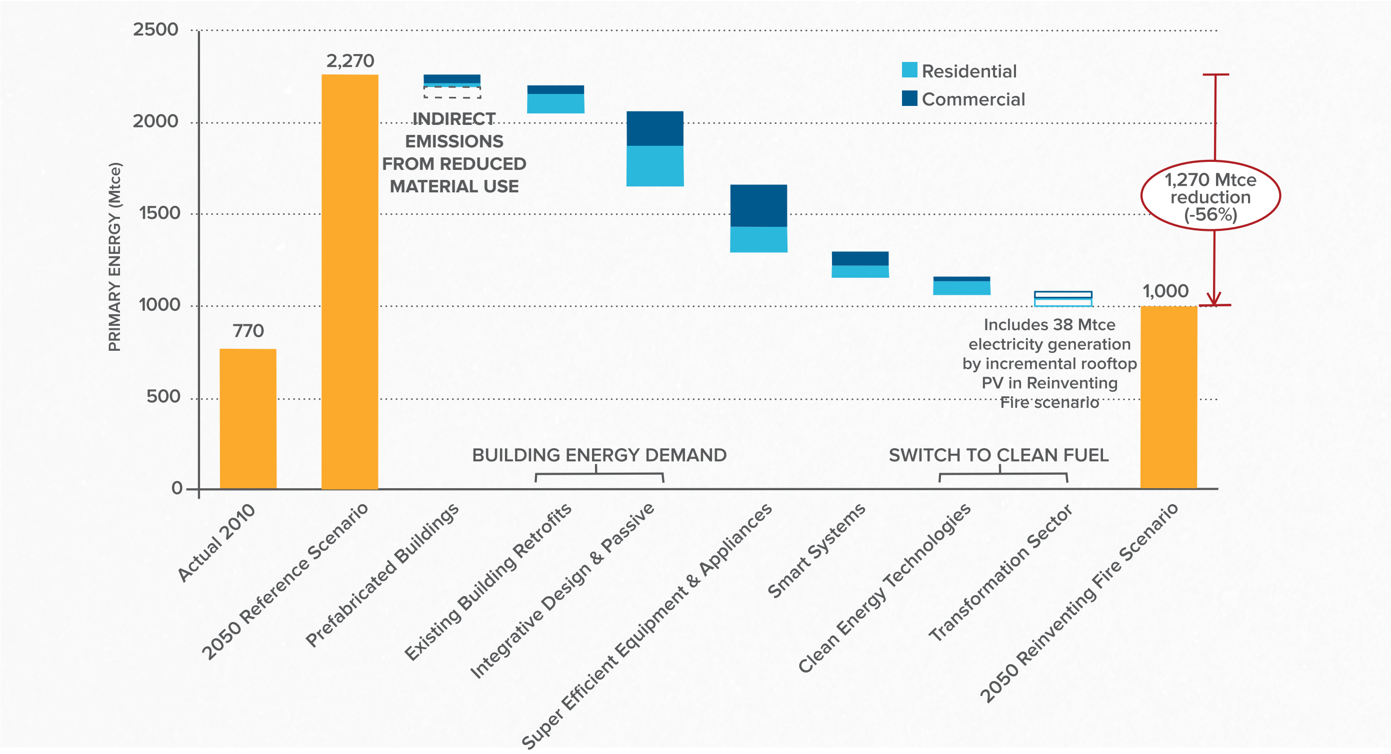
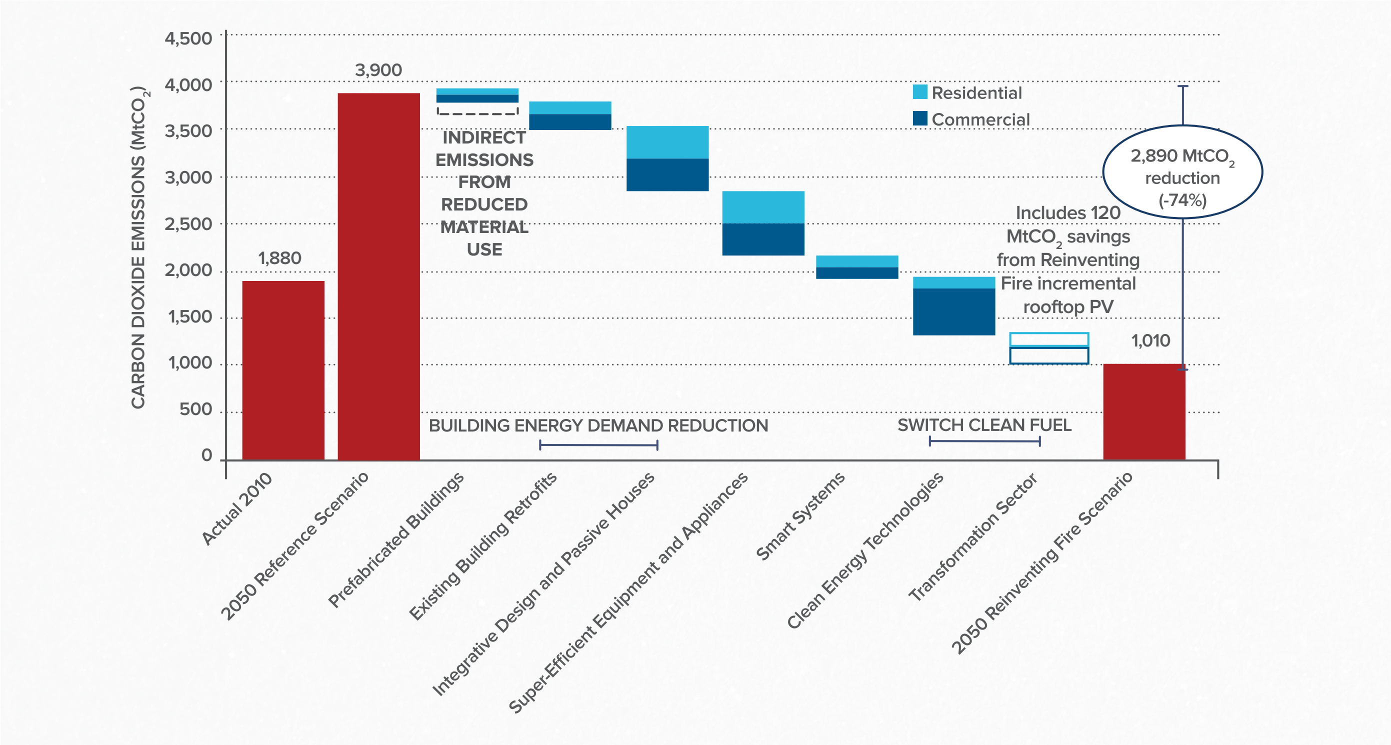


FIGURE 5.7: BUILDINGS SECTOR CO_2 EMISSIONS REDUCTIONS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



5.4.1 PATHWAY #1: ADVANCED CONSTRUCTION PRACTICES

Control floor-area growth and promote prefabricated buildings and components

From 2010 to 2050 for both the Reference and Reinventing Fire Scenarios, total urban residential floor space is expected to grow from 18 billion m^2 to 49 billion m^2 while total commercial floor space is expected to grow from 12 billion m^2 to 23 billion m^2 (Figure 5.8). By 2027, the floor area of urban buildings built after 2010 will exceed the floor area of all urban buildings existing in 2010.

By 2050, urban-rural residential building floor space per capita is assumed to average 46 m^2 and public building floor space per employee in the service industry will not exceed 50 m^2, corresponding to the 2010 average level of per-capita residential floor space and a lower level of per-employee public building floor space on average for developed countries.[21]

Building lifetimes for both scenarios are the same for existing pre-2000 buildings (30 years) and 2000–2009 buildings (40 years). Yet due to better materials and construction methods in the Reinventing Fire Scenario, the lifetime for new buildings is longer. The typical building lifespan increases from 40 to 70 years from 2010 to 2050. This results in 13% less new building floor area in 2050 for the Reinventing Fire Scenario compared to the Reference Scenario (Figure 5.9).

Due to the anticipated rapid substantial growth in building floor area, it is critical to avoid excessive construction, increase building lifespan, and achieve energy-efficient new buildings and communities. Opportunities associated with new construction comprise nearly three-quarters of all Reinventing Fire Scenario 2050 primary energy savings for buildings (Figure 5.10).

FIGURE 5.8: CHINA'S BUILDING STOCK COMPOSITION

2010–2050

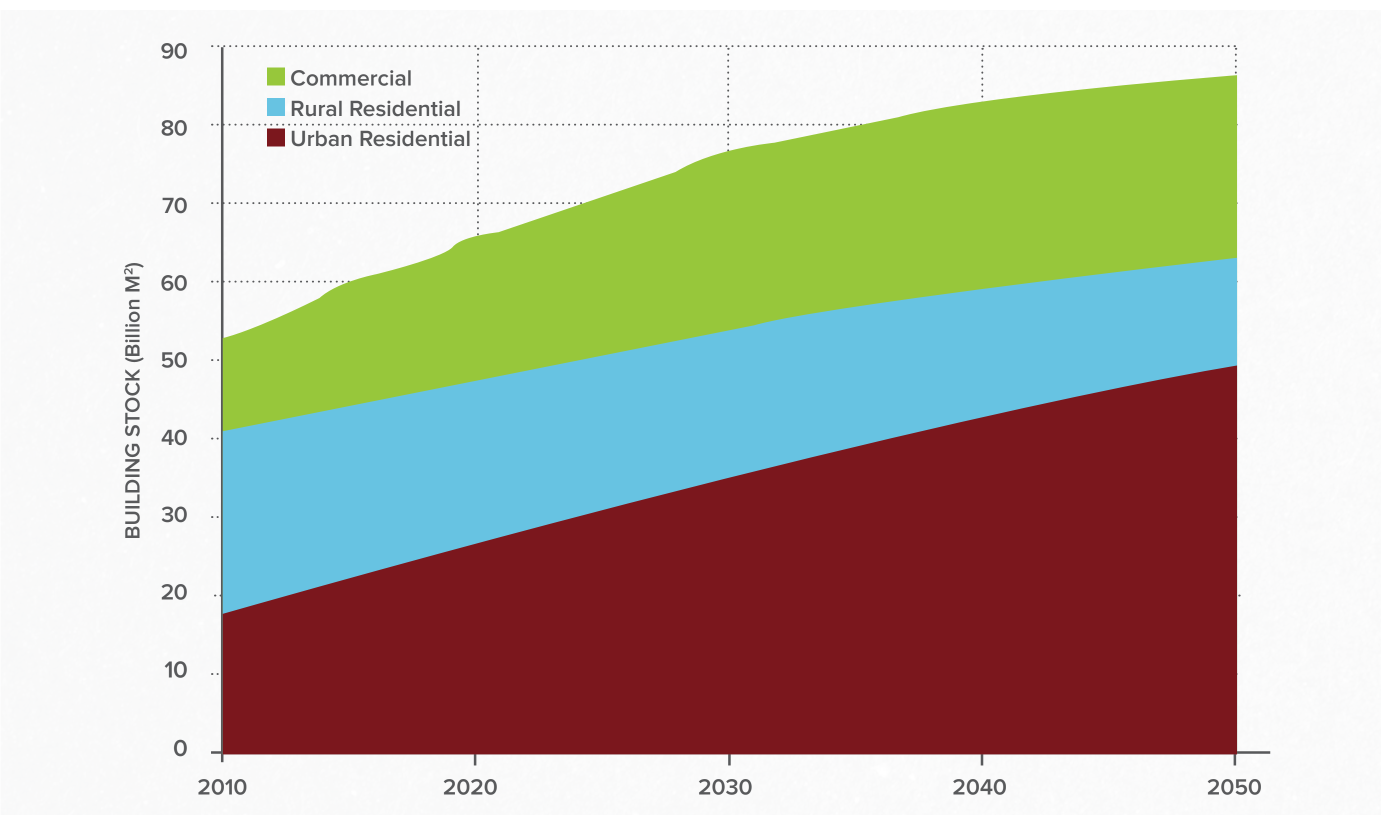


FIGURE 5.9: BUILDINGS SECTOR NEW CONSTRUCTION TRENDS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

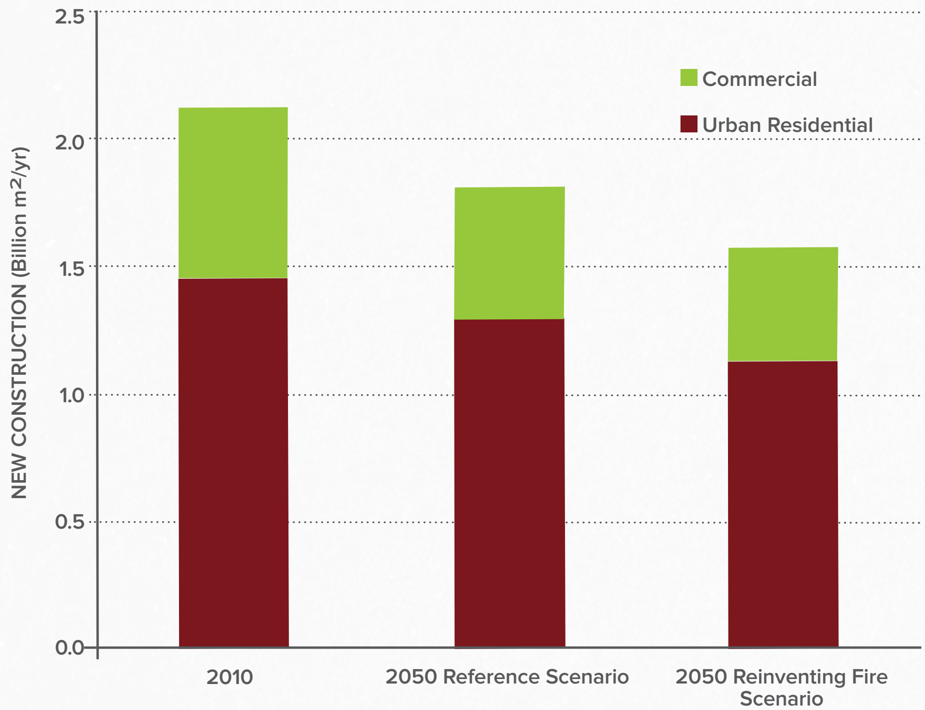
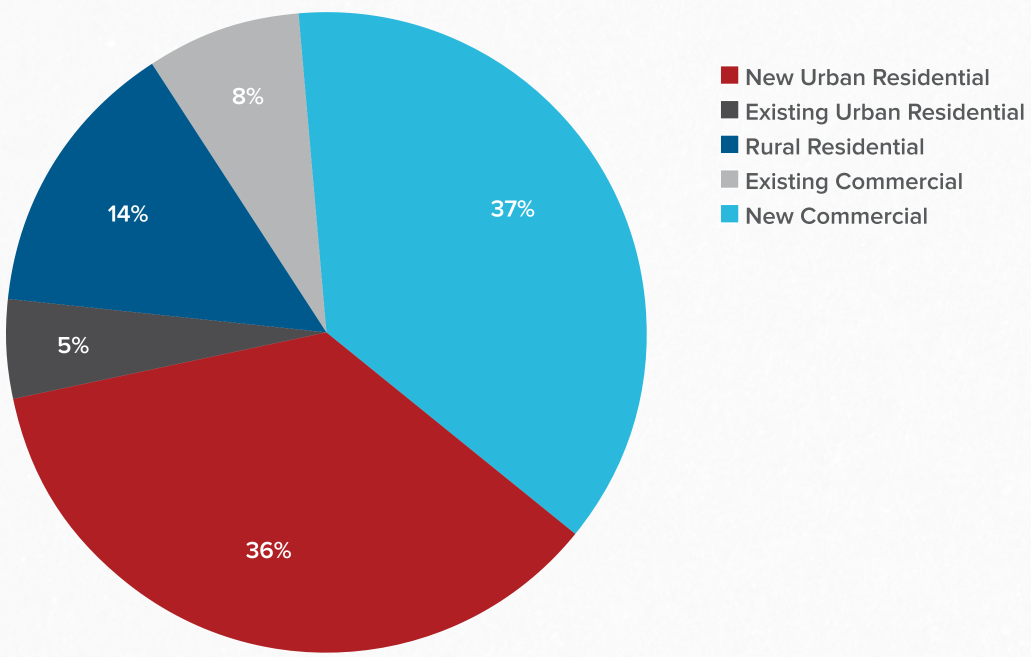


FIGURE 5.10: BUILDINGS SECTOR PRIMARY ENERGY SAVINGS BY BUILDING TYPE AND VINTAGE

2050, REINVENTING FIRE SCENARIO



(1) Control floor space growth

The Chinese building stock is characterized "by rapid new construction and demolition of older buildings, and large scale urban expansion."[22] This results in overbuilding and unoccupied floor space. According to the Survey and Research Center for China Household Finance, more than one in five urban homes are vacant.[23]

China's rapid urbanization is occurring under conditions of a large population, relative shortage of some resources, hazardous air quality, loss of ecosystems, and imbalanced urban-rural development. To minimize negative impacts, both the Reference and Reinventing Fire Scenarios rely on greatly improved processes for controlling total building floor area. This includes urban planning to promote compact, walkable developments with access to mass transit. Compact layouts will improve building space utilization, moderate floor space growth, and decrease overall building envelope area and its associated energy losses. Less urban sprawl will support the efficient distribution of electricity, water, and central heating. It will also contribute to the development of more-efficient, networked transit options, dispersed traffic, and transportation energy savings, which will support the implementation of other Reinventing Fire sector strategies.

(2) Improve construction quality

In China, buildings far from the end of their useful lives are often demolished to make room for new buildings.[24] This is particularly relevant since Chinese buildings have high material intensity levels as measured in volume of construction material (e.g., steel, glass, and cement) per square meter of constructed area.[25] China demolished 345–460 million m^2 of buildings each year during the 11th Five-Year Plan that had not reached end-of-life, compared to 1.5–2.0 billion m^2 of annual new construction floor space in that period.[26] Lack of structural integrity and poor construction quality contribute to the relatively short building lifespans and high demolition rates, but there are also financial growth incentives that motivate demolition.

Moving forward, new buildings can be constructed for durability and adaptability through prefabrication—following an industrialized process for producing construction components and systems. This dramatically reduces material waste and on-site construction time and improves quality and durability, increasing building lifespan. In addition, higher quality assurance ensures greater building thermal integrity and better energy performance. There is much to be gained by accelerating the manufacturing of prefabricated buildings in China. For example in 2013, China saw

CASE STUDY 5.1: PREFABRICATION AT T30 HOTEL IN XIANGYIN, CHINA

In Xiangyin, China, prefabrication enabled the fast construction of a 30-story, 330-room hotel that featured a structural steel frame and curtain wall system. With 93% of the building made in a factory, the on-site installation took only 15 days—just a fraction of the normally required time. Low-emission manufacturing and efficient products (such as quad-pane glass and efficient air conditioning units) make the building particularly energy efficient and low carbon. The building also had lower steel and concrete requirements: the construction used 10–20% less steel and 80–90% less concrete compared to a similar building produced by conventional construction practices, yet it was constructed to withstand a 9.0 Richter-scale earthquake. There was no on-site fire, water, dust, welding, concrete, or polishing required during construction. The construction waste was less than 1% of a conventional building. The construction cost, about $1,000 per square meter, was almost 30% less than a comparable building in China.[27]

construction waste reach 1 billion tons, 26% of it from construction and 74% from demolition.[28] But only 5% of construction waste is recycled—about 30 million tons annually.[29] Cases of prefabrication in China and elsewhere have increased lifetimes by 10–15 years,[30] reduced construction material loss by 60%, and decreased overall building waste by 80%.[31]

Barriers

While the strategies presented above represent significant opportunities for energy savings and CO_2 emissions reductions in China's building sector, there are similarly significant barriers for implementing those strategies. There are two main barriers to using building materials more efficiently and reducing materials demand. The first is the practice by cities of demolishing existing buildings before the end of their useful lives for economic stimulus. The second is rapidly constructing buildings with low-quality materials that leads to premature structural and other issues relative to international standards.

Solutions

- Establish a comprehensive national government-led system for urban planning to avoid urban sprawl. Incorporate sustainable urban form principles into urban planning regulations.
- Develop an evaluation framework that can be used in different planning stages.
- Emphasize plan monitoring and evaluation, particularly for the five-year short-term plans that support the longer-term Master Plan.[32]
- Introduce and implement property taxes to reduce the unoccupied building rate and discourage excessive demand for housing purchases.
- For urban residential buildings, promote the development of smaller-size residences and more-efficient affordable housing units.
- Improve building quality and the indoor living environment.
- Establish and improve the standardization of prefabricated building design, construction, and components production.
- Reform the existing construction management system to make it applicable to the pre-cast technology.
- In the early stages of industrialization, the government can provide financing, adopt tax incentives, and strengthen support to industry.

5.4.2 PATHWAY #2: INTEGRATIVE DESIGN, PASSIVE STRATEGIES, AND RETROFITS

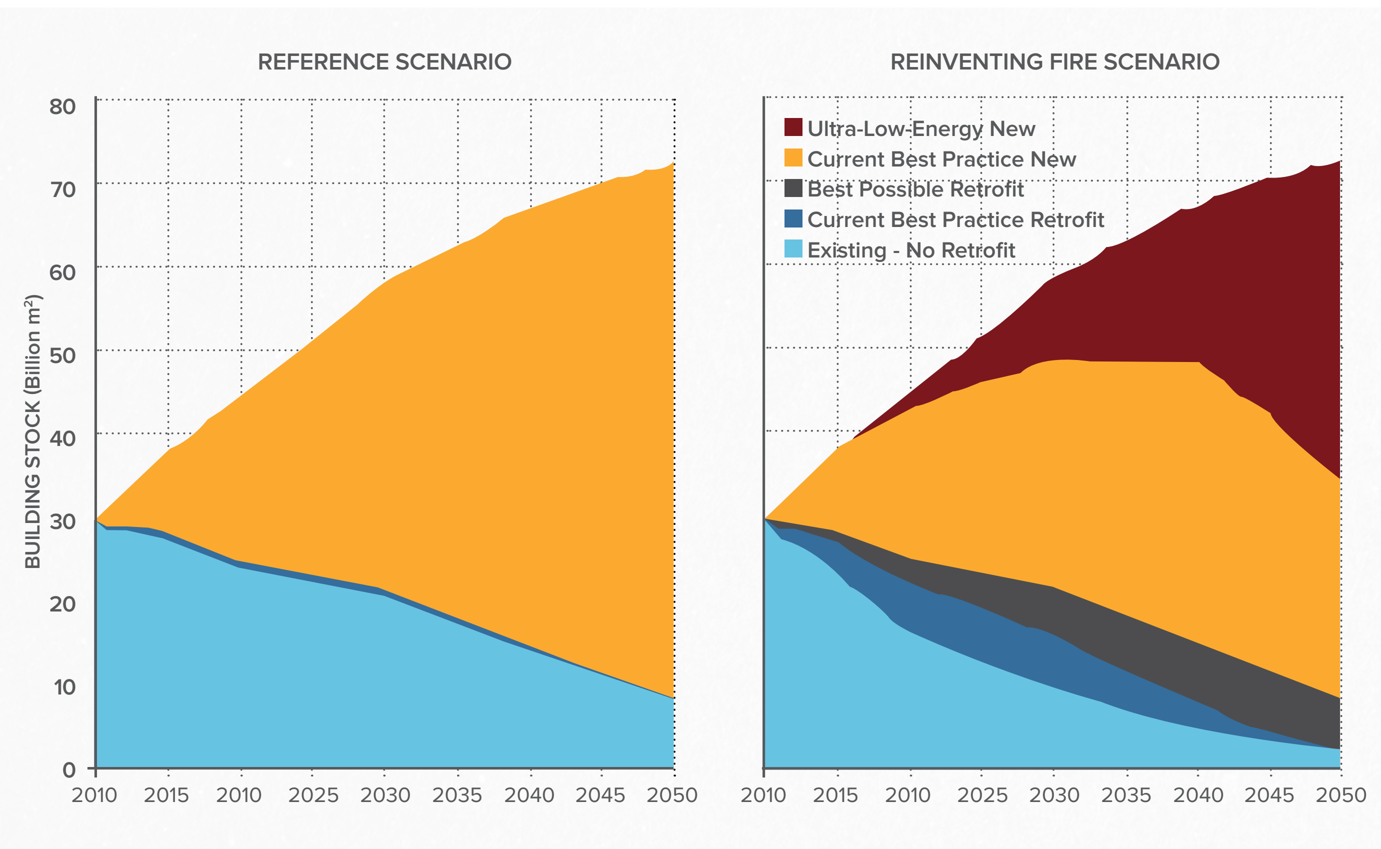
Construct new low-energy buildings and improve the energy-use performance of existing buildings

The largest savings potential—accounting for 33% of the total annual primary energy saved in 2050—resides in the increased adoption of integrative design and passive strategies for new and existing commercial and residential buildings. If light retrofits of existing buildings is added, these categories combine to account for 44% of the total economic savings opportunity.

In the Reference Scenario, improved thermal comfort in residential buildings greatly increases heating and cooling loads relative to 2010 use in some climate zones and building types. Predominantly through applying integrative design concepts and incorporating passive strategies, the Reinventing Fire Scenario maintains heating loads close to 2010 levels. Correspondingly, cooling loads are also controlled—typically increasing about 30% compared to 2010 levels (varies by climate zone and building type). Under the Reinventing Fire Scenario in 2050 for urban residential and commercial buildings, ultra-low-energy new buildings constitute 60% of floor area of buildings built post-2010 (Figure 5.11). By 2050, 75% of existing, pre-2010 building floor area will have undergone a deep retrofit (Best Possible Retrofit, Figure 5.11), representing 9% of the total building floor area. In contrast, in the Reference Scenario only 3% of existing buildings undergo light retrofits by 2050 (Figure 5.11).

FIGURE 5.11: BUILDINGS SECTOR STOCK BY BUILDING TYPE AND VINTAGE

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS



Passively designed buildings and those following an integrative design process that 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.

To realize the Reinventing Fire vision, China will need to promote the widespread practice of integrative and passive design concepts in new construction projects and deep energy-saving retrofits in existing buildings.

(1) Integrative design process

Integrative design is an approach to optimize individual technologies and components at the whole-building level. It enables cost trade-offs among multiple energy-using building systems (e.g., envelope, appliances, lighting, ventilation, cooling, and heating) to reach a high level of energy performance and other project goals at zero or little added cost.[33] It is a design process that emphasizes cross-disciplinary design team collaboration, often including the owner, builder, designers, and other project stakeholders, to achieve design goals.[34] The process involves evaluating all measurable benefits and costs while repeatedly checking solutions against project goals. This requires that the team defines the minimum end-use requirements, incorporates passive strategies to reduce loads, selects energy-efficient equipment, integrates and properly sizes components, optimizes controls, and installs renewable energy systems, while achieving all important non-energy goals of the building.

(2) Passive design approach

Passive design is an approach that meets project goals with as little reliance on mechanical systems as possible. Ancient buildings in China were passively designed and utilized strategies such as daylighting, shading, thermal mass, and natural ventilation, which continue to

CASE STUDY 5.2: SHENZHEN INSTITUTE OF BUILDING RESEARCH[35]

The Shenzhen Institute of Building Research (IBR) applied integrative design concepts to systematically utilize energy efficiency in its office building in South China. Located in the Futian district of Shenzhen and built in 2009, the building has 14 floors and over 18,000 m^2 of total floor space. The IBR building incorporates over 40 sustainable technologies and strategies. Passive strategies are incorporated throughout the building, including natural ventilation, daylighting, and green patio work areas. Many of the functional spaces are half-outdoors, achieving high occupant satisfaction while significantly reducing the conditioned and electrically lit floor space. The IBR Building received Three-Star Green Building recognition in 2011 and the first place award on green building innovation from the Ministry of Housing and Urban-Rural Development (MOHURD).[iii] Construction and installation costs were 4,300 RMB/m^2, much lower than the average of 6,000–8,000 RMB/m^2 for an office building in the same area. The measured total building energy consumption in 2011 was 63 kWh/m^2, or about 60% of the mean value for similar buildings in the region.

[iii] *The Chinese government developed the Three-Star Green Building Rating System in 2008. A one-, two-, or three-star rating can be earned for two rating categories, which account for either design (simulated) or operation (measured) of the building.*

work today. Effective passive design is "bioclimatic"—that is, sensitive to the local climate and occupants. Effective passive designs in cold climates are not always appropriate for warm climates. For example, cold climate passive strategies include highly-insulated walls, high-performance windows, and seasonal solar heat gain controlled through properly-sized overhangs. Hot and humid climate passive strategies include maximizing airflow with natural ventilation and minimizing heat gain using building shading.

(3) Mainstream Implementation of Energy-Saving Retrofits

As building lifespan increases and new construction rates decline, increasing the frequency and depth of energy-saving retrofits will be of considerable importance. Energy retrofits ensure that a building maintains efficient operation and improved energy performance over its lifespan. Energy retrofits can 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. Instead of demolishing and rebuilding with new materials, maintaining a high level of building energy performance maximizes the value of existing building systems, construction materials, and the associated embodied energy.

CASE STUDY 5.3: QINHUANGDAO PASSIVE BUILDING DEMONSTRATION PROJECT[36,37]

Based in the Haigang district of Qinhuangdao, this project has a total construction area of 80,344 m^2 and includes four high-rise residential buildings. Among the buildings, C15 received a two-star green building rating and is certified under the China-Germany passive house standard. C15 has 18 floors and a total floor space of 6,467 m^2. The building design includes a highly-insulated envelope and high-performance windows that maximize natural daylighting while limiting summer heat gain. The building meets strict passive house requirements for minimizing thermal bridges and air leakage. Space conditioning is provided by a variable-refrigerant-flow air-source heat pump. The central air-ventilation system includes 75% efficient energy recovery. Solar thermal systems offset the energy needs for water heating. Solar photovoltaic systems generate electricity for lighting and winter heating, and also power streetlights. Residential units tested during operation demonstrated an energy use intensity of 89–105 annual kWh/m^2 of primary energy. The building heating demand was 25% of that of other residential buildings in the area. The overall construction costs amounted to a 12% premium compared to the cost of constructing a conventional building. However, the inclusion of passive strategies resulted in smaller systems and minimized service areas; this led to more saleable floor space that more than offset the incremental cost. In addition, indoor $PM_{2.5}$ level were 10 times lower than neighboring buildings during periods of heavy haze.

Barriers

There is both a lack of stringent codes that raise the threshold for new building design and quality and a lack of awareness among key decision makers. Additionally, there is a general lack of available capacity in the market place to deliver these solutions.[38,39] Designers, builders, and operators do not always have the proper training to implement the design approaches, ensure construction quality, and operate the building as intended. Some necessary technologies (e.g., windows, air sealing) are not available in China.

Another barrier is China's current use of prescriptive codes rather than codes based on whole-building energy use. Unlike a whole-building energy use code, individual components prescribed by code can lead to energy performance below intended whole-building energy use targets. Additionally, each province is currently able to adapt prescriptive building codes to its own unique situation, which creates vast variations that increase the work load for China's slim enforcement teams. A whole-building energy use code is simpler to enforce. Outcome-based codes ensure energy efficiency is achieved by requiring report compliance verification based on 12 consecutive months of qualifying energy data. This approach provides the foundation for energy-use disclosure (discussed later). Codes need to be well enforced to capture anticipated energy savings. While China's code compliance rate increased from 2% at construction stage in 2005 to above 80% in 2010, inspections are usually limited to larger cities.[40] It is key to expand efforts to smaller cities and towns using a third-party inspector, a compliance checking system, and standardized tools.

Other barriers include China's lack of comprehensive compliance information and data, specialized knowledge among implementation officials, and a weak infrastructure for compliance monitoring.[41] But, voluntary green building and labeling programs are starting to influence market demand, along with the demand for building efficiency experts. Continuing advances in government-led and market-driven solutions will benefit from education and awareness programs designed to either promote the concept of building energy efficiency or strengthen the workforce understanding of its application. Developing additional institutional and technical capacity will support the creation of more stringent and up-to-date codes, along with their enforcement and monitoring.

Solutions

- Establish building energy consumption indices and benchmarks; implement the outcome-based energy consumption quota/codes for different types of buildings, especially the standard for ultra-low-energy buildings.
- Establish codes, standards, and construction regulations for passive houses.
- Focus codes on whole-building energy use and establish a framework for routine improvement.
- Establish regular code updates to signal the need to act early to design institutes, developers, property mangers, and technology vendors.
- Set targets and roadmaps for longer-term building codes (2030 and 2050) and update periodically with timelines. Possibly stipulate updates every five years in law and regulations.
- Strengthen supervision of implementation of energy savings. Expand inspections to midsize and small cities.
- Better define building energy consumption baselines and incentivize measuring, monitoring, and benchmarking.
- Establish information/statistical systems for building energy consumption data (e.g., similar to the U.S. Environmental Protection Agency's Portfolio Manager system).
- Increase brand strength of more-efficient building labels (e.g., Three-Star Label for Green Buildings) by ensuring precision in the design, construction, and operation of buildings as specified by those

labels (e.g., consider requiring certifications by a third party) and promote their business case.

- Continue and expand national efforts laid out in the 12th Five-Year Plan to set mandatory retrofit targets in residential buildings and public institutions.
- Develop awareness and incentivize implementation to demonstrate the value of retrofits and build confidence among banks and other potential lenders.
- Introduce innovative financing models for building efficiency projects.
- Offer government incentives (financing or tax policies) to offset the cost of energy-saving retrofits and attract more energy service companies (ESCOs) to the market.
- Provide workforce training to reduce both the cost and risk of energy-efficient building improvements and in turn improve the cost effectiveness of market-based solutions.
- Promote the concept of smart and low-energy buildings. Further educate legislators, real estate developers, designers, and energy-efficiency examiners of the improvement potential of building efficiency.
- Provide guidebooks for smart and low-energy buildings and develop comprehensive evaluation tools for building efficiency. Provide efficiency improvement pathways to real estate developers and designers and encourage quick action.
- Implement more trainings for builders and operators of smart, ultra-low-energy buildings.
- Strengthen R&D of relevant technology for smart and ultra-low-energy buildings, including system design methods, construction, and quality control.
- Offer industrial support for scaling up smart, ultra-low-energy buildings.

5.4.3 PATHWAY #3: SUPER-EFFICIENT EQUIPMENT AND APPLIANCES

Create performance disclosure programs and improve equipment and appliance labeling programs

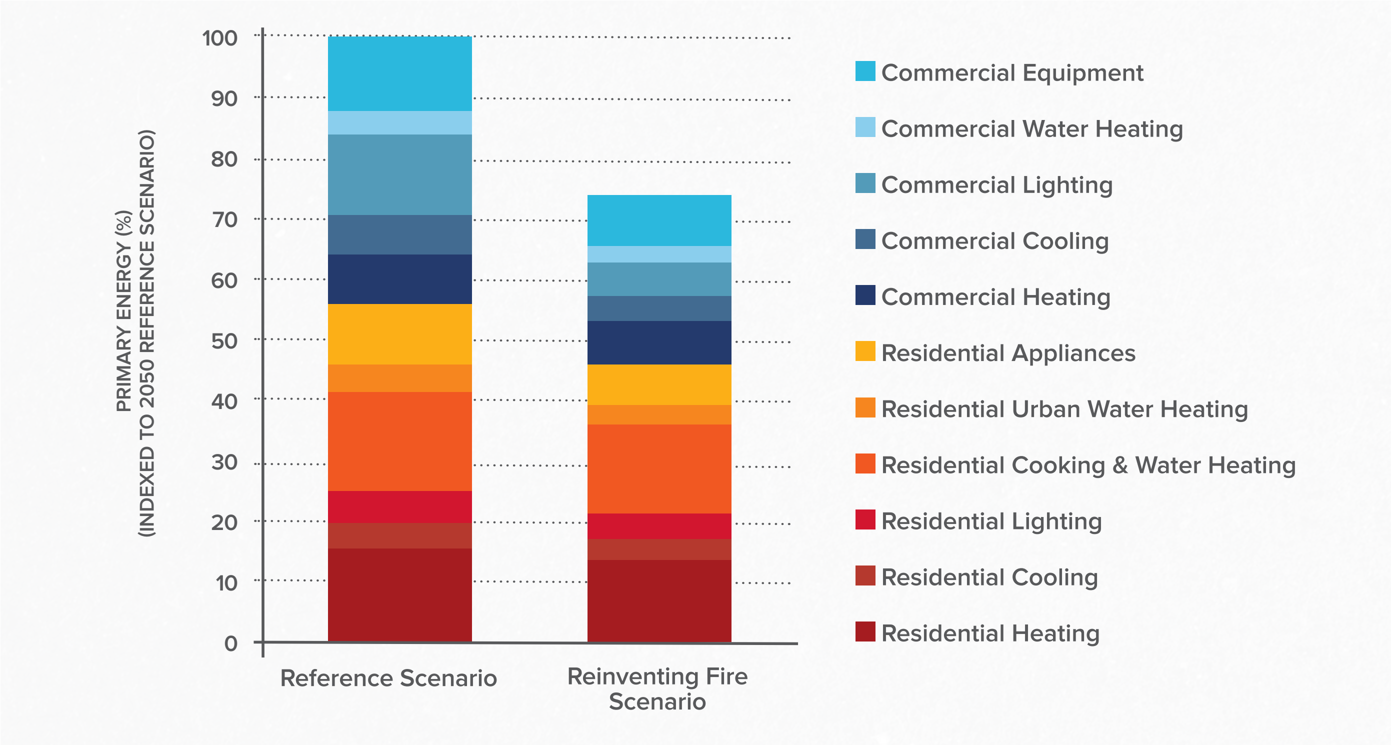
The second largest savings potential—accounting for 29% of the total annual primary energy saved in 2050—is attributed to the installation of super-efficient equipment and appliances in new and existing buildings. The Reinventing Fire Scenario incorporates aggressive adoption of today's global best-in-class technologies, achieving 100% market penetration by 2050. Comparatively, the Reference Scenario in 2050 achieves penetration of only 29–40%, depending on the type of equipment.

(1) Adopt super-efficient products

Improvements in efficiency occur for the various equipment types serving different building energy end uses. In the 2050 Reference Scenario, the largest uses of buildings-related primary energy (Figure 5.12) are residential heating (24% of building sector energy) and residential cooking and water heating (15%). Other residential end uses include appliances (8%), cooling (6%), and lighting (5%). The largest commercial uses are lighting (11% of building sector energy), heating (11%), and equipment (9%), followed by cooling (7%) and water heating (4%) These energy uses can be met more efficiently using today's best equipment, with large improvements available in technologies such as heat pumps, lighting, plug loads, and room air conditioners. In the Reinventing Fire Scenario, 100% adoption of super-efficient technologies yields the largest magnitude of primary energy savings in commercial lighting, followed by residential appliances, commercial equipment, commercial cooling, and residential heating and cooking (Figure 5.12).

FIGURE 5.12: BUILDINGS SECTOR PRIMARY ENERGY BY SUBSECTOR AND END USE

2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



(2) Select the most-appropriate fuel source and equipment type for the application

Heating energy consumption for buildings in northern China is the largest component of China's buildings sector energy consumption. In the Reinventing Fire Scenario, centralized coal-fired district heating in northern China becomes more efficient, including growth of cogeneration and industrial waste heat. For buildings not connected to a distributed heating system, the share of air-source heat pumps will increase. For new ultra-low-energy buildings with low heating loads, air-source heat pumps, electric heating, and other decentralized systems will be utilized (Figure 5.13).

In both the Reinventing Fire and Reference Scenarios for urban residential buildings in the transition climate, such as in the Yangtze River area, decentralized heating systems dominate. District heating plants are less common outside North China as they are less cost effective in shorter heating seasons and there are limited local resources for coal and natural gas. In the Reinventing Fire Scenario, a large majority of urban residential buildings in the Yangtze River area are heated and cooled using air-source heat pumps—replacing the direct electric heating equipment and air conditioners used in the Reference Scenario (Figure 5.14). Transition zone residential buildings have historically had lower indoor temperatures and levels of thermal comfort compared to those in North China. For both Scenarios, significant improvements in comfort occur as economic and social development improves living standards. Increased use of heating in the transition areas will cause incremental growth in China's building energy consumption.

FIGURE 5.13: NORTHERN CLIMATE RESIDENTIAL SPACE HEATING MIX BY FUEL AND TECHNOLOGY

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

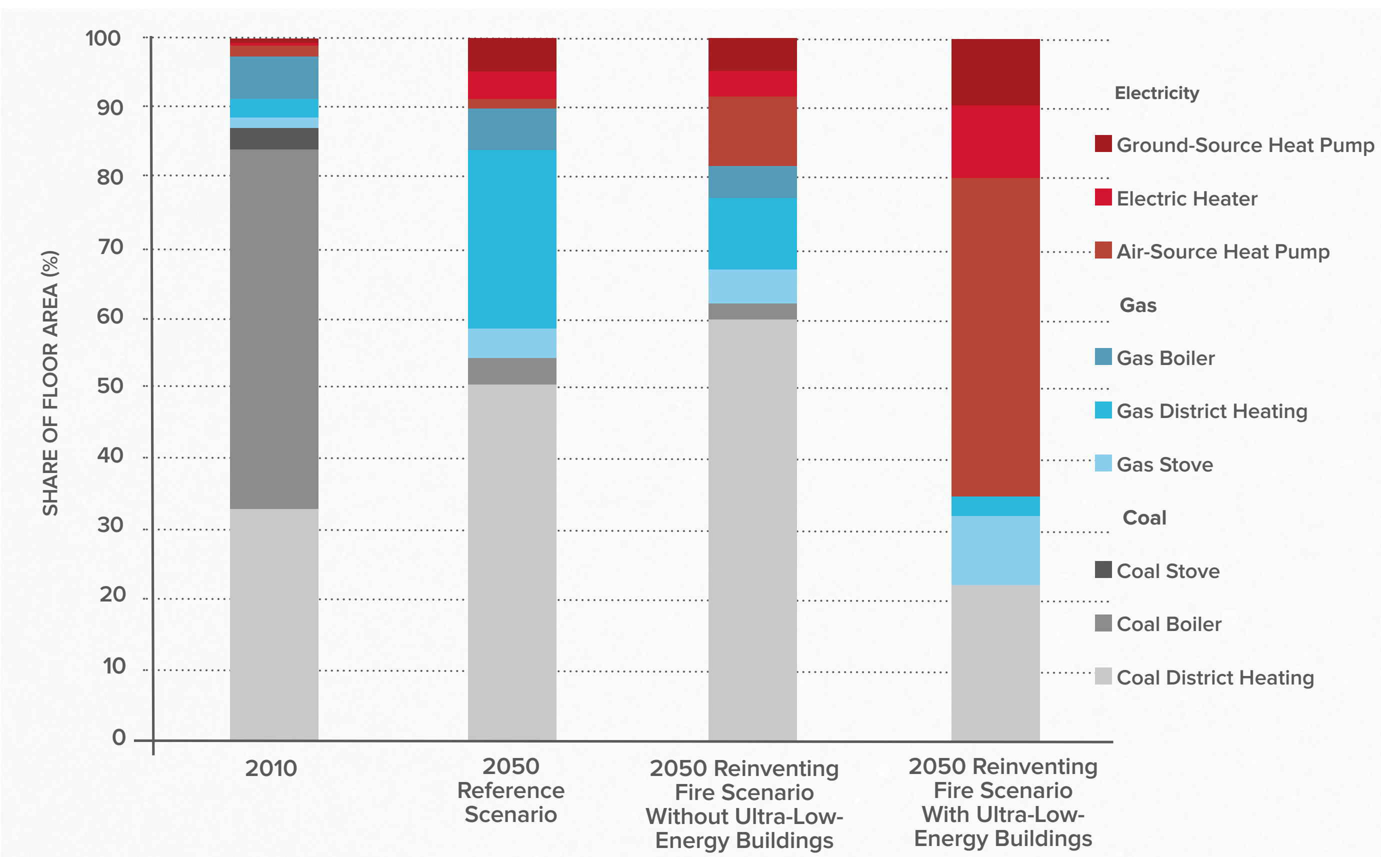
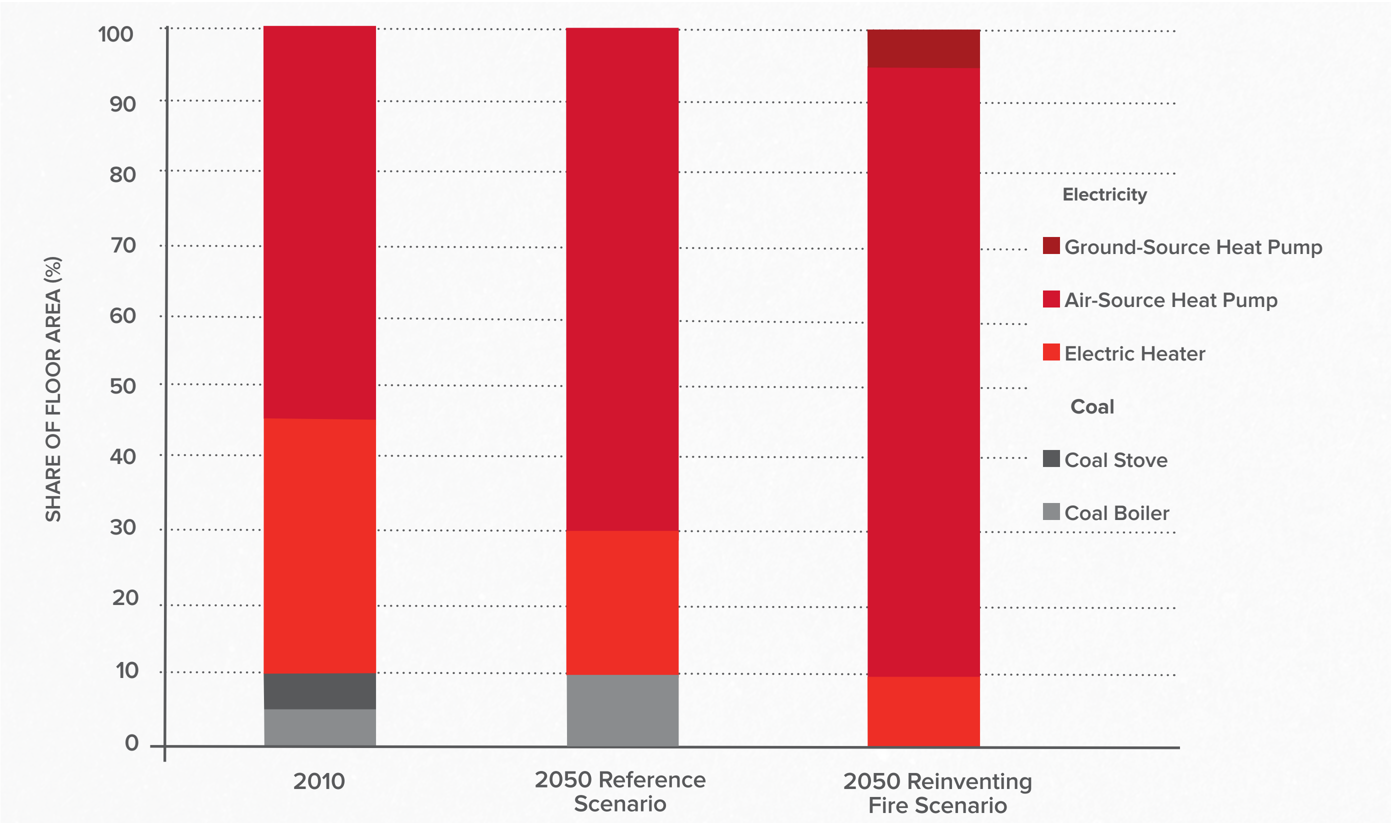


FIGURE 5.14: TRANSITION CLIMATE RESIDENTIAL SPACE HEATING MIX BY FUEL AND TECHNOLOGY

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



Barriers

China's appliance efficiency standards program have a strong legal basis but relevant laws and regulations are outdated and do not reflect rapid changes in China's standards and labeling programs. Both the appliance standards and labeling programs also operate under very limited financial and human resources, which constrains the standards and labeling development process. Furthermore, local enforcement agencies lack funding and capacity to conduct sufficient enforcement testing, resulting in uneven compliance rates.

China's current appliance energy labeling has increased the market share of energy-efficient appliances, but there's still more market share to capture before levels are commensurate with the U.S., EU, and Japan. One barrier is the lack of information for consumers and building owners to select the most-efficient appliances or products, even when there is product label. Also, high upfront costs and split incentives often inhibit purchases of more efficient products.

Recently, ENERGY STAR introduced a "Most Efficient" designation to further identify the most-efficient models out of all ENERGY STAR-qualifying models, thereby further promoting innovative manufacturers and helping early adopters identify and purchase super-efficient products.

Solutions

- Improve the stringency of efficiency standards and regularly update for home appliances and building equipment to achieve best standard internationally.

- Invest resources to increase public awareness of efficient appliances/equipment and consumer utilization of information tools (e.g., mandatory China Energy Label identifying efficient appliances) and encourage the public to purchase with financing support from the government.
- Offer funding to initially offset the higher cost of more-efficient appliances for consumers who are capital constrained.
- Separate the current labeling programs from the standards so that it can be updated more frequently to reflect market changes and technological advances.
- Support the development of initiatives to identify the most-efficient product within the labeled products.
- Establish designated budgets for standards enforcement and market surveillance at national and local levels.
- Conduct consistent national enforcement check-testing, possibly with targeted sampling.
- Provide more training and capacity building at local levels.
- Fund R&D of high-performance building materials and super-efficient equipment.
- Establish regulations to make information available and data transparent.

5.4.4 PATHWAY #4: SMART SYSTEMS

Promote whole-building energy consumption transparency and reward the reduction of electricity consumption during peak periods

Incorporating smart systems into building operation accounts for 10% of the total 2050 primary energy savings under the Reinventing Fire Scenario. 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. For commercial buildings, it includes optimizing all systems across the building to dynamically reduce electric demand and respond to real-time price signals. For residential buildings it includes smart meters and customer systems like in-home displays, programmable communicating thermostats, and web portals.

Utilizing smart systems can also help to provide whole-building energy metering data allowing owners, tenants, and their brokers to understand a building's relative energy performance, informing the sale or lease of a building and eventually affecting the valuation process. It 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.

Employing smart systems helps achieve other sector visions for Reinventing Fire as well. For example, by modulating electricity consumption and generation, a building can become a grid generation or storage asset and provide services such as reserve capacity, load following, or ancillary services. These services can be appropriately compensated (see the Electric Power chapter Section 7.4.3).

Barriers

Similar to the barriers facing efficient appliances, high upfront costs and split incentives can inhibit the implementation of smart systems. Smart building systems are new in China and there is a general lack of availability in the marketplace. However, when smart building systems make buildings a grid asset they can create value streams and improve the return on investment. In addition, lack of data on building energy consumption is a key barrier in Chinese buildings. Publishing whole-building energy metering data allows owners, tenants, and their brokers to understand their buildings' relative energy performance, informing the sale or lease of a building and eventually affecting the valuation process. It also enables retrofit service providers and others interested in reducing energy use to target the buildings with greatest opportunity for efficiency improvement. Finally, gathering and publishing statistically valid building performance data enables the tracking of national building energy use intensity and efficiency improvement from policies.

Solutions

- Better define building energy consumption baselines and incentivize measuring, monitoring, and benchmarking.
- Establish information/statistical systems for building energy consumption data (e.g., similar to the U.S. Environmental Protection Agency's Portfolio Manager system).
- Establish legislation to make information available and data transparent. Informed owners, tenants, and agencies make better decisions, which in turn offers opportunities for energy-saving service providers to improve building efficiency.
- Create a market that rewards the reduction of electricity consumption during peak periods by:
  - Decouple electricity sales from generation and profit of utilities and power companies. Fully

CASE STUDY 5.4: INTELLIGENT, NET-ZERO-CARBON COMMUNITY CENTER IN QIBU DISTRICT, TIANJIN[42]

In China's cold northern region, the Tianjin Architecture Design Institute designed the Indoor Sports Center in the Qibu District, Tianjin. Completed in 2014, the building combines a low-energy-use design with renewable energy systems to achieve net-zero-energy consumption and zero carbon emissions. The building uses solar PV, microgrids, and a smart energy management system. The building incorporates passive strategies taking into account solar orientation and predominant wind direction. The building shape, insulation level, window-to-wall ratio, and window type were designed to maximize natural lighting, natural ventilation, and reduce building energy load. The installation includes high-efficiency appliances and lighting systems, as well as a ground-source heat pump for heating and cooling. Renewable energy systems provide domestic hot water and electricity. A smart energy management system optimizes the building operation and overall energy performance. Based on building energy performance simulation results, the estimated energy intensity of the building is 68.5 annual kWh/m^2 and the annual energy balance is -17 MWh (798 MWh consumed and 815 MWh produced), resulting in a net savings of 316 tons of CO_2 emissions per year.

enforce environmental dispatch to prioritize energy efficiency as the first fuel.

- Implement real-time electricity pricing that reflects the environmental costs of fuels.

- Raise the demand charge in tariff rate structures to encourage the reduction of peak loads and lower capacity. This can help create a market for demand response that encompasses smart meters, distributed energy, and smart controls.

5.4.5 PATHWAY #5: CLEAN ENERGY SOURCES

Electrify buildings and apply on-site renewable energy

The Reinventing Fire vision for buildings realizes carbon savings by switching to cleaner energy sources. This includes 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). Under the Reinventing Fire Scenario, switching to clean fuels on site and through clean power production accounts for 7% and 6% of potential 2050 primary energy savings, respectively. The 2050 carbon emission savings attributed to clean fuels are more substantial, totaling 21% and 11% of the total reduction.

Switching to clean on-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 more-efficient 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.

As part of the Reinventing Fire Scenario, coal water heating is eliminated, and solar hot water heating increases for residential and commercial buildings (Figure 5.15). In commercial buildings, natural gas water heating declines while cogeneration water heating increases. In rural areas, the use of coal cookstoves is eliminated and the use of liquefied petroleum gas (LPS) cookstoves is greatly reduced. Instead, electric stoves become prominent, along with an increased use of biomass and biogas cookstoves (Figure 5.16).

Additional savings in primary energy use result from the power sector using cleaner sources to generate electricity and providing district heating to buildings. On-site roof-mounted PV systems offset primary energy use by 40 Mtce and CO_2 emissions by 120 $MtCO_2$. This represents 3% and 4% of total Reinventing Fire Scenario primary energy and CO_2 emission savings, respectively.

FIGURE 5.15: COMMERCIAL WATER HEATING MIX BY FUEL AND TECHNOLOGY

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

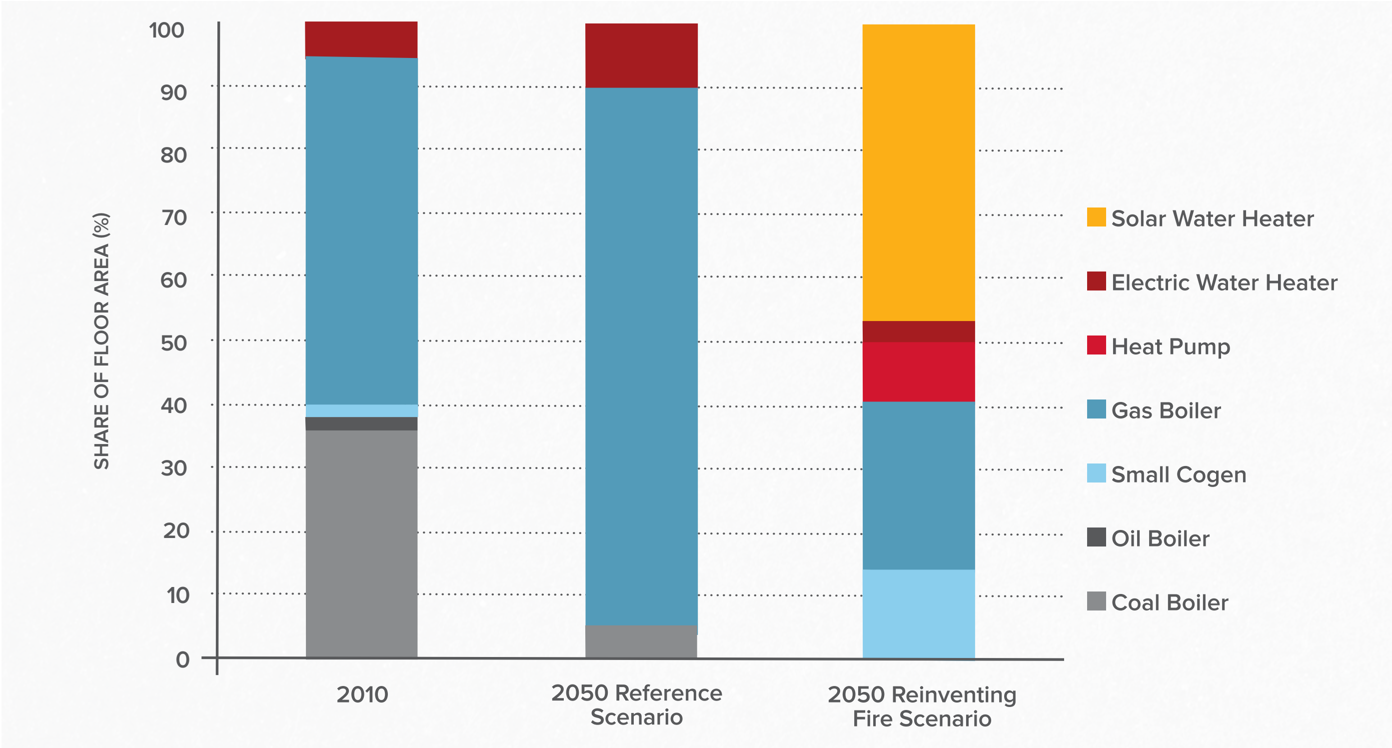
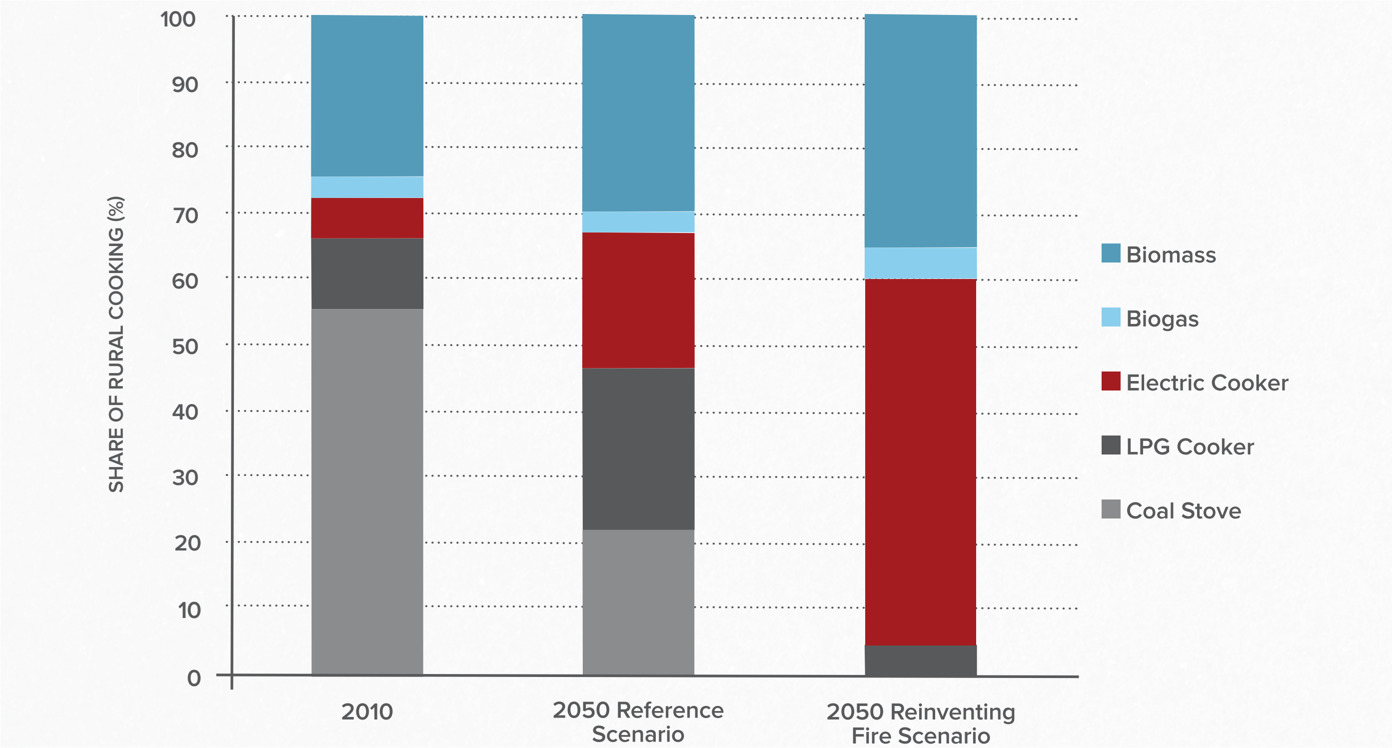


FIGURE 5.16: RURAL COOKING MIX BY FUEL AND TECHNOLOGY

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



Barriers

The main barrier to clean energy is the upfront cost. Consumers and businesses alike often lack extra capital to spend on new equipment or have competing investment options such that clean energy is low priority. The lack of availability or accessibility to cleaner energy sources such as solar also hinders adoption.

Solutions

Continue with incentives, such as the subsidies for qualified PV demonstration projects, and provide low-cost project financing.

- Implement the existing distributed generation policy.[43]
- Implement new policies to encourage grid integration of on-site generation such as a feed-in tariffs and net-metering.
- Encourage private investments in clean energy (e.g., create a "fund of funds that invests the public fund to form new venture capital funds or increase the equity of existing venture capital funds to target start-up companies that pursue innovation in emerging strategic industries and high-tech to transform traditional industries").[44]
- Improve electricity grid and natural gas pipeline infrastructure in rural areas.
- Support research on low-grade industrial waste heat to replace coal-fired boilers.
- Install renewable power on buildings including mandatory installation of solar water heaters in proper regions and biomass energy for heating and cooking in rural areas with incentive policies.
- Develop and promote distributed generation and microgrid systems and encourage power integration.
- Support the reform of the electricity sector and pricing formation. Liberalize the electricity market to allow self-generation and independent providers. Provide consumers with correct price signals (e.g., peak/off-peak price, seasonal price, etc.) and encourage innovation in efficiency and cost savings mechanism with feed-in tariffs and net metering.
- Introduce heating and cooling metering relating to consumer behaviors and link directly to service cost.

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06

TRANSPORTATION

TRANSPORTATION

6.1 DEVELOPMENT STATUS AND PROSPECTS FOR THE TRANSPORTATION SECTOR

China's transportation infrastructure has undergone extremely rapid development since the turn of the 21st century. China has among the world's largest road networks, port throughput capacities, lengths of navigable inland waterways, and total passenger and freight road and water transportation volumes.[1]

Between 2000 and 2013, China's passenger and freight transport activity grew annually by 6.4% and 10.8%, respectively, while the transportation sector's energy demand grew annually by 9.0%, outpacing the overall national rate of 7.9%. In 2010, final energy consumption from China's transportation sector reached over 300 million tons of coal equivalent (Mtce), representing 13% of the nation's total energy demand, more than double the level in 2000.[2] Because of this, transportation is an important source of new energy demand in China and its share of overall consumption is growing.

China's transportation system development lags behind the developed world in many areas, including roadway network density, per-capita kilometers of freeways and civil aviation corridors, and cars per 1,000 people.[3] The per-capita passenger travel distance in China is one-tenth of that in the U.S. and one-fifth of Japan's, despite Japan's smaller and narrower landmass, so there is plenty of room to grow.[4]

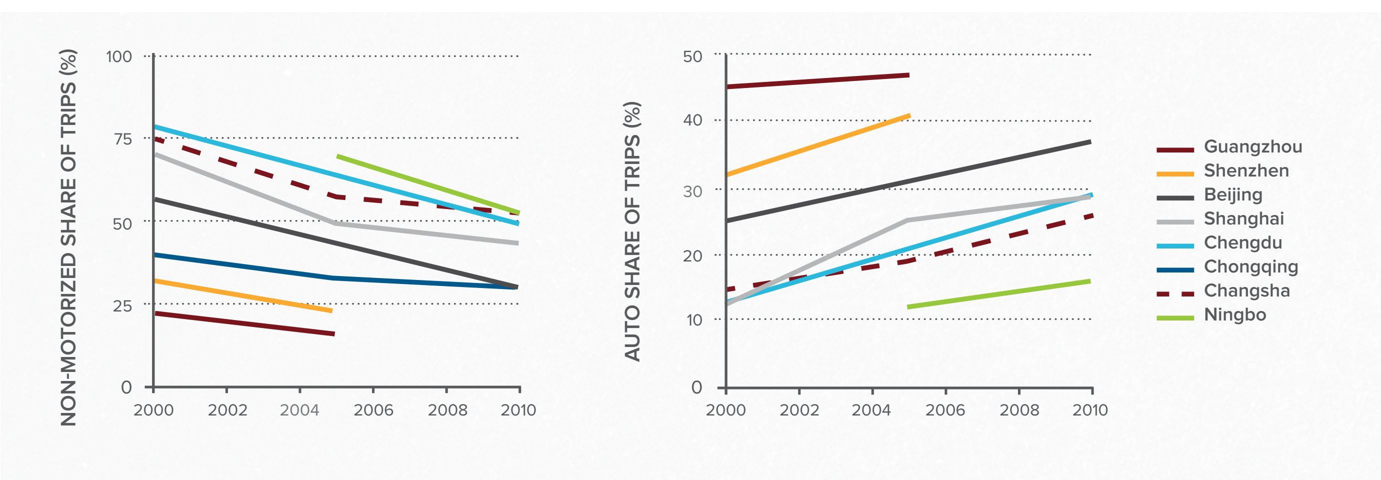
In the Reference Scenario, China's annual freight transport demand is projected to grow 4.6 times and passenger travel is projected to quintuple, driving primary energy consumption to 1.7 Btce for transportation, nearly five times higher than 2010. This higher demand will negatively impact China—worsening resource constraints and ecological and environmental problems. Alternatively, changing the current development model and slowing the growth of transportation's energy consumption will benefit China.

6.1.1 REINVENTING THE TRANSPORTATION SECTOR IS ESSENTIAL TO IMPROVING URBAN QUALITY OF LIFE AND SOCIOECONOMIC DEVELOPMENT

Rapid urbanization puts pressure on transportation systems and requires smart growth. Middle-class commuters in major cities forgo public transportation despite the promotion of transportation-oriented development. In the last 15 years, private-vehicle

FIGURE 6.1: AUTOMOTIVE AND NON-MOTORIZED TRAVEL TRENDS

2000–2010



ownership accelerated as urban transportation demand grew rapidly (Figure 6.1).[5] There is a similar trend away from rail travel and towards road and air travel in intercity passenger transport.[6]

Increasing vehicle use resulted in more particulate matter air pollution, congestion, and urban land shortages and reduced transportation reliability and quality of life. In 2013, smog covered more than 1.3 million km^2 in eastern China and affected more than 800 million people.[7] Nitrogen oxide (NO_x) from motor vehicle emissions, along with ozone, creates a mix in the air that causes photochemical smog in the atmosphere. For example, in 2014, 41% of fine particulate matter ($PM_{2.5}$) emissions came from motorized vehicles in Shenzhen, 31% in Beijing, and 21% in Guangzhou.[8]

Addressing these challenges becomes even more important as urbanization continues in China. By 2025, China's cities will have over one billion urban inhabitants—with 221 cities with more than one million residents—and account for 90% of China's GDP.[9]

6.1.2 THE ROLE OF REINVENTING TRANSPORTATION IN IMPROVING ENERGY SECURITY

China's oil demand from transportation is growing quickly, presenting a major challenge to energy security. China's transportation sector consumed 360 Mtce of primary energy in 2010, of which 313 Mtce (86%) came from petroleum products. Transportation accounts for 56% of total oil demand in China. Transportation sector oil demand was 50% diesel, 32% gasoline, and 8% jet fuel due to the recent rapid development of the aviation industry.[10] In 2010, internal-combustion-powered vehicles (i.e., cars, buses, and trucks) accounted for over 70% of the sector's total oil consumption, with 44% of the sector total used by freight trucks alone.[11] Rapidly increasing car ownership is the largest contributor to growth; 47% of the total new demand for oil between 2000 and 2009 came from automobiles.[12]

In the Reference Scenario, which includes autonomous improvements to vehicle efficiency, China's oil consumption grows to over 1,142 million tons of oil equivalent (Mtoe) by 2050, of which 890 Mtoe is consumed by transportation.[i] This level of oil demand is equivalent to 27% of 2014 global consumption and 40% of total global oil trade.[13] China's long-term domestic oil production will only reach about 200 Mtoe, even with increased production of unconventional oil and natural gas resources.[14] This means that China's import dependency ratio for oil will exceed 80% by 2050, surpassing America's peak dependency ratio of 65%.[15] This will limit China's energy security strategy and the flexibility of its foreign policy. Promoting a diversified and clean energy mix is essential to national security and energy security.

6.1.3 TECHNOLOGICAL INNOVATION AND ACCELERATING CHANGE OFFER AN OPPORTUNITY TO REINVENT TRANSPORTATION

A third industrial revolution is emerging globally and electric vehicles are an important technological component.[16] Annual electric vehicle sales have grown from fewer than 10,000 globally in 2010 to over 300,000 in 2014.[17] Electric vehicles offer significant advantages, including relatively high energy efficiency, low pollutant emissions, energy storage system integration potential, and a complementary role in the development of a smart grid.

Information and communication technology (ICT) will lead to fundamental changes in transportation demand. ICT is being used to streamline freight logistics while also replacing passenger trips with e-commerce and telecommuting. China currently has 630 million mobile phone users who, through smart capabilities of today's newest phones, can get travel directions, search public transit stations and routes, and compare the cost and time of arrival across different options. Rea-time updates to this data are become increasingly common and, as more vehicles, infrastructure, and users link up, innovation and opportunities for ICT will only increase.

[i] *1,142 Mtoe is equivalent to 1,632 Mtce. Based on official energy contents of 29,306 J/kg of coal and 41,868 J/kg of crude oil.*

6.2 VISION AND GOALS OF REINVENTING FIRE FOR THE TRANSPORTATION SECTOR

The Reinventing Fire Scenario can support China in meeting the ever-growing transportation demands of 1.3 billion people while creating a clean, low-carbon, convenient, fast, comfortable, competitive, and modern transportation system. By 2050, it is envisioned that China will have the world's most-efficient multimodal transportation system with complete rural and urban coverage. This system will integrate transportation networks, information networks, and smart traffic systems. Modern, electric cars and highly-efficient trucks will be widely adopted. Next-generation high-speed rail (HSR), airplanes, and ships will be widely deployed. Electrification and other alternative fuels will increase markedly and will help to reduce China's oil dependence. To realize this future, the transportation sector decouples economic growth and the delivery of transportation services.

1. **Decouple energy consumption from economic growth**
   Improved land use and planning for both cities and industry reduces travel distance and streamlines access to transportation networks. Infrastructure and management improve, especially for more-efficient modes like public transit and water/rail freight. Finally, Reinventing Fire prioritizes the development and adoption of technologies to improve vehicle efficiency, especially for energy-intensive freight trucks, taxis, and private autos.

2. **Reduce China's reliance on oil**
   The widespread adoption of electric vehicles diversifies the fuel mix, primarily for taxis and private autos, but also for urban light-duty trucks, buses, and others. Plug-in hybrid electric and natural gas vehicles are important before 2030, after when electric-only vehicles will be most prominent.

3. **Decouple carbon dioxide (CO_2) emissions from economic growth and transportation**
   By reducing energy consumption and switching away from oil-based fuels, CO_2 emissions will peak early and will no longer be tied to transportation demand. At the same time, urban quality of life can improve by easing traffic congestion and reducing air pollution. Logistics cost and reliability can improve to support continued economic growth.

6.3 RESULTS OF REINVENTING FIRE IN THE TRANSPORTATION SECTOR

6.3.1 TRANSPORTATION ENERGY DEMAND DECOUPLES FROM TRANSPORTATION DEVELOPMENT

China's future transportation demand continues to grow in the Reinventing Fire Scenario but at a markedly reduced rate compared to the Reference Scenario. Between 2010 and 2050, the Reinventing Fire Scenario's compound annual growth rate of transportation primary energy is only 2.1%, despite growth rates of 5.8% for GDP, 4.5% for passenger travel, and 3.9% for freight demand. China's 2050 primary energy demand from transportation is 840 Mtce, approximately half of that in the Reference Scenario (Figure 6.2). Transportation's primary energy demand peaks in approximately 2035 and then begins to fall.

6.3.2 ENERGY IS ELECTRIFIED, CLEANER, AND MORE DIVERSE; TRANSPORTATION SECTOR ENERGY USE IS DECOUPLED FROM OIL DEMAND

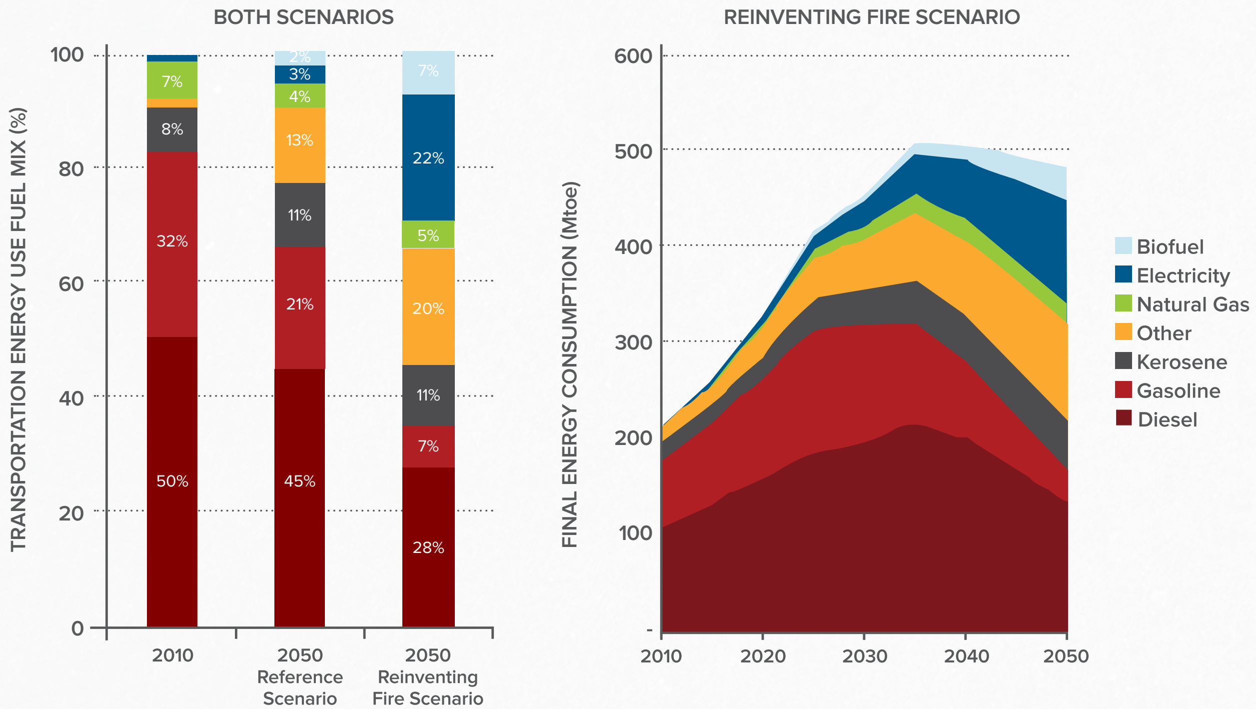
In the Reinventing Fire Scenario, electricity, natural gas, and biofuels develop quickly and account for 50% of 2050 transportation final energy demand. Electricity and natural gas are the second- and third-largest source of transportation energy, behind diesel. Transportation energy use is clean and diversified. China's diesel demand only grows by 24% during 2010–2050, to 192 Mtce (134 Mtoe). Gasoline demand falls 51% lower than 2010 levels, to 49 Mtce (34 Mtoe) (Figure 6.3). Transportation energy use growth fundamentally decouples from demand for petroleum products.

FIGURE 6.2: TRANSPORTATION SECTOR PRIMARY ENERGY DEMAND-SIDE SAVINGS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

FIGURE 6.3: TRANSPORTATION SECTOR FINAL ENERGY FUEL MIX AND DEMAND

2010–2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



6.3.3 CO_2 EMISSIONS AND OIL DEMAND BOTH PEAK AND ARE DECOUPLED FROM GROWTH AS A RESULT OF REDUCED ENERGY CONSUMPTION AND THE CHANGING FUEL MIX

China's transportation oil demand and CO_2 emissions grow continually in the Reference Scenario. Growth in oil use is slower in the Reinventing Fire Scenario: 2050 oil demand reaches only one-third of that in the Reference Scenario. Oil demand in 2050, at 381 Mtce (266 Mtoe), is only 22% greater than 2010 and oil demand peaks around 2033 at 677 Mtce. CO_2 emissions from transportation peak around 2035 at 1,925 megatonnes (Mt) CO_2 emissions progressively fall to 1,289 $MtCO_2$ by 2050 (Figure 6.4).

6.3.4 SIGNIFICANT ECONOMIC, SOCIAL, AND ENVIRONMENTAL BENEFITS ACCRUE

Increased investment between 2010 and 2050 creates net-present-value fuel savings of 23 trillion RMB ($3.5 trillion, in 2010 currency), leading to a net savings of 11 trillion RMB (Figure 6.5). In the Reinventing Fire Scenario, increased investment is primarily in high-speed rail (HSR) service, freight rail infrastructure, and higher-efficiency and alternative-fuel cars and trucks, all of which are required to reduce energy use.

The analysis above only compares capital, operating and maintenance, and infrastructure costs to fuel savings. The Reinventing Fire Scenario also sees reduced upfront infrastructure costs and ongoing investment, but these savings are not included in the analysis. For example, increased use of freight rail greatly reduces truck traffic, decreasing road wear and increasing the life of road infrastructure. In the analysis, decreases in truck traffic are factored, but lengthened road infrastructure lifetimes are not. In other areas, increased emphasis on certain modes of travel in the Reinventing Fire Scenario is offset by overall system efficiency. For instance, current development plans reflected in the Reference Scenario require 11,000 kilometers of additional subway lines by 2050 to keep pace with demand. The Reinventing Fire Scenario holds required investment in subway lines constant while reducing private vehicle by optimizing urban areas, encouraging ICT innovation, and accelerating development of infrastructure for non-motorized transit such as walking and biking.

The analysis also excludes environmental and social benefits that are more difficult to measure and price, yet are significant. The problems of congestion, affordability, equitable access to transport, and regional pollution directly and negatively impact the quality of life and health in China. The Reinventing Fire Scenario results in greatly reduced pollutant emissions and urban congestion, improved health and quality of life, and improved healthcare costs and overall economic productivity, but these benefits are not valued in the economic analysis.

6.4 PATHS FOR REINVENTING FIRE FOR CHINA'S TRANSPORTATION SECTOR

Four pathways together achieve the Reinventing Fire Scenario's vision for China's transportation sector. Applied in the following order they reduce primary energy consumption in the sector by 51% (Figure 6.6). These measures include:

- Reducing unnecessary transport demand (41% of the total reduction)
- Optimizing transportation mode share (20%)
- Improving vehicle energy efficiency (18%)
- Shifting to clean fuels (21%)

In addition, the transportation fuel mix is diversified and CO_2 emissions reduced (Figure 6.7). All four pathways are cost effective, with the potential to create trillions of RMB net present value between 2010 and 2050 while reducing congestion and improving transportation services.

Several barriers prevent China from realizing the

FIGURE 6.4: TRANSPORTATION SECTOR PEAKING AND DECOUPLING OF ENERGY, OIL, AND CO_2

2010–2050, REINVENTING FIRE SCENARIO

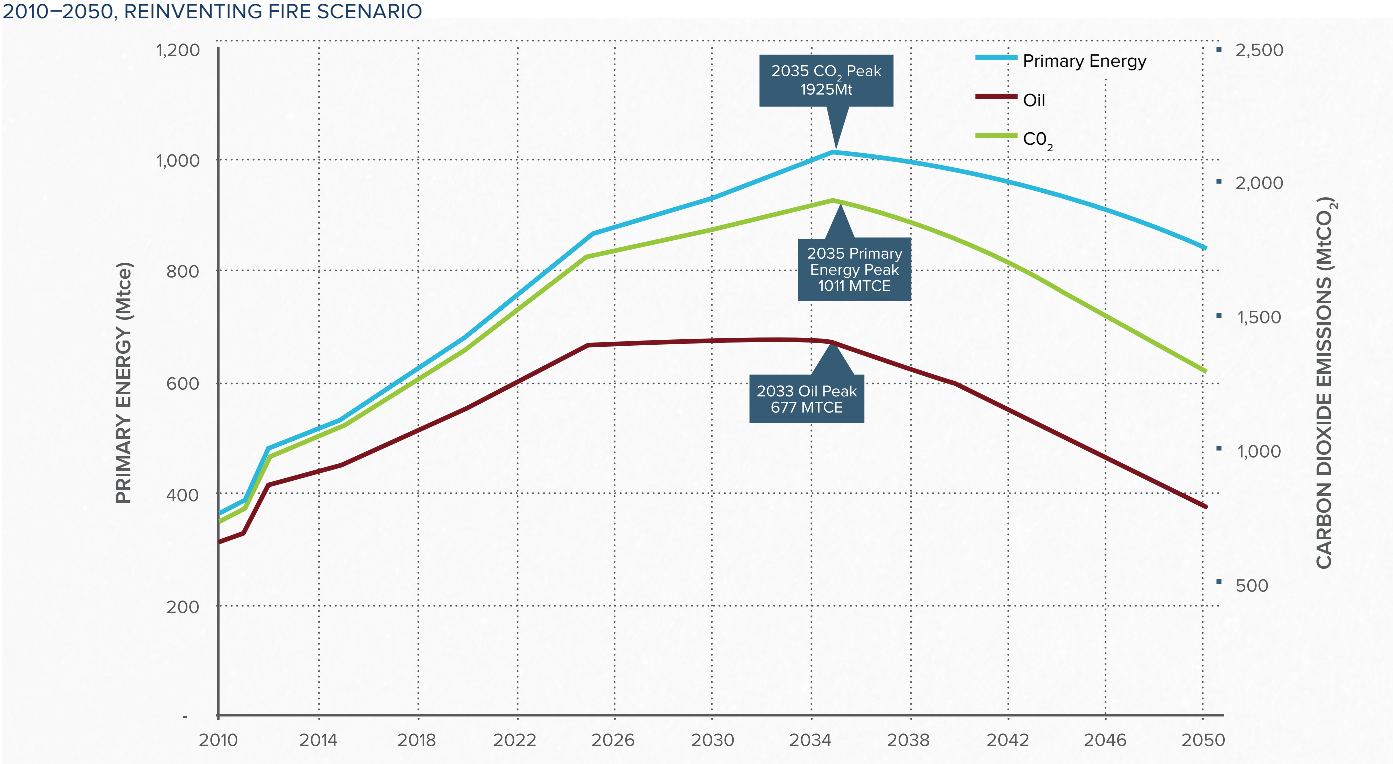
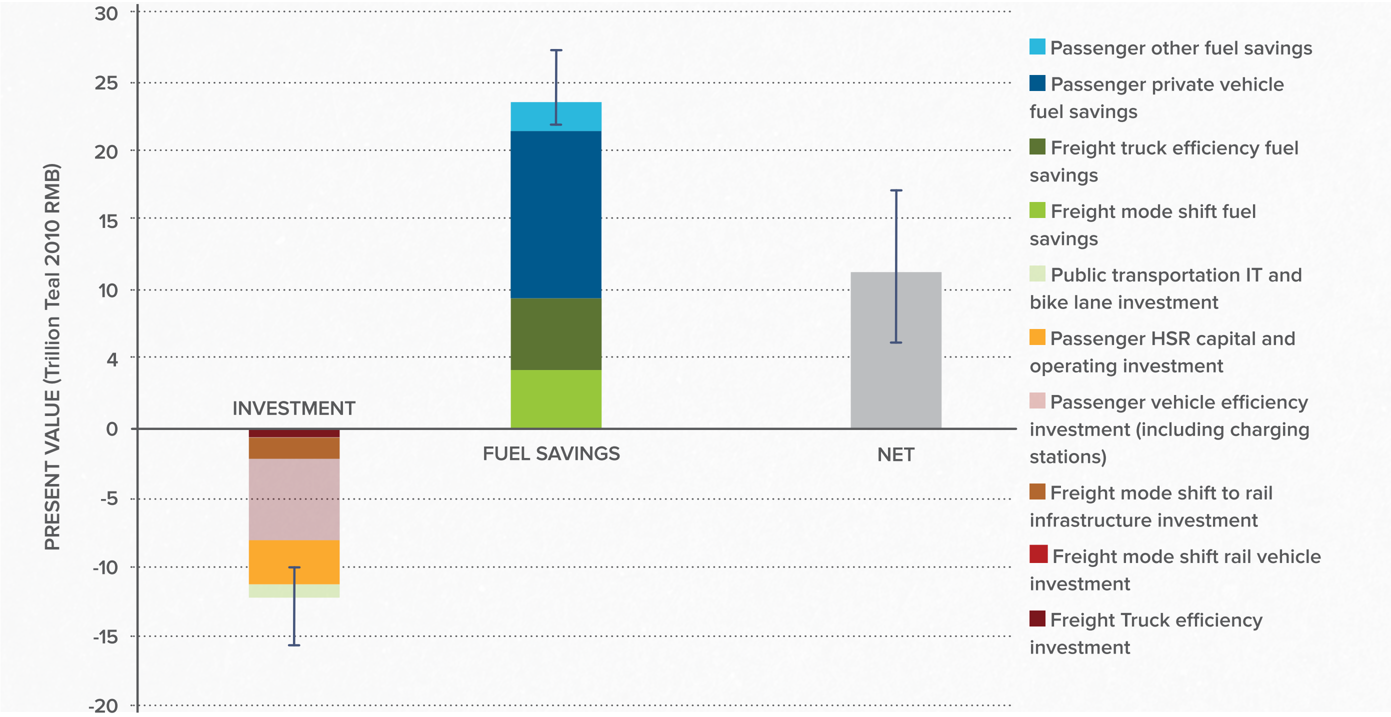


FIGURE 6.5: TRANSPORTATION SECTOR REINVENTING FIRE SCENARIO NET PRESENT VALUE

2010–2050



Reinventing Fire vision for transportation despite the fact that only proven and cost-effective technology is used. Government policy can help to overcome these barriers.

A discussion of each transportation pathway's barriers and solutions to those barriers is included here. Economic restructuring barriers and solutions are discussed in the industry sector.

6.4.1 PATHWAY #1: REDUCE UNNECESSARY DEMAND

Improve urbanization, industrial, and city planning while taking full advantage of ICT to replace physical travel and optimize logistics

In the Reinventing Fire Scenario, China begins to change the size and layout of cities around the country and the layout of infrastructure within cities. These changes, coupled with ICT, reduce unnecessary travel and increase overall transportation efficiency. Six aspects of reducing China's transportation demand are described below.

(1) Pursue a coordinated industrialization and urbanization model to reduce freight demand

China's historical approach to industrial development and urbanization failed to coordinate the locations of production and consumption centers across the country, creating excessive demand for long-distance transportation.[18] As China continues to urbanize, existing cities will grow and new cities will emerge. Effectively managing urbanization can help control the growth of freight transportation demand. Placing production centers closer to demand centers (together with logistics improvements discussed in the following section) and encouraging strategically positioned industry and cities can reduce the distance that freight travels and reduce overall energy demand from freight transportation.[19]

A structural economic shift towards service industries and high-value-added manufacturing (see Industry chapter) can further reduce freight intensity.[20] Experiences from developed nations show that transforming industrial development can greatly decrease freight transport intensity (Figure 6.8A and Figure 6.8B).

(2) Use information and communication technology (ICT) to reduce empty-truck driving and reduce overall freight demand

Efficient logistics reduces activity and saves energy for a given amount of freight transport. Chinese trucks are empty for an estimated 40% of total driving compared with 22% in Europe and the U.S.[21,22] Using sophisticated software and order tracking, companies can reduce waste, eliminate empty-truck driving, and find the most-direct, least-congested routes. Logistics will increase in importance as China shifts towards higher-value goods that require fast, flexible, and reliable delivery.[23]

(3) Standardize freight equipment and increase truck size to reduce freight travel demand

Equipment choice affects logistics efficiency. Developed countries have widely adopted using standardized tractor-trailer combinations to quickly "drop and hook" new loads. Pilot projects in China have shown that the shift to drop-and-hook trucking can reduce empty running to 20% from 40–60% today and improve yearly ton-km per truck by 78%, reducing costs by 10–20%.[24]

Truck size also matters and can increase as logistics improve and the trucking industry matures. The current payload of a heavy-duty truck in China averages 14 tons. A medium-duty truck payload averages four tons. Severe overloading in China is common.[25,26] In the U.S., 36-ton, heavy-duty trucks with a standardized trailer and 20–23 tons of payload are nearly ubiquitous (with the exception of urban delivery vehicles). When fully loaded, these larger trucks reduce fuel consumption by over 30%.[27] In the UK, increasing truck weight limits from 41 to 44 tons saved 135 million tons of CO_2 emissions per year.[28]

FIGURE 6.6: TRANSPORTATION SECTOR PRIMARY ENERGY SAVINGS AND PATHWAYS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

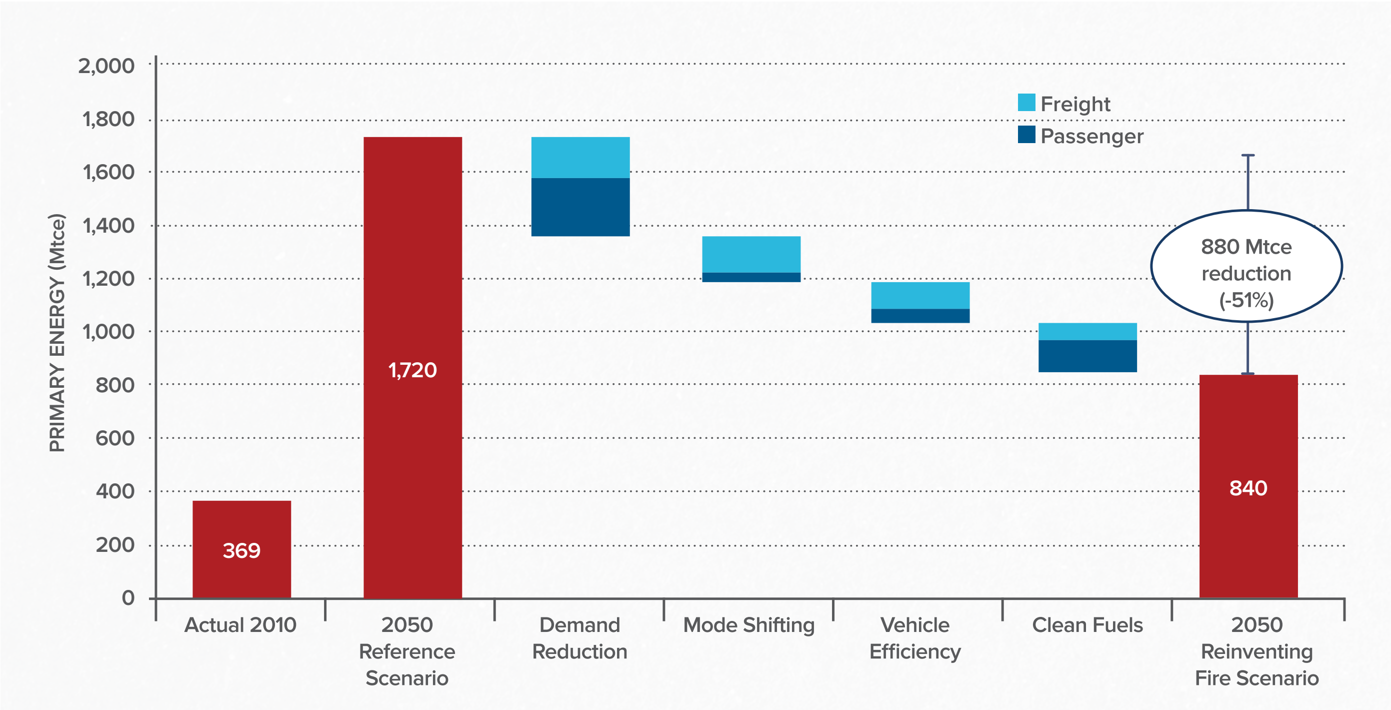


FIGURE 6.7: TRANSPORTATION SECTOR CO_2 EMISSIONS REDUCTIONS

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

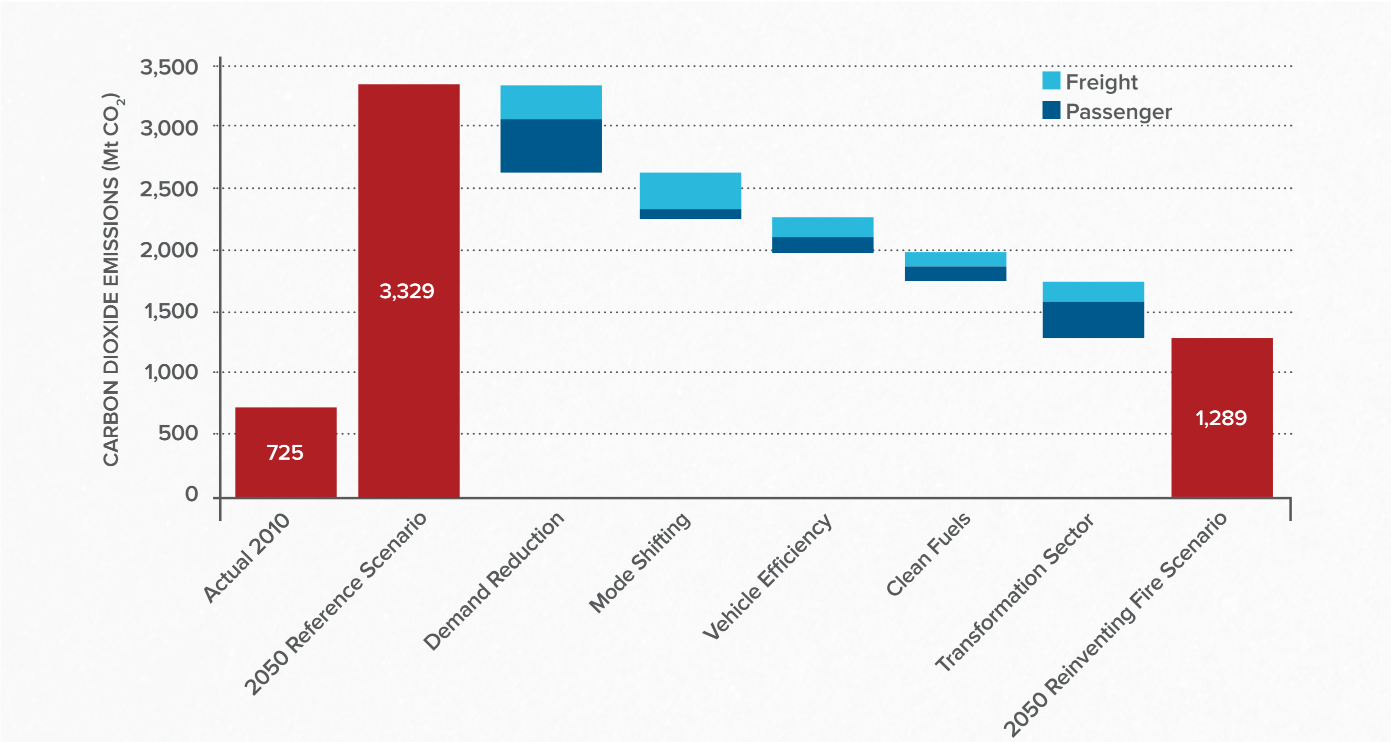


FIGURE 6.8A: FREIGHT ACTIVITY PER GDP FOR SELECT COUNTRIES

1995–2005

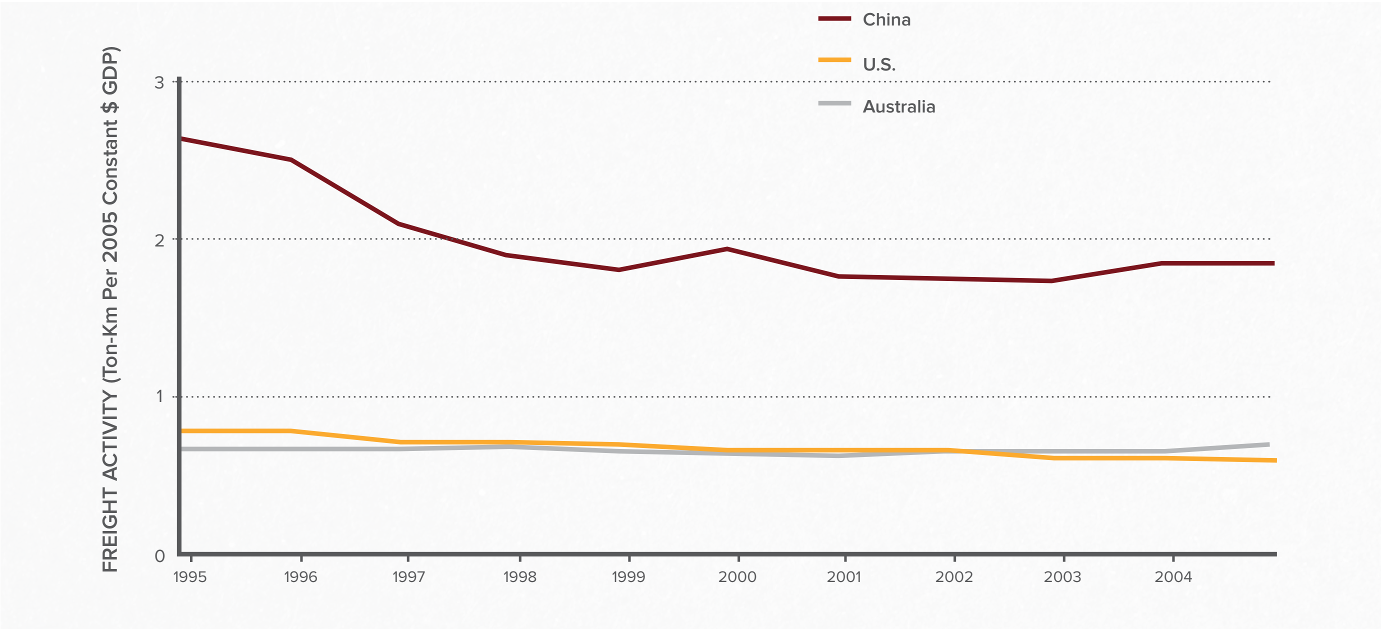
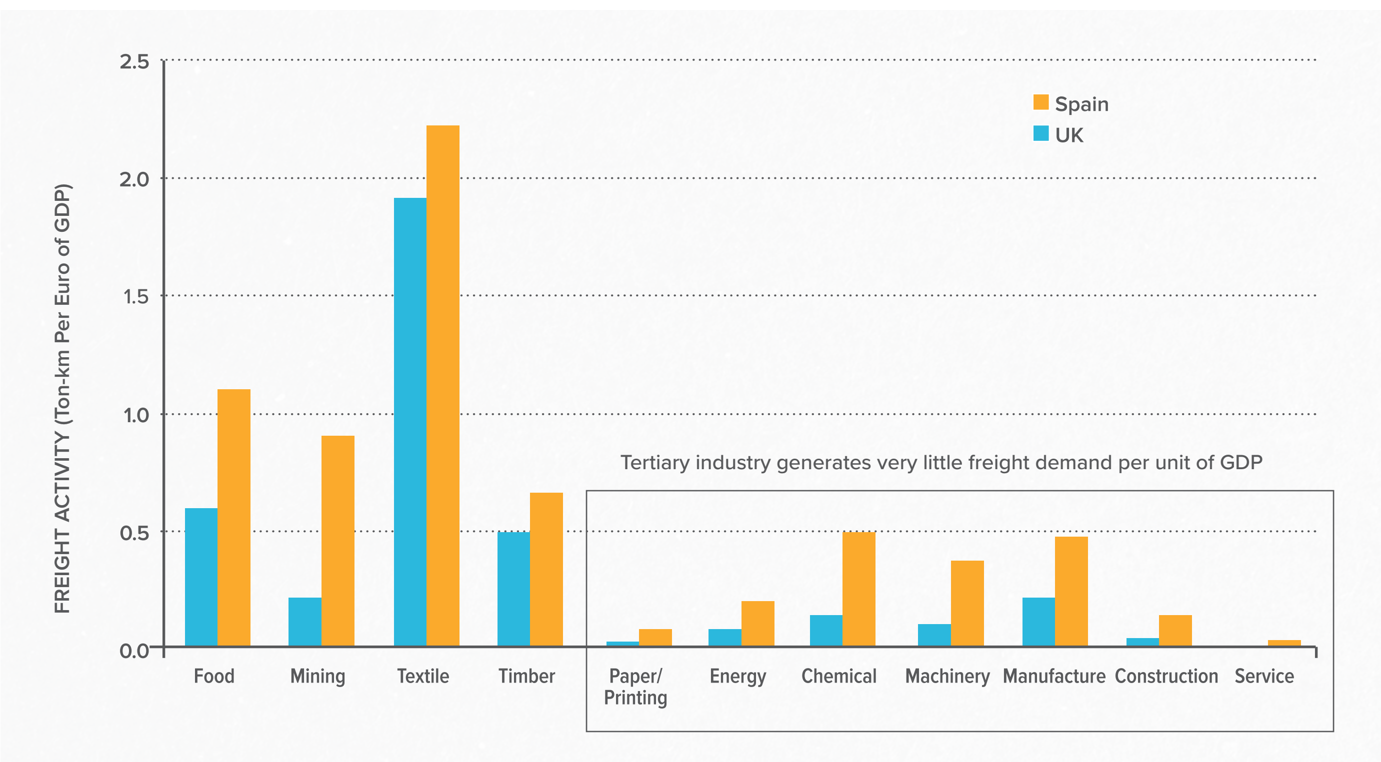


FIGURE 6.8B: ROAD FREIGHT ACTIVITY PER GDP FOR SELECT INDUSTRIES

2007

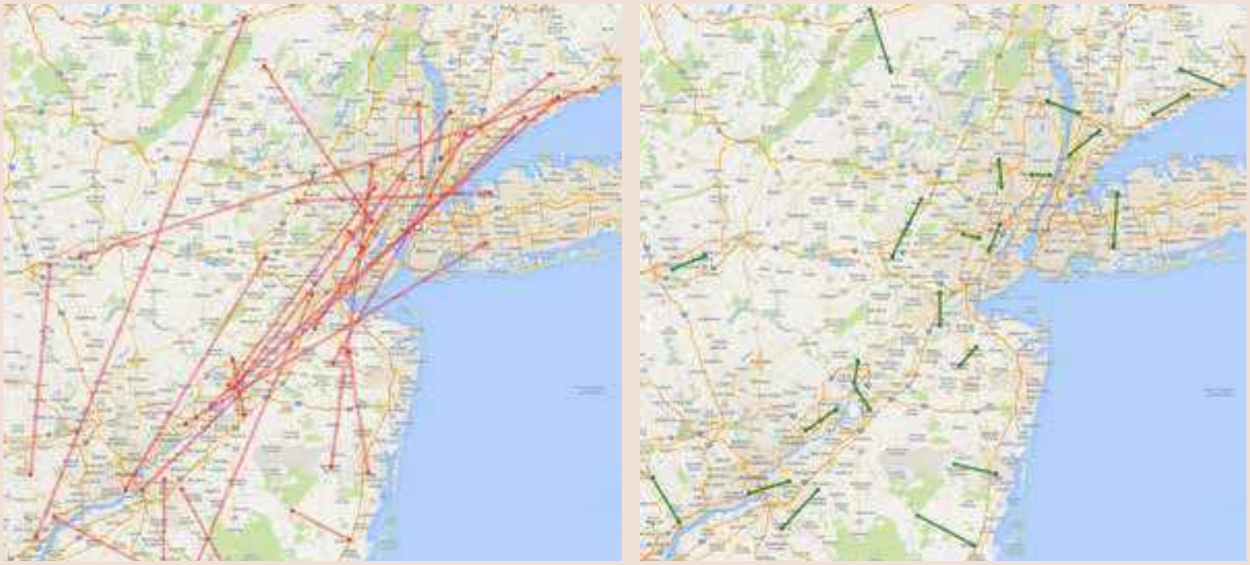


CASE STUDY 6.1: REAL-WORLD EXAMPLES OF IMPROVED LOGISTICS

Large fleets and specialized third party logistics providers (3pl) can collect data and run simulations to optimize operations. When Sinotrans Chem redesigned its distribution network, it cut trucking travel distance by half, avoiding 2.4 million km per year. Transportation costs fell by nearly two-thirds and diesel fuel consumption dropped 60%.[29]

Platforms for collecting data across companies can be used to match loads and avoid empty return trips. In Henan province, creating a public logistics-information platform reduced the share of empty truck driving from 53% to 38% of total travel distance, saving 52 million liters of fuel, valued at 316 million RMB ($50.89 million).[30] Advanced second-generation load-matching systems, such as the one under development by Transfix in the U.S., use software to further optimize routes and the match between trucks and freight (Figure 6.9).[31] Transfix has reduced its clients' empty running by up to 50% in real-world conditions.[32]

FIGURE 6.9: FREIGHT MARKET LOAD MATCHING



Freight activity in the Reinventing Fire Scenario is cut 13% by 2050 compared with the Reference Scenario by shifting to higher-value goods, optimizing the distribution of cities and industrial centers, and improving logistics efficiency. At the same time, increasing payload and eliminating empty miles allows for the elimination of overloading practices without increasing energy consumption.

(4) Site cities and develop populations in a well-balanced manner to reduce passenger travel demand

Distributing large cities across China can reduce the need for intercity passenger travel. In the Reinventing

Fire Scenario, city locations are optimized in three main ways: first, cities are developed in the center, west, and east of China; second, city sizes are distributed between small, medium, and large; and third, migrant populations are encouraged to settle down locally. At the same time, the wide use of modern communications, information and network technologies, teleconferencing, and remote work can reduce demand for intercity trips.[33]

In the Reinventing Fire Scenario, China's intercity passenger transportation demand rises at an average annual growth rate of 4.4% from 2.79 trillion passenger-kilometers (pkm) in 2010 to 15.3 trillion pkm in 2050—7.5% less than in the Reference Scenario.

(5) Develop smart cities to reduce the demand for motorized urban transit

Urban sprawl in China increases travel demand. Smart growth offers an alternative by rationally utilizing existing urban land, balancing residential areas and commercial areas in city design (e.g., mixed-use development), establishing public transportation networks that enable and shape development, developing non-motorized transit infrastructure, and reducing sprawl and focusing development around transit hubs (e.g, transit-oriented development). Smart growth calls for urban layouts with multiple hubs, mixed-purpose buildings, and small city blocks. This style of development effectively reduces commute distances for shopping, work, and other trips (Figure 6.10); increases the proportion of non-motorized travel; and reduces urban vehicle travel demand.[34]

(6) Use information technology to reduce unnecessary urban travel

Information technology can also help reduce demand for urban travel. Development of e-commerce, e-banking, and other internet-based services is accelerating, teleconferencing systems are increasingly being adopted in offices, and SOHO (small office/home office) and other working models are becoming common. A study at Chinese online travel agency Ctrip found that telecommuting employees were 13% more productive, took fewer sick days, and were happier than office-based employees.[35]

Together, smart growth city design and information technology can greatly reduce urban travel demand. In the Reinventing Fire Scenario, urban annual travel demand grows to 898 billion person-trips by 2050, 18.5% lower than in the Reference Scenario.

FIGURE 6.10: TRAVEL DISTANCES IN A SUPERBLOCK AND URBAN NETWORK GRID[36]

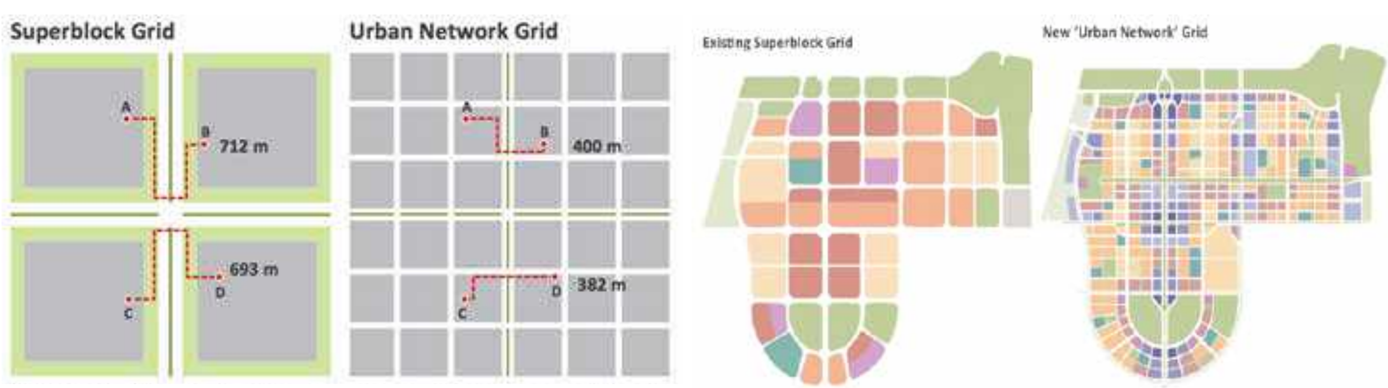
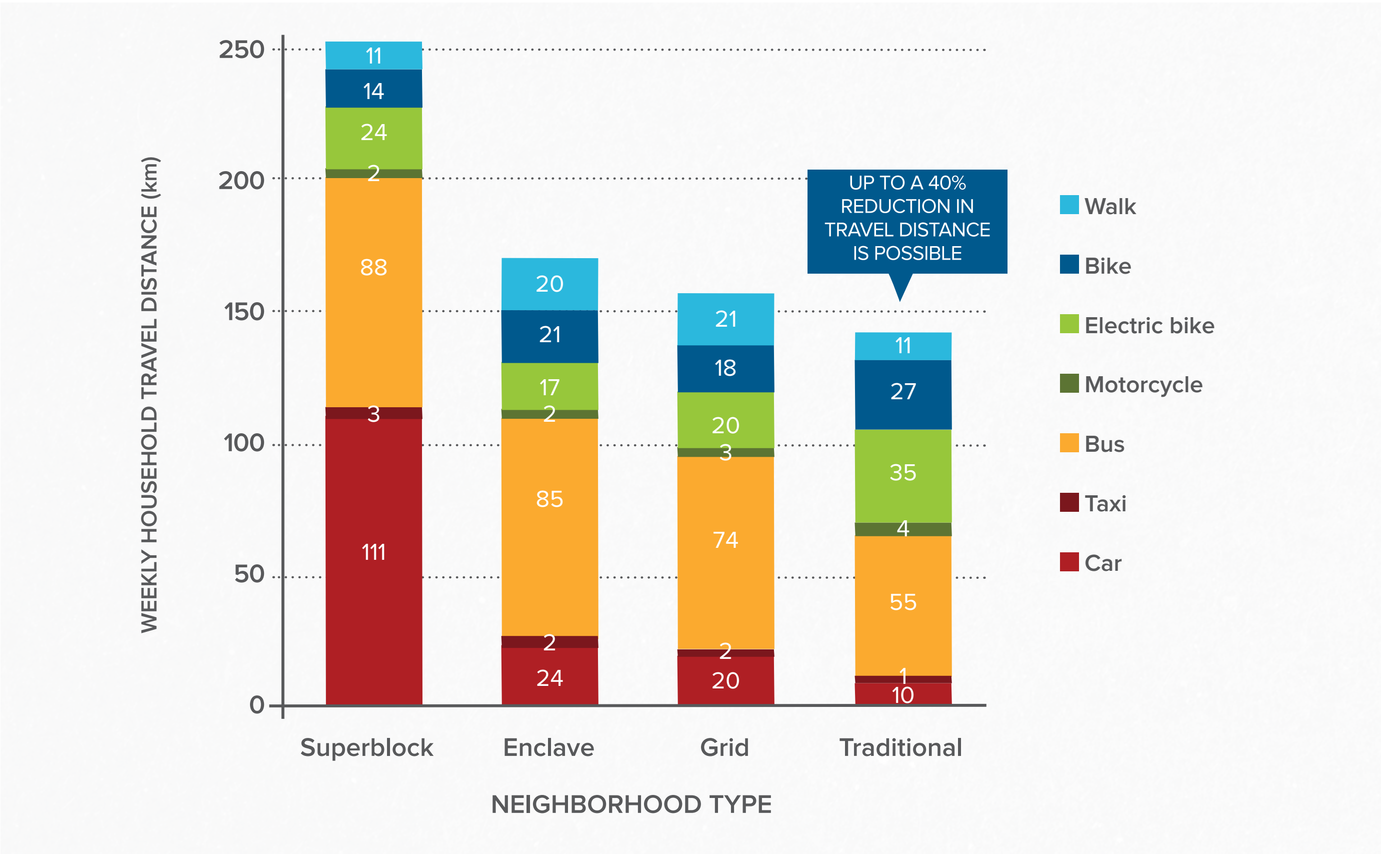


FIGURE 6.11: WEEKLY HOUSEHOLD TRAVEL DISTANCES BY NEIGHBORHOOD TYPE



CASE STUDY 6.2: EXAMPLES OF SMART GROWTH AND NON-MOTORIZED TRANSPORTATION

Jinan, the capitol city of Shandong province, provides a glimpse into how urban design affects travel distances and travel type. Households living in neighborhoods following smart growth design principles reported 40% less total travel and 80–90% less motor vehicle travel than those living in superblock-style neighborhoods (Figure 6.11). Superblocks are large city blocks, typically devoted to a single use, such as commercial or residential.[37]

Another way to reduce motorized transportation demand is by building dedicated bicycle infrastructure. The Netherlands offers the best examples of modern cities with a strong emphasis on non-motorized urban transportation. After the 1970s oil price shock and an increase in traffic-related deaths, the Dutch government invested heavily in biking infrastructure. Once an uncommon form of transit in Amsterdam and The Hague, biking now makes up close to 70% of all trips within the two cities.[38]

Barriers

Barriers to reducing unnecessary demand include: concentrating populations in megacities, poor coordination between transport planning and city development (leading to urban sprawl and superblocks), trucking industry market conditions that discourage logistics improvement, and a lack of logistics technical experience.

Solutions

To reduce freight and passenger intercity travel demand:

- Pursue a harmonized urbanization model that supports efficient industry placement—minimizing the haul length for raw materials and consumer goods.
- Continue to develop western China to create employment opportunities away from the east coast and reduce migrant flows to coastal cities.
- Strengthen comprehensive urban planning to make transport more efficient.
- Strengthen cooperative planning between provinces and cities.
- Site industry in transport-efficient locations through land use and tax policies.

To reduce city passenger travel demand:

- Closely coordinate urban and transportation planning on the city level and establish centralized planning agencies to coordinate disparate groups.
- Adopt smart growth urban planning principles (especially among city planners) including: compact urban development, planning for urban grids with a dense network of streets and paths, and zoning for multi-use buildings and neighborhoods.
- Pursue transit-oriented development, creating areas with short commutes and easy access to public transit, including high-quality, non-motorized transportation infrastructure.

To reduce unnecessary freight travel demand:

- Promote consolidation and develop strong national industry leaders.
- Improve the legal framework governing logistics providers. Allow third-party logistics companies to provide expertise. Update legal treatment of tractors and trailers and enable drop-and-hook trucking.
- Support innovative freight markets, such as mobile phone app-based load matching and routing.

6.4.2 PATHWAY #2: OPTIMIZE TRANSPORTATION MODE SHARE

Create a modern transportation system that is focused on public transportation

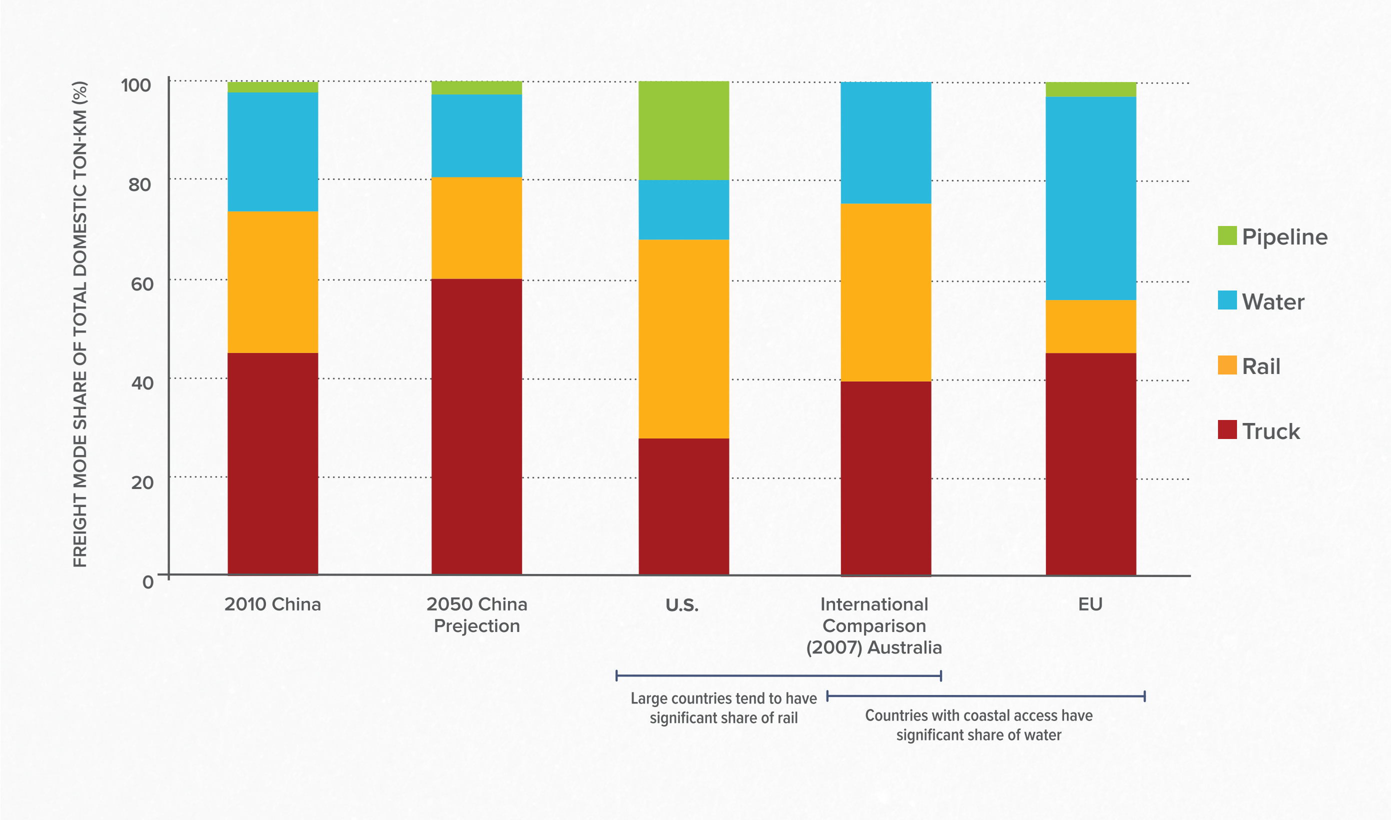
In the Reinventing Fire Scenario, China reverses the recent trend towards private cars, trucks, and other energy-intensive modes of travel. Freight, rail, high-speed passenger rail, and public transportation take the place of inefficient modes and reduce overall energy use. Three aspects of optimizing passenger and freight mode share are discussed below.

(1) Expand rail transportation to improve the efficiency of freight mode share

Increasing the share of freight carried by rail is critical to reducing transportation energy consumption. Because of rail capacity shortages, the share of rail in transportation falls yearly.[39] In the Reference Scenario, this trend continues. But other large countries show that a high reliance on trucks is not inevitable. In the U.S., rail handles a large share of freight activity (39%).[40] Europe has a high share of water freight transportation (40%).[41] And Australia relies on both rail (40%) and water (25%) (Figure 6.12).[42]

Rail and water modes can be used for bulk freight as well as higher-value goods. Consider shipping containers traveling across the Pacific Ocean bound for

FIGURE 6.12: CHINA'S HISTORICAL AND PROJECTED DOMESTIC FREIGHT MODE SHARE VS. INTERNATIONAL COMPARISONS



North America's central and eastern markets. These containers are loaded directly onto trains at west coast ports and move across the U.S. by rail, only relying on trucks for the final few kilometers.[43] In 2007, rail carried 14.3 million twenty-foot equivalent units (TEU) of international shipping containers in the U.S., or 33% of total port container throughput.[44] China, in contrast, had only 2% of containers going through its ports delivered by rail.[45]

There is a strong economic argument for emphasizing rail and water modes over trucking. The average 2015 price for rail transportation in China was 0.155 RMB ($0.02) per ton-kilometer,[46] about 50% cheaper than truck transport.[47] China's road haulage rates will rise as Chinese trucker wages increase and overloading problems are resolved. Simultaneously, rail transport costs will decrease as China's rail sector reforms and productivity improves. Rail transport is 80% cheaper than road transport in the U.S.[48] For bulk goods, with a low cost per ton, transportation can make up a significant portion of the delivered price. At the same time, intermodal rail can reduce logistics costs for higher-value goods, improving the competitiveness of inland cities and supporting China's western development.[49]

In the Reinventing Fire Scenario, the development of rail and water modes accelerates and capacity expands by upgrading train length and weight, by improving train signaling and spacing technologies, and by building more track for freight trains. Intermodal rail and water move high-value goods more efficiently. By 2050, rail accounts for 24% of freight transport (including international ocean shipments) in the Reinventing Fire Scenario, 5.5% higher than 2010 levels and 8% higher than the Reference Scenario in 2050. The 2050 share of water freight is 5% higher in the Reinventing Fire Scenario than in the Reference Scenario.

(2) Build an intercity passenger transit system that primarily relies on HSR and regular rail instead of airplane and private-car travel

HSR should be the foundation of a reinvented intercity passenger transportation system. HSR consumes one-tenth the energy of air travel per passenger-kilometer (pkm).[50] In addition, HSR has both cost and time advantages over civil aviation for trips of 1,000 km or less.[ii] In the past decade, opening new HSR lines caused five air-travel routes between 500 and 1,000 km to close due to lack of demand.[51] Currently, 65% of Chinese air transport is under 1,200 km and 35% is under 800 km.[52] If HSR replaces air travel on the majority of sub-1,000-kilometer air corridors and other rail replaces a similar share of intracity passenger car transit, it is possible to build a passenger transportation system that primarily relies on the most-efficient forms of transportation: urban rail and HSR.

China already has the world's largest HSR network.[53] By October 2014, China had almost 16,000 km of HSR track (both mixed use and dedicated lines), accounting for 60% of the world's total.[54] The total length of China's HSR track will reach 25,000 km by 2020.[55] The proportion of railway passenger transport using HSR increases to 40% by 2050 in the Reinventing Fire Scenario without requiring additional track beyond the Reference Scenario.[56] To take full advantage of this opportunity, it is necessary to focus on: (1) improving the convenience of HSR travel by planning for stations near urban centers;[iii] (2) building new cities near HSR stations; and (3) seamlessly integrating stations into urban public transportation networks.[iv,v,57,58]

[ii] Only operational costs were considered as they will determine ticket prices and capital costs vary widely.

[iii] Currently, many new stations are built far outside of cities without good connections to transit.

[iv] In Hong Kong, the MTR Corporation opens up stations to retail shops. This increases convenience for riders and boosts profits. A similar approach could work just as well with HSR. Encouragingly, last year China's State Council allowed railway companies to develop the land near railway stations.

[v] At Shanghai's Hongqiao, HSR, metro, and air all meet, making intermodal travel amazingly simple.

(3) Improve urban public transportation infrastructure and integration to increase public transit mode share

International experience shows that developing public infrastructure for subway, light rail, bus rapid transit (BRT), and non-motorized transit is an important pathway for developed cities to save energy (Figure 6.13). Automobile energy consumption per passenger trip is three times higher than for buses and automobiles have a 40-times-larger vehicle footprint per passenger, worsening already heavy congestion in cities.[59]

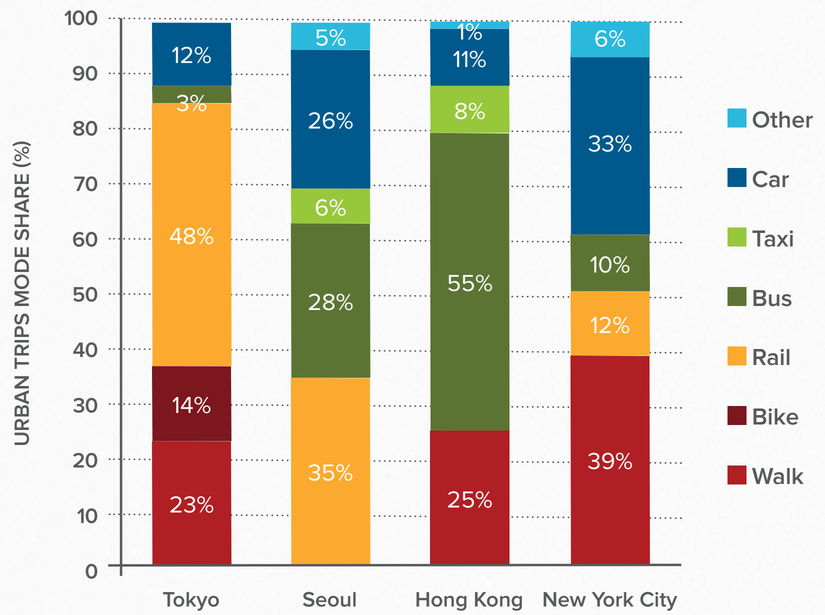
After providing public transportation choices, cities can manage private auto use through congestion pricing (for example, in London, Stockholm, and Singapore)[60] and parking policy reform. Several decades ago, New York City found that increasing the number of parking spots led to more driving and increased traffic.[61] In 2003, Parisian authorities reduced street parking by 9%, which led to a 13% reduction in driving.[62] Information technology can be used to change parking prices based on demand, enforce parking use automatically, and allow drivers to check parking availability and price before they drive. San Francisco recently installed parking sensors in parts of downtown to implement these three strategies, reducing targeted traffic by an estimated 10%.[63]

In the Reinventing Fire Scenario, transportation networks in Chinese cities with over five million residents will primarily rely on fast rail transportation, surface public transportation, and non-motorized transit, and will use taxis as a supplement. Cities with over one million people will primarily use public transportation; small and medium cities will primarily use electric vehicles. Building these modern, seamless, integrated public transportation systems will promote balanced development between urban and suburban areas and interweave urban and intercity transportation options.

Barriers

Rising service requirements and infrastructure limitations are causing a shift to higher-energy modes of transportation in both passenger and freight transport. Current infrastructure planning, investment, and management does not support transport efficiency.

FIGURE 6.13: URBAN TRIP MODE SHARE FOR SELECT GLOBAL CITIES



CASE STUDY 6.3: TRANSIT-ORIENTED DISTRICT PLANNING IN SINGAPORE

Leading cities often divide their city into transit-oriented districts, each with a public transit hub within walking distance.[64] In the 1970s, Singapore began a multi-decade program to ensure all citizens could easily reach and use public transit. Formerly disparate, ad hoc transportation services, including buses and taxis, were united under a single coordinating body, eventually including a new mass rapid transit system (MRT). This gave Singapore the ability to plan long term for how passengers could walk to public transit and move from bus to train.[65] In 2014, 65% of trips within the city were made on public transit. By 2030, 80% of homes will be within a 10-minute walk of the MRT.[66]

Freight, rail, and water transport capacity is insufficient and demand spills over onto less-efficient modes. Management is often based on administrative, rather than market, considerations. Railways' access to private capital is limited and the market does not dictate prices. Production and industry are not physically aligned with the rail network.

For passenger transit, the focus on private-car infrastructure over public transportation inhibits the ease and comfort of using public transit. Public transit transfers are inconvenient and the last-mile problem remains unsolved. Cities have not focused on developing ICT to improve public transportation. Intercity and HSR network development is ongoing and some large cities remain disconnected. HSR stations and urban transportation are not well linked. HSR prices and schedules are inflexible and limit potential users.

Solutions

To improve freight mode share:

- Strengthen infrastructure investment to increase capacity in freight, rail, and water modes. For rail, this could include continued segregation from passenger traffic and upgrades to allow heavier and longer trains. Inland waterways would benefit from both improved connectivity and increased maximum ship sizes on key routes.

- Improve the quality of investment decisions in infrastructure planning. Data collection and analysis can help identify key areas of supply and demand and the network bottlenecks that limit capacity. Data can also inform commercially-driven decisions on logistics parks and modal connectivity.

- Increase exposure to market forces to better allocate capacity, improve investment decisions, improve productivity, and increase private investment. Investing in rail reforms can attract capital (called rail marketization). Rail deregulation increases the quality of investment decisions by strengthening the commercial focus of investment decisions.

To limit private-vehicle use:

- Create targets for private-vehicle mode share for all cities.

- Adopt more policies that limit private-car use. Cities can choose from effective local and international best-practice regulations and market mechanisms. Examples include:
  - Congestion pricing in London and Singapore[67]
  - Dynamic parking pricing in San Francisco[68]
  - High parking fees in Paris[69]
  - Parking space purchase requirements in Hong Kong
  - Vehicle purchase quotas in several large Chinese cities[70]

To shift air travel to HSR:

- Improve connections between HSR stations and urban centers. City planning agencies incorporate HSR stations into their urban transit plans, allowing for easy access from downtown. Future HSR stations are located as close to downtown as possible and all stations have easy connections to urban transportation systems.

- Make schedules and pricing flexible based on demand. Lowering fares during off-peak hours can increase ridership.

To encourage comprehensive, competitive, multimodal transportation:

- Implement plans to create an intermodal rail network. Upgrade key corridors to accept double-stacked container cars. Rail is directly linked to major ports for efficient transfers. Creating specialized inland linkages at key hubs and logistics parks allows efficient transfer onto trucks for initial pickup or final delivery.

- Encourage the development of intermodal logistics expertise, including ICT, to manage the increased complexity of intermodal trip planning and tracking.

- Use ICT to improve public transit for passengers. Inexpensive sensors can track public transit, traffic, and parking spaces while consumer-facing applications provide travellers with real-time, multimodal transit information and a simple payment interface.

- Improve the quality of investment decisions in infrastructure planning. Data collection and analysis can help identify key areas of supply and demand and the network bottlenecks that limit capacity. Data can also inform commercially driven decisions on logistics parks and modal connectivity.

- Increase exposure to market forces to better allocate capacity, improve investment decisions, improve productivity, and increase private investment. Investing in rail reforms can attract capital (called rail marketization). Rail deregulation increases the quality of investment decisions by strengthening the commercial focus of investment decisions.

FIGURE 6.14A: GLOBAL HISTORICAL AND PROJECTED ELECTRIC VEHICLE BATTERY PRICE AND PRODUCTION VOLUME

2010–2030

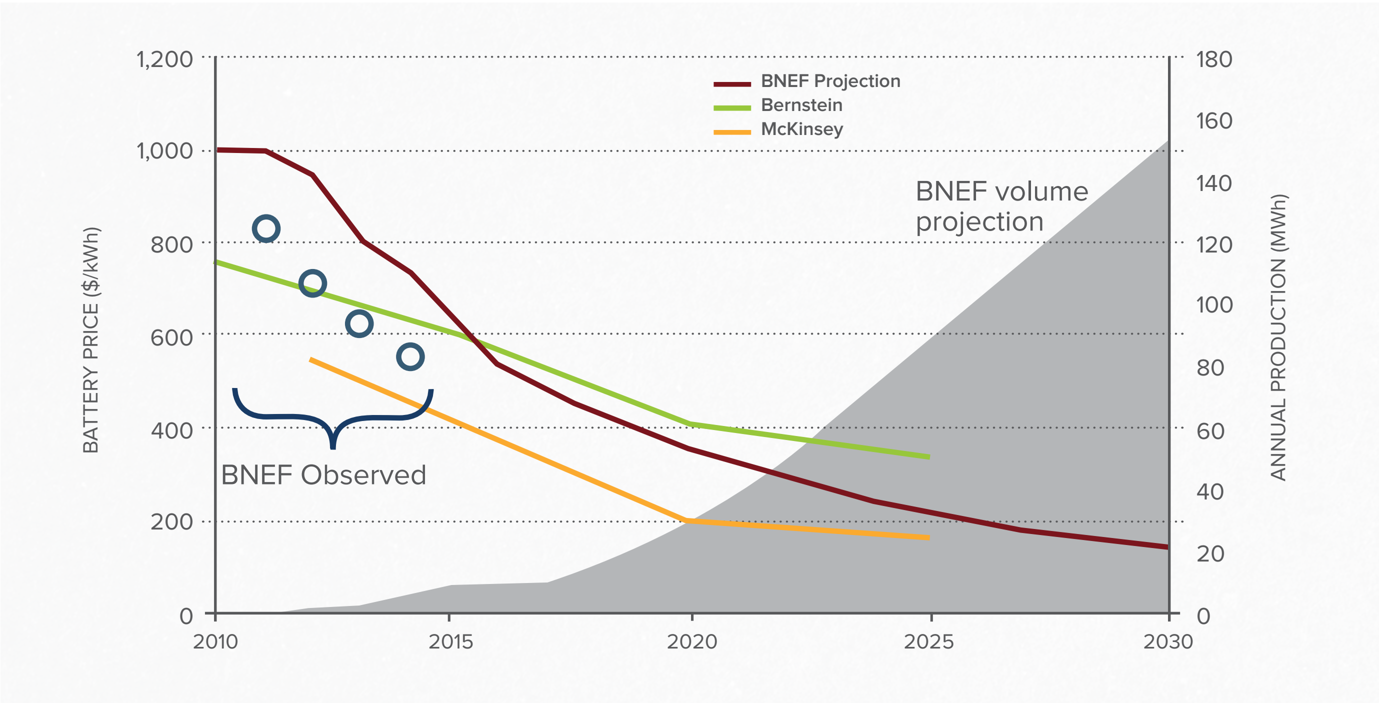
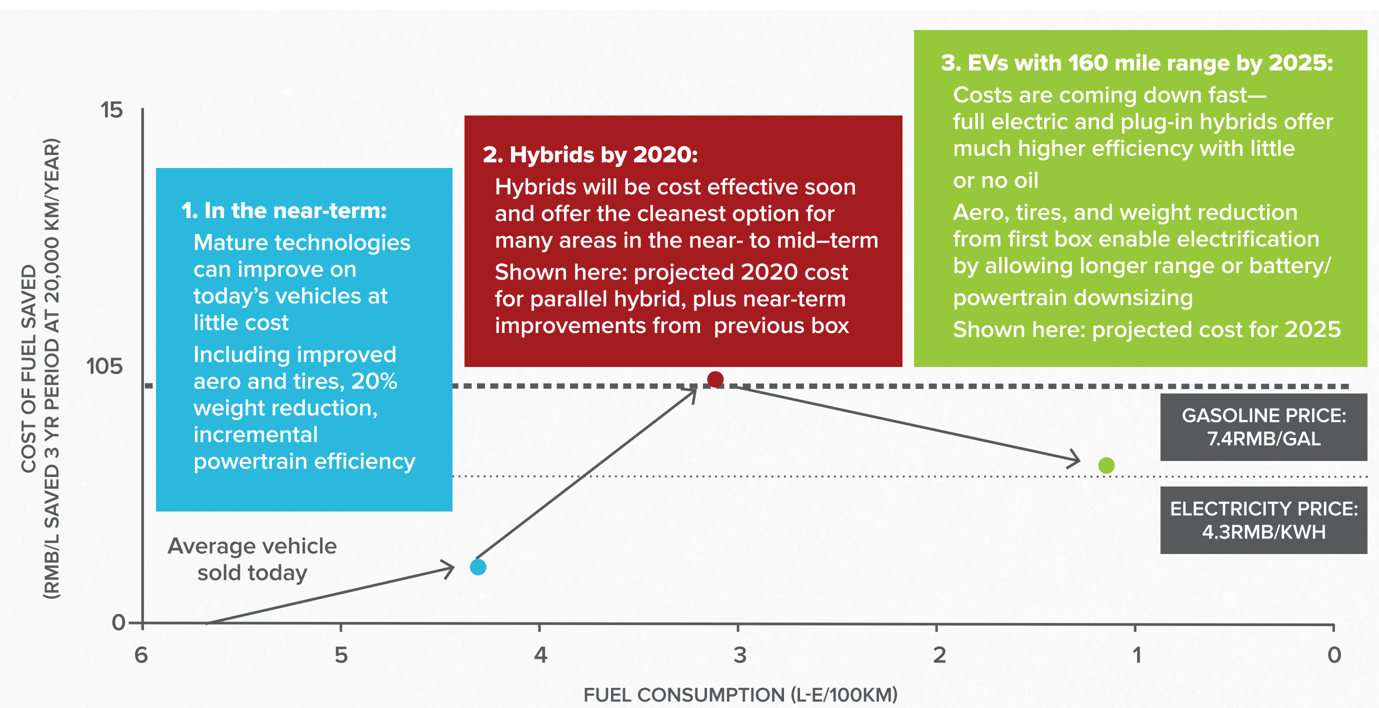


FIGURE 6.14B: TECHNOLOGICAL DEVELOPMENT AND ECONOMIC VIABILITY OUTLOOK FOR EFFICIENT VEHICLES



6.4.3 PATHWAY #3: SHIFT TO CLEAN FUELS

Optimize fuel mix and promote the electrification of vehicles

In the Reinventing Fire Scenario, China moves away from fossil fuel energy sources towards electric and renewable sources, reducing the country's dependence on oil. Three paths for shifting to cleaner fuels are discussed below.

(1) Promote universal adoption of plug-in hybrid electric vehicles and electric vehicles to improve efficiency and reduce oil demand

China, along with many developed countries, has instituted policies to support electric vehicle (EV) adoption.[71] Consumer subsidies, expansion targets, production policies, construction of charging infrastructure, and other policies encourage the spread of EVs. Growth in EVs in China has been extremely robust. Annual sales grew by approximately eight-fold between 2014 and 2016, from 36,000 units sold to 283,000 units sold, making China the largest EV market in the world.[72]

EVs can save more than 35% of energy over their lifecycles compared to traditional gasoline-powered cars and can reduce emissions by approximately 20%. Using China's current electricity generation mix, electric vehicles can reduce energy-related CO_2 emissions 10–35%, depending on the region.[73] Emissions reductions will deepen in the Reinventing Fire Scenario as more of China's power grid is based on renewable energy sources.

Plug-in hybrid electric vehicles (PHEVs) occupy the middle ground between hybrids and pure electric vehicles. PHEVs operate the same as EVs for most driving but can switch to conventional fuels when the battery runs out and longer range is needed. In the near to medium term, natural gas and PHEV vehicles are prioritized in the Reinventing Fire Scenario. However, in the medium to long term, as charging infrastructure expands and the technology for PHEVs and EVs matures, costs will drop and these vehicles will be cost effective for widespread adoption, with little or no subsidies or incentives required (Figure 6.14A and Figure 6.14B).

In the Reinventing Fire Scenario, the share of electric vehicles (including PHEVs) reaches 80% by 2050. Over 60% of urban buses are also electrified by 2050.

Light-duty trucks used for urban freight delivery are also an attractive candidate for hybrid, PHEV, and pure-electric vehicles. These configurations are especially well suited for urban, stop-and-go traffic. Major U.S. delivery companies have piloted both hybrid and full electric delivery vehicles.[74,75] PHEV trucks could be the best fit for wider adoption, offering electric driving for most trips and the flexibility of a conventional combustion engine for longer trips. At current battery prices, PHEV technologies have favorable economics for vehicles with high utilization. As battery prices fall, the economic viability of PHEV technology will extend to greater market segments.[76]

(2) Encourage the spread of natural gas-powered trucks and boats

Heavy-duty trucks (HDTs) drive long distances on varied routes, require quick refueling, and so are difficult to electrify. HDTs will increasingly rely on natural gas and biofuels (discussed below) in the Reinventing Fire Scenario, as they move to diversified and sustainable fuel sources. Natural gas trucks have a small market share in China today, but sales have been growing rapidly.[77] Pilot projects in Guangzhou show that natural gas-fueled trucks bring significant environmental benefits, especially for SO_x and particulate matter. Fuel savings pay back the increased capital costs and far outweigh slightly higher maintenance and insurance costs. In total, the payback period is 1.5 years.[78] In the Reinventing Fire Scenario, the share of natural gas vehicles reaches 8% of total vehicle ownership in 2050, primarily in HDTs and urban public transportation fleets. Natural gas-fueled trucks will account for over 25% of total truck travel.

(3) Accelerate the development of biofuels

Global biofuel production grew rapidly from 2000 to 2010. In 2009, biofuels supplied around 22% of vehicle energy consumption in Brazil and 3–4% in the U.S. and EU.[79] Existing engines only require a small modification to use biofuels and sometimes require no modification at all. Biofuel prices are expected to become competitive as production technologies improve and facilities scale up.[80] China's available arable land and water resources somewhat limit the domestic supply of biofuels. However, there is room for significant biofuels development without competing with food supplies. China's potential energy production from biological resources is approximately 590 Mtce.[i] With this biomass endowment, and after accounting for conversion efficiency, the substitution potential for liquid biofuels into the transportation sector in 2050 is 47–114 Mtce. In the Reinventing Fire Scenario, biofuels account for approximately 7.5% of transportation final energy demand by 2050, equivalent to 35 Mtce of energy consumption.

Liquid biofuels also have potential to be used in the aviation sector, where different types are undergoing testing. In 2015, using waste vegetable oil as fuel, a partnership between Chinese oil company Sinopec, China-based Hainan Airlines, and Boeing successfully flew test flights from Haikou to Shanghai.[81]

Barriers

In both freight and passenger transit, high upfront costs and poor refueling technology and infrastructure are the major barriers to switching to clean fuels.

Consumers and business will not adopt alternative fuel vehicles without reliable access to charging or refueling infrastructure. For natural gas and biofuels, supply must be guaranteed and pricing mechanisms must mature.

Even though costs are falling rapidly, high upfront costs still limit passenger EV adoption. Local protectionism hurts competitiveness and innovation in Chinese EV production. PHEV urban freight vehicles need further development and scale to achieve cost effectiveness. Similarly, the technology for dual-fuel LNG/fuel oil ships is expensive.

[i] *Calculated using the direct equivalent method.* "

Solutions

To improve refueling/recharging infrastructure:

- Build electric charging infrastructure in cities and along major intercity corridors for EVs and PHEVs.
- Build out natural gas refueling infrastructure for longer-distance passenger and freight travel. Consider retrofitting existing gas stations to add natural gas refueling capabilities.
- Secure natural gas fuel supply. Domestic resources are limited and the prospects of unconventional natural gas development are uncertain. Domestic production and a diversified import portfolio are both important. LNG import facilities will be critical for supply reliability. Reform natural gas prices in order to ensure effective allocation of natural gas resources.
- Invest in biofuels development. The biofuels industry requires incentives and subsidies until innovation, scale, and mature technology bring prices down to a competitive level (this is especially true while global oil prices are low).
- Build out the electricity transmission infrastructure to electrify rail.

To address the high upfront costs of fuel switching:

- Create strong and varied incentives for clean-fuel vehicle purchases. Financial incentives could include various subsidies and favorable tax treatment. Nonfinancial incentives could include exemptions from license plate lotteries, priority access to parking or highway lanes for passenger vehicles, or unrestricted urban access for freight vehicles.
- Create targets (as a share of total sales) for clean-fuel vehicles. This will spur adoption and ensure a return on research and development (R&D) expenditures for manufacturers.
- Increase the capability of manufacturers to achieve widespread adoption. Increase investment in R&D for EVs, PHEV urban delivery vehicles, and dual-fuel ships. Pilot, test, and refine technologies to help increase capabilities. Consolidate production to bring scale and expertise.
- Design policies to avoid local protectionism and encourage the emergence of large-scale, highly-competitive manufacturers.

6.4.4 PATHWAY #4: IMPROVE VEHICLE EFFICIENCY

Accelerate technological innovation

China pursues the world's most-modern and fuel-efficient technologies in the Reinventing Fire Scenario, reducing the country's dependence on oil. Two key aspects of efficiency are discussed below.

(1) Increase the share of advanced, highly-efficient trucks

Demand for trucking is expected to quadruple in the Reinventing Fire Scenario despite activity reduction and mode shifting. Key technologies to improve efficiency in trucking include improved aerodynamics and tires, tire pressure monitoring, engine waste heat and pressure recovery (turbocompounding), and electrified pumps and fans (Figure 6.15). In the U.S., the Department of Energy carried out a SuperTruck program using only existing, mature, and cost-effective technologies. Real-world testing of the SuperTruck prototypes by truck manufacturers Daimler and Cummins showed over a 50% reduction in fuel consumption.[82,83] Light-duty trucks are improved using similar technologies except for urban delivery vehicles, for which hybrid electric and PHEV drivetrains are projected to become cost effective.[84]

In the Reinventing Fire Scenario, HDT fuel consumption drops over 40% from 2010 to 2050—this includes the effects of emissions-control technology that can reduce particulate matter and NO_x emissions by up to 95%. Light-duty truck (LDT) efficiency improves by 50%.

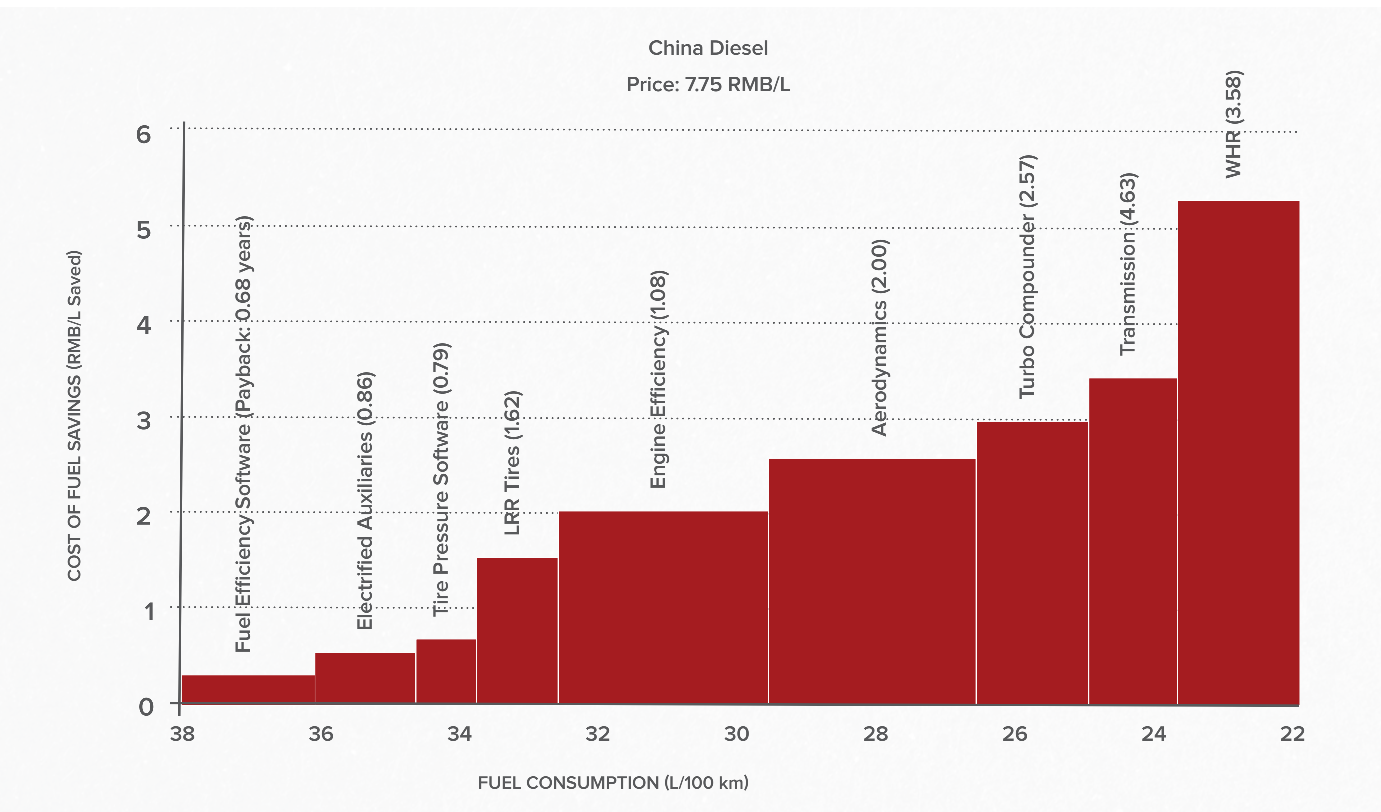
(2) Adopt new technologies and new materials and constantly improve fuel economy of passenger cars

Increasing the efficiency of Chinese passenger cars becomes crucially important as private vehicle ownership rapidly expands. The Chinese fleet's average performance indicators—such as engine displacement, curb weight, footprint area, and horsepower—fall to between the levels of European, gasoline-powered passenger cars and U.S. car fleets. China's passenger car fleet is 9% heavier and 1% larger than the EU's, on average, yet its average fuel consumption is 26% higher. Compared to the U.S., China's fleet is 21% lighter and 11% smaller, yet its average fuel consumption is only 4% lower.[85]

Many countries have implemented strong fuel economy standards and targets. The EU, Japan, the U.S., and other countries have rolled out new vehicle fuel economy targets for 2030 that represent a 50% improvement over current vehicle efficiency. The Chinese government is carrying out the fourth stage of passenger car fuel-consumption limits, which establishes a 2015 target of 6.9 L/100 km and a 2020 target of 5 L/100 km (Figure 6.16).[86] Proven and cost effective technologies can further improve vehicle efficiency. In the Reinventing Fire Scenario, vehicle efficiency improves to 3 L/100 km by combining improved tires and aerodynamics, a 20% weight reduction, engine and drivetrain improvements, and some hybrid electric drivetrains (Figure 6.15).

Detectors and software, not humans, drive autonomous vehicles (AVs). These cars can connect with other vehicles and infrastructure to optimize driving for efficiency and safety. Although uncertainty remains about the future of AVs, technological progress and investment accelerated over the last five years. Some technologies, like automated parking and adaptive cruise control, are already available and many experts

FIGURE 6.15: PATHWAYS FOR IMPROVING HEAVY-DUTY-TRUCK FUEL EFFICIENCY



predict fully autonomous vehicles will be on the market in the next 5–10 years.

Widespread adoption of AVs could achieve huge safety and productivity benefits, and these technologies will only reinforce the Reinventing Fire Scenario's potential for energy efficiency and renewables. For example, AVs can coordinate movement—relieving congestion and adjusting speed to avoid stopping at traffic lights. They can work together by drafting on highways to reduce aerodynamic drag. For trucks, this can reduce fuel consumption 5%–10%.[87] In the longer term, experts predict much larger efficiency improvement if autonomous taxis gain a dominant share of travel and cars can be better tailored for their exact use (e.g., size, top speed, and range).[88]

In the Reinventing Fire Scenario, the fuel economies of China's traditional internal combustion engine (ICE) cars and hybrid cars improve significantly over the Reference Scenario. Buses also have significant fuel economy improvements over the Reference Scenario.

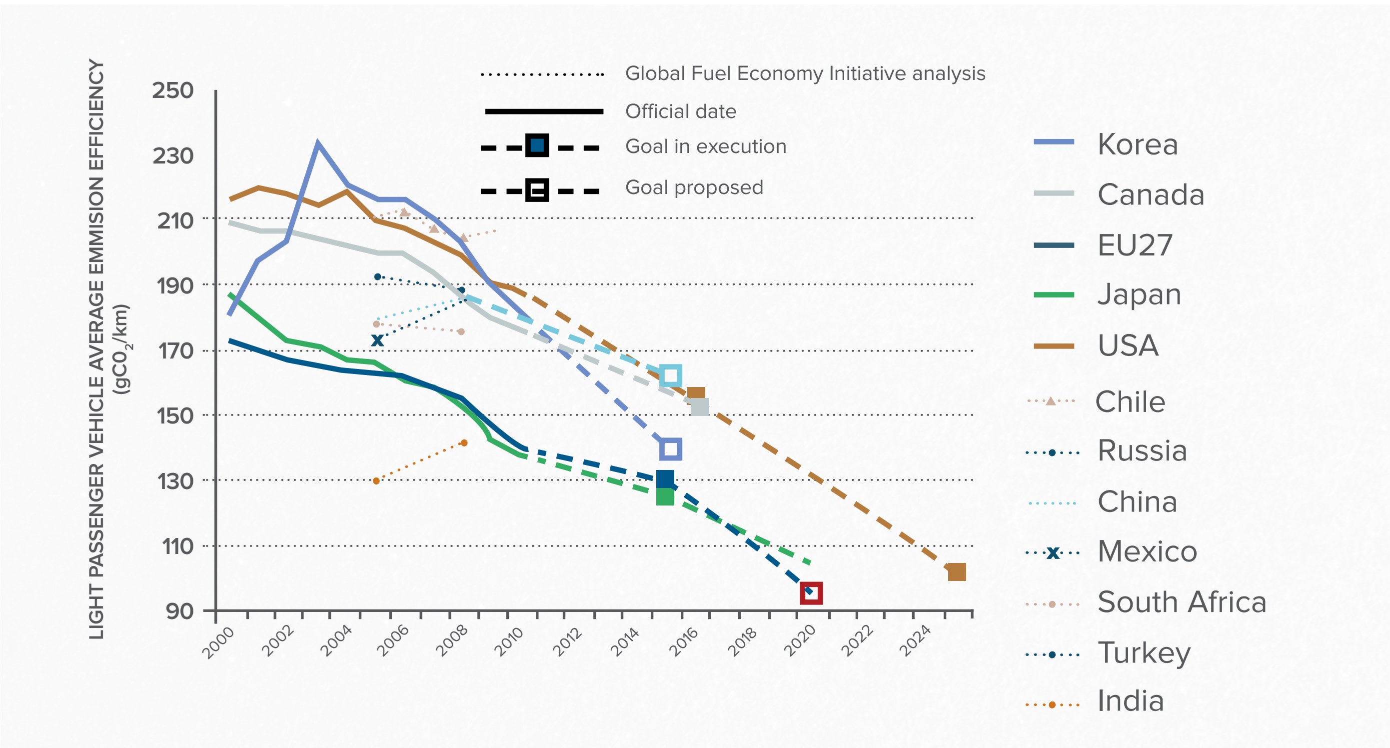
In the Reinventing Fire Scenario, the fuel consumption of conventionally fueled vehicles is reduced by over 40%. Including electric vehicles, the average energy consumption (on an oil-equivalent basis) is reduced by over 60%.

Barriers

In passenger vehicles, there is a trend towards larger private cars with a higher engine displacement. Weight-based vehicle efficiency requirements give automakers little incentive to reduce vehicle weight. Vehicle efficiency information is limited; there is a large difference between claimed and actual fuel economy.

For trucks, overloading shortens the useful vehicle life and unsophisticated logistics reduces annual utilization. Both of these reduce the payback for investing in fuel economy. Unreliable fuel quality fouls some advanced fuel-efficiency and emissions-control equipment. The immature trucking industry lacks access to capital, leading purchasers to focus heavily on minimizing

FIGURE 6.16: ENACTED AND PROPOSED FUEL ECONOMY STANDARDS FOR SELECT COUNTRIES[89]



upfront costs. In turn, truck manufacturers have been slow to innovate and offer new technologies.

The efficiency of buses, ships, planes, and trains can also be improved.

Solutions

To improve both passenger and freight vehicle efficiency:

- Apply increasingly stringent fuel economy standards to drive further technology adoption and innovation. Improve enforcement of current fuel economy standards and improve consumer information on real-world fuel economy.[90]

To improve passenger vehicle efficiency:

- Create a tiered tax for differing vehicle displacement to encourage development of smaller cars.

- Change from weight-based to volume- or footprint-based fuel economy standards to incentivize auto manufacturers to reduce vehicle weight.

- Encourage the adoption of hybrids by expanding new-energy-vehicle (NEV) purchase subsidies to hybrid vehicles and support local production of hybrid vehicles. Hybrid electric drivetrains offer a particularly large efficiency boost. They are cost effective, but are not available in China and lack policy support.

To improve freight vehicle efficiency:

- Improve logistics capabilities and limit overloading to increase both truck lifetime and truck utilization and therefore the financial benefits of fuel savings.

- Improve access to capital for small and medium-sized trucking enterprises at reasonable terms to reduce the imperative to minimize upfront costs.

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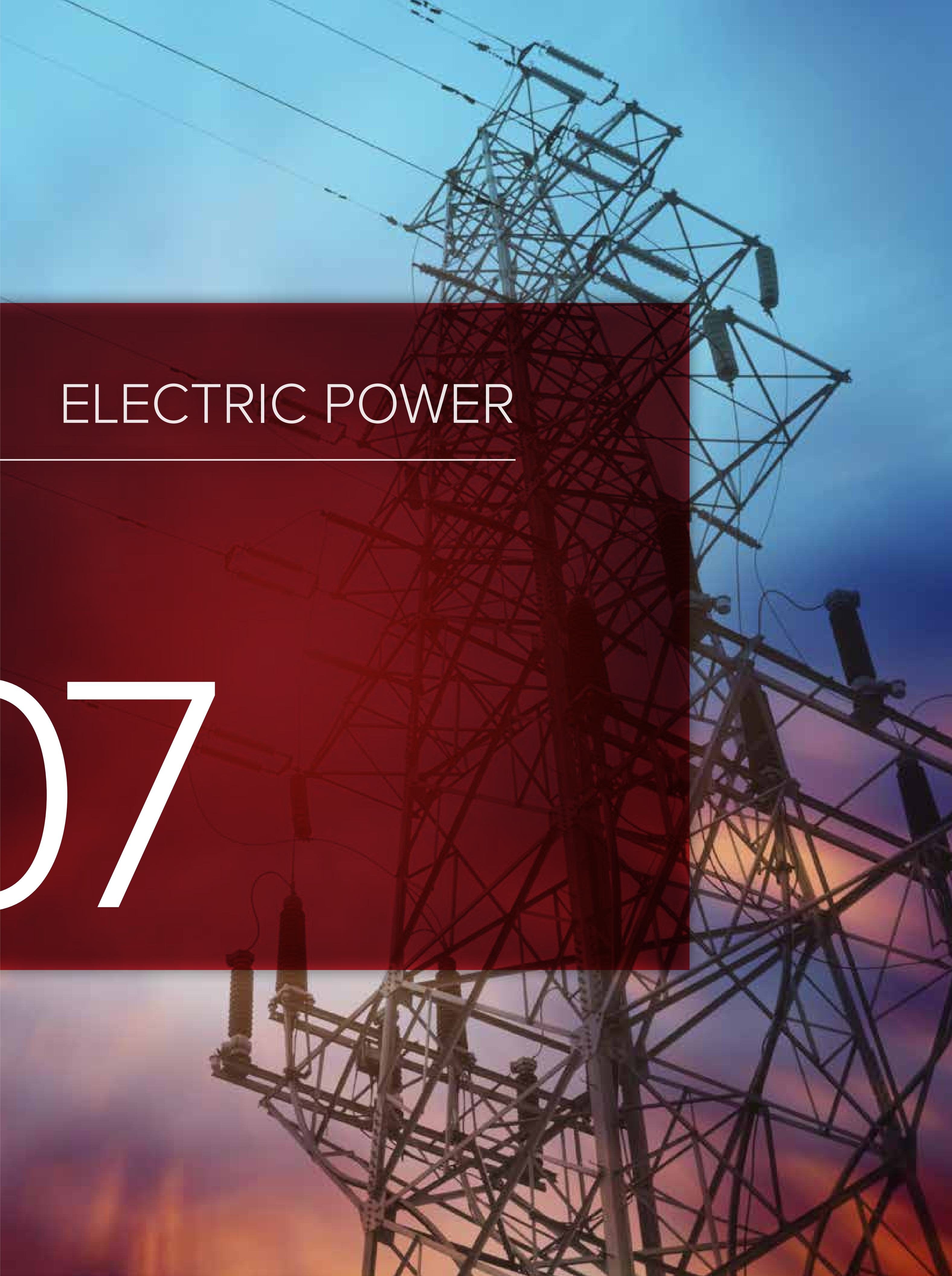
ELECTRIC POWER

07



ELECTRIC POWER

7.1 DEVELOPMENT STATUS AND PROSPECTS FOR THE ELECTRIC POWER SECTOR

7.1.1 CHINA'S ELECTRICITY DEMAND WILL CONTINUE TO GROW

The electric power sector is vital to China's economic growth and development. Chinese annual per-capita electric power consumption grew from 0.29 MWh in 1980 to 3.83 MWh in 2013.[1,2] This growth enabled China's rapid economic development, but per-capita power consumption is relatively low compared to advanced economies (Figure 7.1).[i] Per-capita energy use will rise as China grows and modernizes, despite the end-user energy efficiency measures envisioned in the Reinventing Fire Scenario.

7.1.2 CHINA'S POLLUTION PROBLEM REQUIRES THE POWER SECTOR TO SHIFT AWAY FROM COAL

China's pollution is caused by a heavy reliance on fossil fuels, particularly coal for power generation. In 2012, China's total sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions were 21.2 million tons and 23.4 million tons, respectively, of which the power sector contributed about 40%, or 8.8 million and 9.0 million tons, respectively.[3] These pollutants have serious implications for human health, the economy, and the climate. China is prioritizing reducing pollution and greenhouse gas (GHG) emissions from its energy-supply sectors.

The *U.S.-China Joint Announcement on Climate Change* targeted peaking China's CO_2 emissions around 2030 with efforts to peak earlier, while increasing the non-fossil-fuel share of primary energy to around 20% by 2030.[4] These targets were affirmed in China's Intended Nationally Determined Contributions submitted to the United Nations and subsequently confirmed as part of the Paris Agreement.[5] Achieving these targets requires further electrifying the industry, buildings, and transportation sectors and rapidly decarbonizing electric-power generation by turning from coal to non-fossil energy.

China's transition from a coal-centric electricity system will be difficult. Over the past 30 years, coal consistently produced around 80% of China's electricity. In recent years, demand for electricity increased so rapidly that new generation failed to keep up. After a series of rolling outages in the mid-2000s, China started building coal plants rapidly to meet demand and keep the grid balanced. From 2005 to 2014, annual new coal construction averaged about 59 gigawatts (GW) of capacity (Figure 7.2).[6] This resulted in an overcapacity of coal plants, which was further compounded by China's slowing electricity demand growth in recent years, further driving underutilization.[7] And with more than 51 GW of wind and solar capacity added in 2014 (more than any other country), wind and solar generators are also strained by this over-capacity issue, as limited operating hours make it difficult for generators to earn a sufficient return. China's grid operators—more familiar with operating dispatchable coal assets—curtail large amounts of renewable energy rather than ramp down coal (wind had a 17% curtailment rate in 2016 while solar was around 10%).[8] This is just one of the barriers to transitioning from a coal-centric electric power system and illustrates the need for comprehensive, long-term strategies for effective reform.

7.2 VISION AND GOALS FOR REINVENTING FIRE FOR THE ELECTRIC POWER SECTOR

In the Reinventing Fire Scenario, China has a clean, low-carbon, secure, diverse, economic, and efficient power system. To achieve this, the Reinventing Fire Scenario encompasses a three-stage transition (Figure 7.3): first, China actively reduces power sector pollutant emissions; second, China shifts away from carbon-intensive investments; and finally, China phases out the use of coal generators.

[i] *For example, annual per-capita electricity consumption in Norway, Finland, and Sweden (which enjoy plentiful hydroelectric power) is 15–25 MWh. The U.S. and Australia consume slightly less at 10–13 MWh per capita annually, while Japan, France, and the UK are much lower at 6–8 MWh.*

FIGURE 7.1: RELATIONSHIP BETWEEN PER-CAPITA GDP AND ANNUAL ELECTRICITY CONSUMPTION[9]

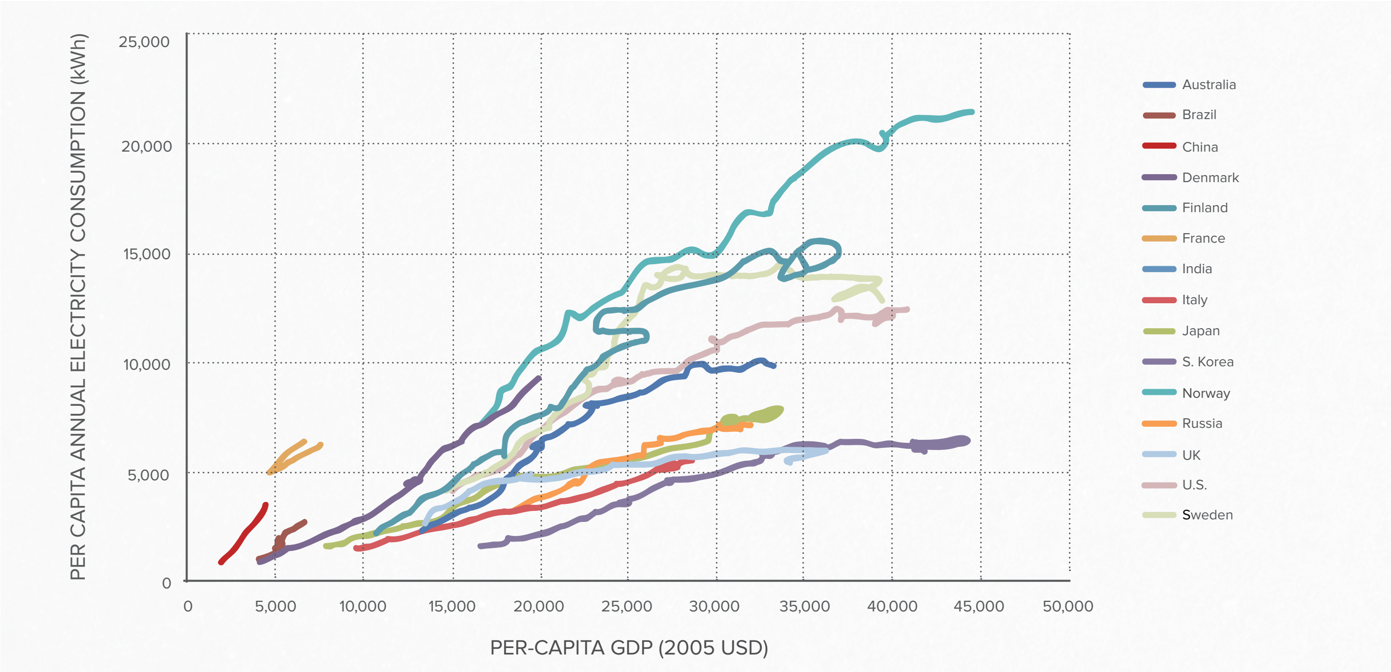


FIGURE 7.2: CHINA'S ELECTRICITY GENERATION MIX (HISTORICAL)[10,11]

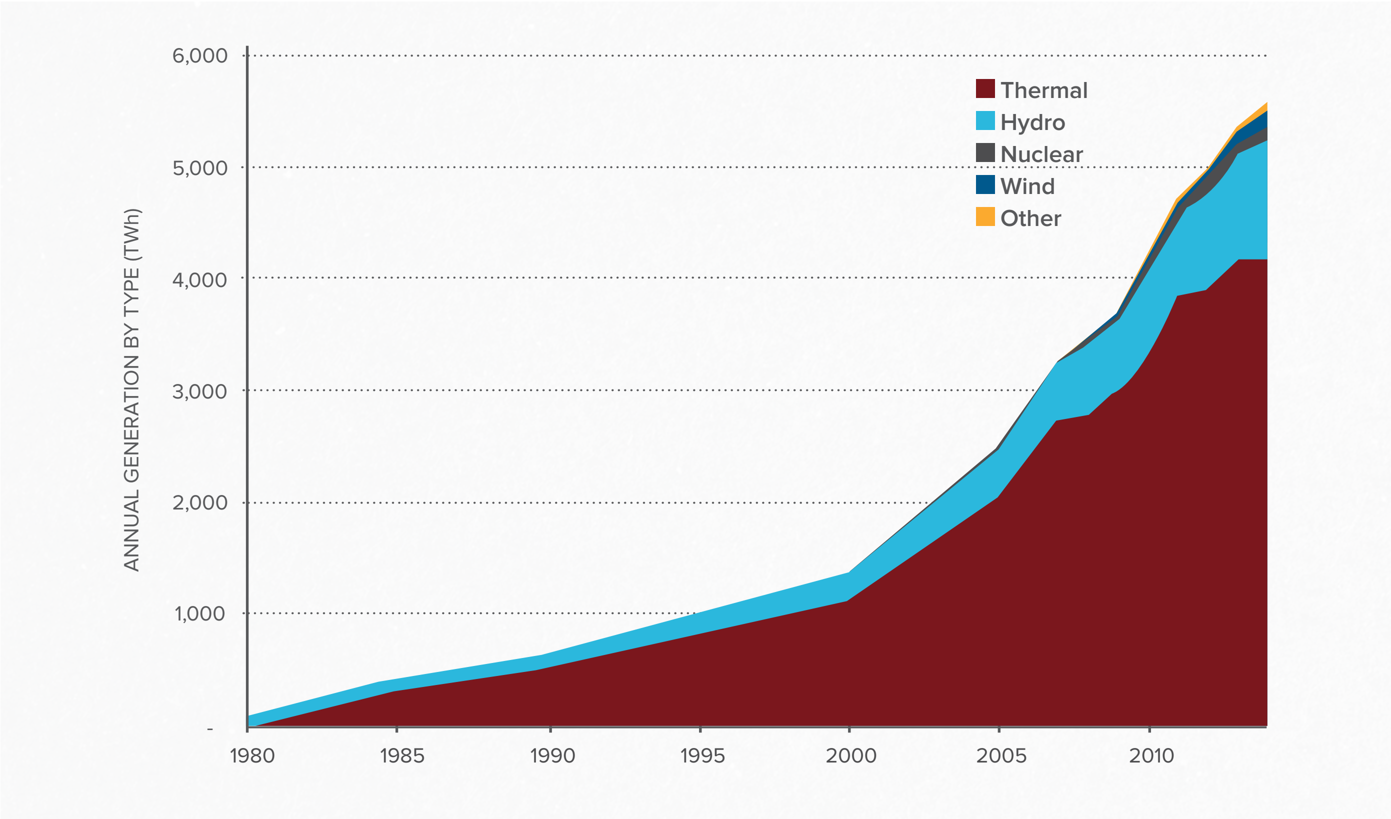
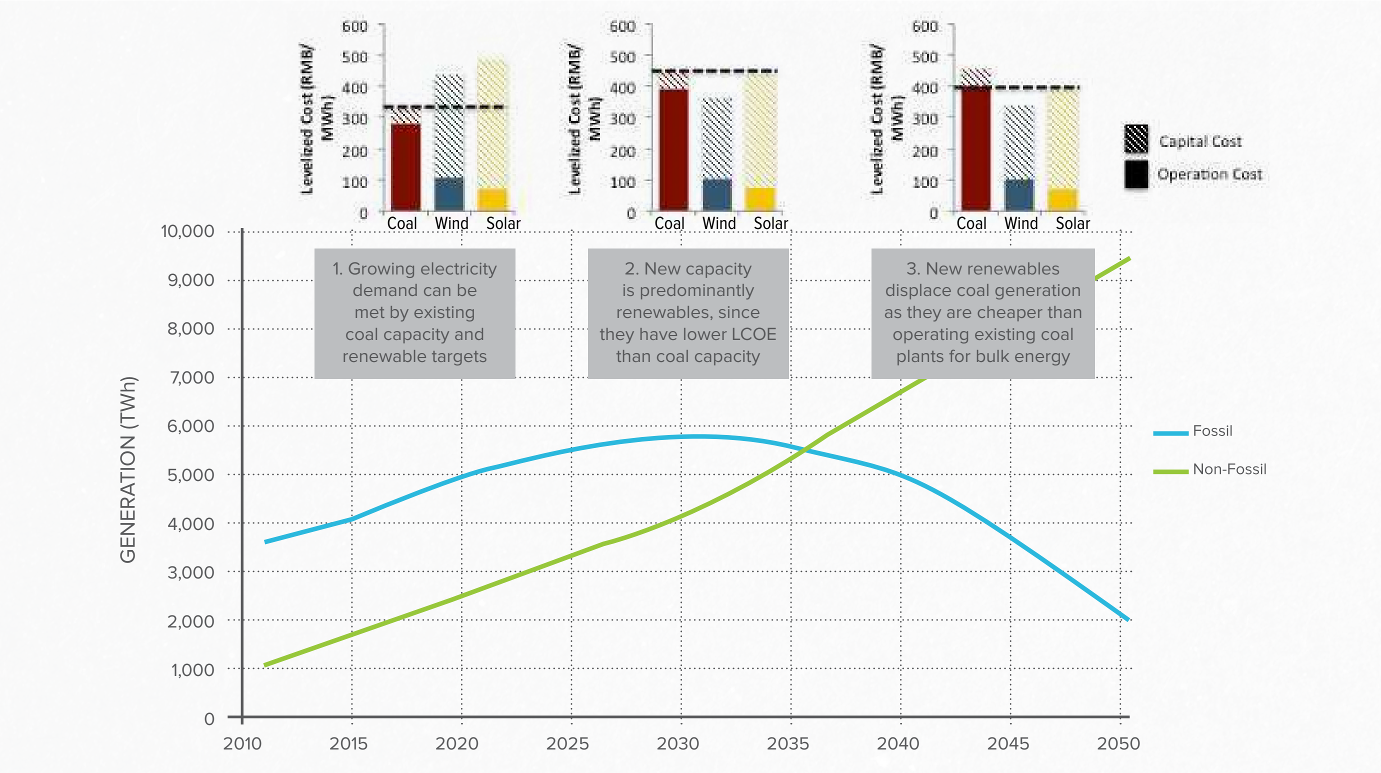


FIGURE 7.3: REINVENTING FIRE SCENARIO'S THREE STAGES FOR ELECTRIC POWER SECTOR DEVELOPMENT

2010–2050



The major targets for the power sector in the Reinventing Fire Scenario are grouped into three stages:

1. **Minimize the use of coal power**
   In the first stage, the levelized cost of electricity (LCOE) of coal-fired power is expected be lower than the LCOE of renewables until around 2025, including transmission and grid-integration costs.[ii] Until the LCOE of renewable power is lower than that of coal-fired power plants, new coal power plant construction and generation should be limited, in part to minimize future stranded coal assets. Demand-side resources (energy efficiency and demand response) can reduce peak electricity demand while better utilization and dispatch of existing generation resources can reduce emissions and generation costs. Meanwhile, grid companies should be required to demonstrate a clear need for new coal assets to receive construction permits. Enforcing and expanding SO_2 and NO_x emissions regulations increases the operating and investment cost of existing coal-fired power plants, resulting in improved air quality; accelerated retirement of old, inefficient coal plants; reduced new coal power plant construction; and improved economics for non-polluting renewables.

2. **Rapidly decarbonize supply**
   The second stage begins around 2025, when the LCOE of new wind and solar photovoltaic (PV) power is less than the levelized cost of a *new* coal plant (the first of two important turning

[ii] *Reinventing Fire: China results and cost assumptions are outlined in Appendix C. Reinventing Fire employs an* Energy Deployment Model (EDO) *to simulate China's electricity system. EDO is a capacity expansion model for China's electricity sector. In addition to basic LCOE variables, such as capital and operating costs, the EDO model also considers geographically specific transmission costs and system balancing. Accordingly, Reinventing Fire does not provide a specific date when national, renewable LCOEs achieve parity, but rather rough estimates.*

points). Coal capacity peaks and almost all new capacity from this point on will be wind or solar power. Accordingly, in the Reinventing Fire Scenario, the power sector's CO_2 emissions peak in 2030. Stage two ends around 2035.

3. **Phase out fossil fuels**
   The third stage begins around 2035, when the cost of installing, operating, and integrating new solar and wind generators is expected to drop below the cost of operating *existing* coal-fired generation (the second turning point). Coal generators are expected to transition from providing bulk energy to "firming" the grid to help further integrate renewables. In the Reinventing Fire Scenario, China's electricity demand is expected to peak around 2040 and coal-generation and power-sector CO_2 emissions will decline rapidly in this stage.

7.3 RESULTS OF REINVENTING FIRE IN THE POWER SECTOR

7.3.1 CHINA'S ELECTRICITY DEMAND GROWS

In the Reference Scenario, China's electricity demand in 2050 is expected to be roughly three times higher than 2010 levels. In the Reinventing Fire Scenario, end-use efficiency drives down electricity demand in 2050 by 2,065 TWh per year. This decrease occurs despite large increases in end-user electrification from 29% in the Reference Scenario to 41% in the Reinventing Fire Scenario.

7.3.2 POLLUTION AND CO_2 EMISSIONS PEAK EARLY UNDER REINVENTING FIRE

The power sector peaks its SO_2 and NO_x emissions around 2020–2025 in the Reinventing Fire Scenario; these emissions continue to climb for another 10 years in the Reference Scenario. By 2050, power sector pollutant emissions will be 75% lower than in the Reference Scenario, effectively returning China to emission levels not seen since 1980.[iii]

Electricity from coal and natural gas generation decreases by 42% between 2010 and 2050 in the Reinventing Fire Scenario. This decrease in fossil fuel consumption results in almost 60% lower CO_2 emissions in 2050 as compared to the Reference Scenario, with power sector CO_2 emissions peaking around 2030. In the Reference Scenario, CO_2 emissions from the power sector do not peak until between 2035 and 2040 and in 2050 are more than 1.5 times 2011 CO_2 emissions.[iv]

7.3.3 NON-FOSSIL ENERGY IS A PILLAR OF ELECTRICITY AND ECONOMIC DEVELOPMENT

In the Reinventing Fire Scenario, non-fossil-fuel generation capacity and renewable energy's share of total generation grows quickly (Figure 7.4). Renewables (including solar, wind, hydro, geothermal, biomass, and ocean energy) grow from 18% of electricity generation in 2010 to 68% in 2050. The Reference Scenario sees significantly less deployment of renewable energy, which makes up only 40% of total generation in 2050.

Nuclear power grows significantly in both scenarios, accounting for 15% of total generation by 2050 in both scenarios. Nuclear generation provides a greater share of total production in the Reference Scenario (20%) due to reduced renewable energy deployment.

In the Reinventing Fire Scenario, fossil-fuel generation evolves to support renewable energy. Existing coal generation shifts from providing baseload energy toward net load-following and firming, and only 13% of generation comes from coal in 2050. In the Reference Scenario, coal makes up 38% of generation in 2050.

Natural gas generation, due to its flexibility, provides essential flexibility generation for the grid and increases to 5% of overall generation in the Reinventing Fire Scenario. The Reference Scenario includes less variable renewable generation and natural gas, not needed for grid firming, makes up only 3% of total generation.

[iii] *Reinventing Fire Scenario China Results - see Appendix C.*
[iv] *Reinventing Fire Scenario China Results - see Appendix C.*

Chemical and pumped-hydro storage also play an important role in providing flexibility to the grid in the Reinventing Fire Scenario, with over 530 GW of storage available by 2050, as compared to only 230 GW in the Reference Scenario.

7.3.4 DISTRIBUTED AND CENTRALIZED RESOURCES ARE COMBINED EQUITABLY ON THE GRID

In the Reinventing Fire Scenario, distributed PV is the most prevalent form of distributed generation in 2050, with over 500 GW installed. This represents 28% of the total solar capacity deployed in the Reinventing Fire Scenario. The Reference Scenario has significantly less rooftop PV deployment at around 340 GW.

The potential for demand response is fully developed in the Reinventing Fire Scenario; this reduces coal capacity by 10% and natural gas capacity by 3% in 2050 compared to the Reference Scenario.

7.3.5 THE REINVENTING FIRE SCENARIO IS COST COMPETITIVE FOR THE POWER SYSTEM

Under the Reinventing Fire Scenario, the nationwide average wholesale price per kWh remains relatively low, 19% cheaper than in the Reference Scenario in 2050 (Figure 7.5). These low rates support economic growth while improving China's energy provision system.

Electricity rates in both scenarios decline in the later part of the analysis due to falling capital costs for renewable energy. While both scenarios significantly increase the share of renewable energy, the increase is far greater in the Reinventing Fire Scenario. The Reinventing Fire Scenario's economics also improve because:

- The capital cost of renewable energy decrease substantially due to economies of scale and technological advancements. By 2025, new solar and wind capacity is less expensive than building new coal capacity (including integration costs and transmission assets required to interconnect renewables).

FIGURE 7.4: CHINA'S ELECTRICITY GENERATION MIX (COMPARISON)

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

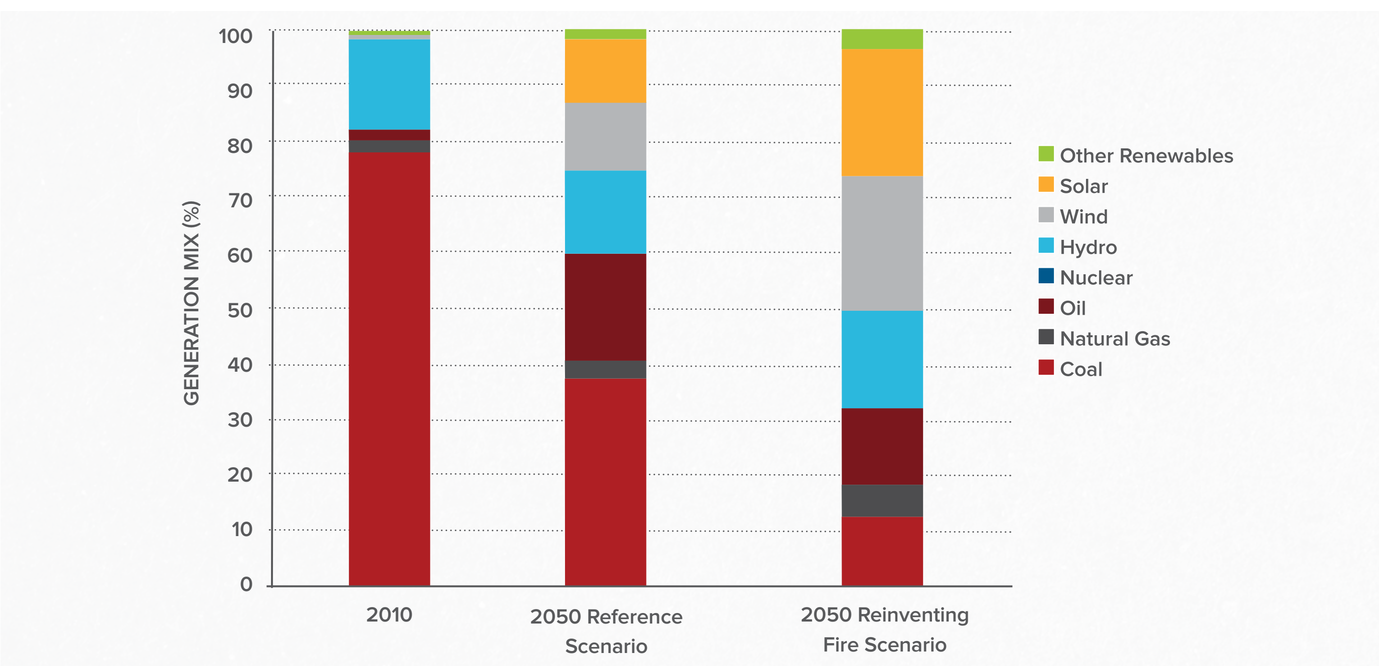
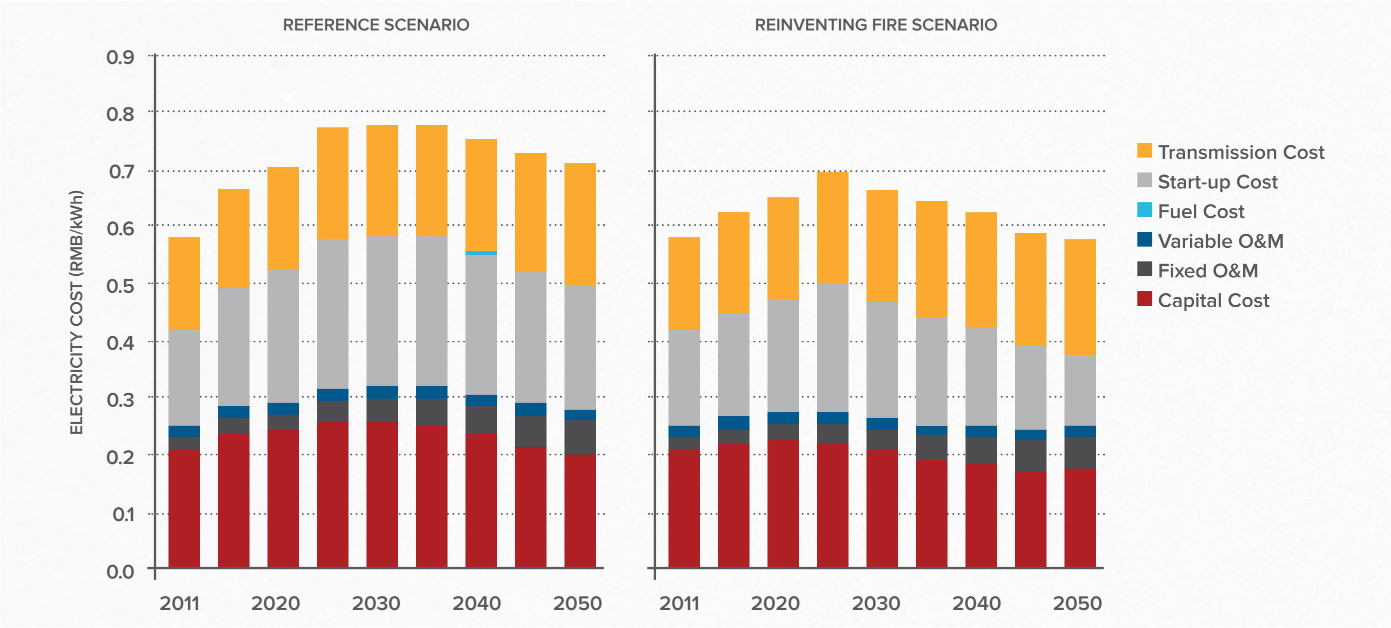


FIGURE 7.5: CHINA'S COST OF ELECTRICITY BY COMPONENT

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS[v]



[v] *Distribution costs are ignored in the analysis because it is assumed that both Reference and Reinventing Fire Scenarios will require similar distribution build out and costs.*

- Fossil-fuel prices are projected to climb steadily, making the transition to renewable generation increasingly economic.
- The potential for customer-sided resources (demand response and electric vehicles) is fully realized, deferring expensive peaking power plants and providing lower-cost ancillary services than centralized assets.

7.4 PATHS FOR REINVENTING FIRE FOR CHINA'S POWER SECTOR

Reinventing China's power sector requires substantial reforms in end-use demand and across all segments of the electricity supply chain:

- Cleaner generation,
- Advanced transmission capabilities, and
- Intelligent distribution.

For **centralized generation**, it is necessary to develop efficient, clean, and flexible resources. Coal generation transitions from providing baseload energy to supporting renewable integration. Older, less-efficient coal plants may become uneconomic and retire early. Hydropower rapidly develops in the medium term, followed by gradual growth after 2025. Nuclear power replaces coal as a provider of baseload energy and drives decarbonization in the power sector. In 2050, nuclear installed capacity reaches 220 GW. Wind power develops rapidly after 2020 and reaches 1.14 TW of installed capacity by 2050. Solar power also develops rapidly after 2025 with 1.30 TW of installed centralized solar capacity in 2050. Natural gas gradually increases to over 270 GW by 2050 and is increasingly used for renewable integration and flexibility. The need for flexibility from natural gas decreases as other forms of flexibility—such as storage and demand response—develop.

For **customer-sided resources**,[vi] it is necessary to access the potential of distributed generation, demand response, and distributed storage resources. In 2050, rooftop solar PV contributes over 500 GW of distributed electricity generation. Demand response, via automated smart home appliances, regulates power demand—reducing peak demand by 11% and new fossil generation capacity by 7%—and helps integrate an additional 1% of renewables.[vii] Electric vehicles (EVs) and other forms of distributed battery storage play an increasingly important role. EVs rise to 289 TWh of demand in 2050. Through smart charging and vehicle-to-grid (V2G) programs, EVs help reduce the system's load factor and smooth distributed PV locally, improving integration.

For **power transmission and distribution**, an intelligent and interconnected grid is required to effectively integrate and coordinate centralized generation and customer-sided resources. The grid continues to expand, connecting regions, and grid companies plan and operate the grid with a wider geographic focus. Microgrid construction increases, resulting in greater resiliency. The grid begins coordinating centralized energy resources with distributed energy resources, regulating supply and demand for optimal system efficiency. This is enabled by a wide deployment of information and communication technology on the grid. Eventually, software becomes just as important as hardware. The two infrastructures begin to comingle—electricity and communications networks run in parallel to maximize the network's connectivity. This leads to a power grid that is a platform of universal connection, where communication and electricity between various providers is coordinated seamlessly.

Together, these three reform pathways help China achieve a clean, low-carbon, secure, and diverse power system that is both economic and efficient.

There are numerous barriers to realizing a clean and efficient power system. This effort requires not only new technologies and other grid hardware, but also soft reforms, including policy measures, planning, and information technologies.

A discussion of each power system pathway's barriers and solutions to those barriers is included here, as is a discussion of barriers and solutions that cut across all three pathways.

7.4.1 PATHWAY #1: REINVENTING CHINA'S POWER GENERATION

Actively develop efficient, centralized, clean power resources

To effectively develop the power sector, China minimizes demand while also shifting from coal to cleaner, non-fossil resources (Figure 7.6).

In the Reinventing Fire Scenario, China first minimizes its demand growth by improving end-user efficiency and promoting a structural shift from energy-intensive

[vi] Customer-sided resources include any electricity system asset that exists at a customer's premises, including distributed generation, distributed storage, and demand response.
[vii] This was determined by running the EDO model for the Reinventing Fire Scenario with and without demand response and comparing the results. The increase and decrease of projected capacity by the model was attributed as a benefit of demand response implementation.

manufacturing to an economy based on high-value services (see Industry chapter). By treating energy efficiency as the first energy resource, China reduces its demand for electricity by roughly 6,000 Twh annually by 2050 compared to the Reference Scenario. China produces electricity in a cleaner, more flexible way. China minimizes the impacts of coal by adopting energy efficiency and demand response, prioritizing the most efficient coal plants, developing non-fossil generating plants in accordance with current commitments, and regulating coal power plant pollution emissions. These measures reduce coal generation by 2,600 TWh annually in 2050 compared to the Reference Scenario. The remaining 490 GW of coal generation capacity in the Reinventing Fire Scenario is more efficient than today's coal power plants and operates with greater flexibility (to support high amounts of renewable generation). To offset coal, China develops low-carbon generation sources such as hydro, nuclear, wind, solar, and natural gas, with renewable power contributing 68% of electricity generation in 2050 (Figure 7.7).

This requires China's generation fleet to grow to roughly 4.9 times its 2010 generating capacity and to include over 3.75 TW of non-fossil generating capacity (Figure 7.8). These resources will be geographically diverse and each region will have a unique generation mix (Figure 7.9).

FIGURE 7.6: CHINA'S PATHWAY TO A CLEANER ELECTRICITY GENERATION MIX

2010 AND 2050, REFERENCE VS. REINVENTING FIRE SCENARIOS

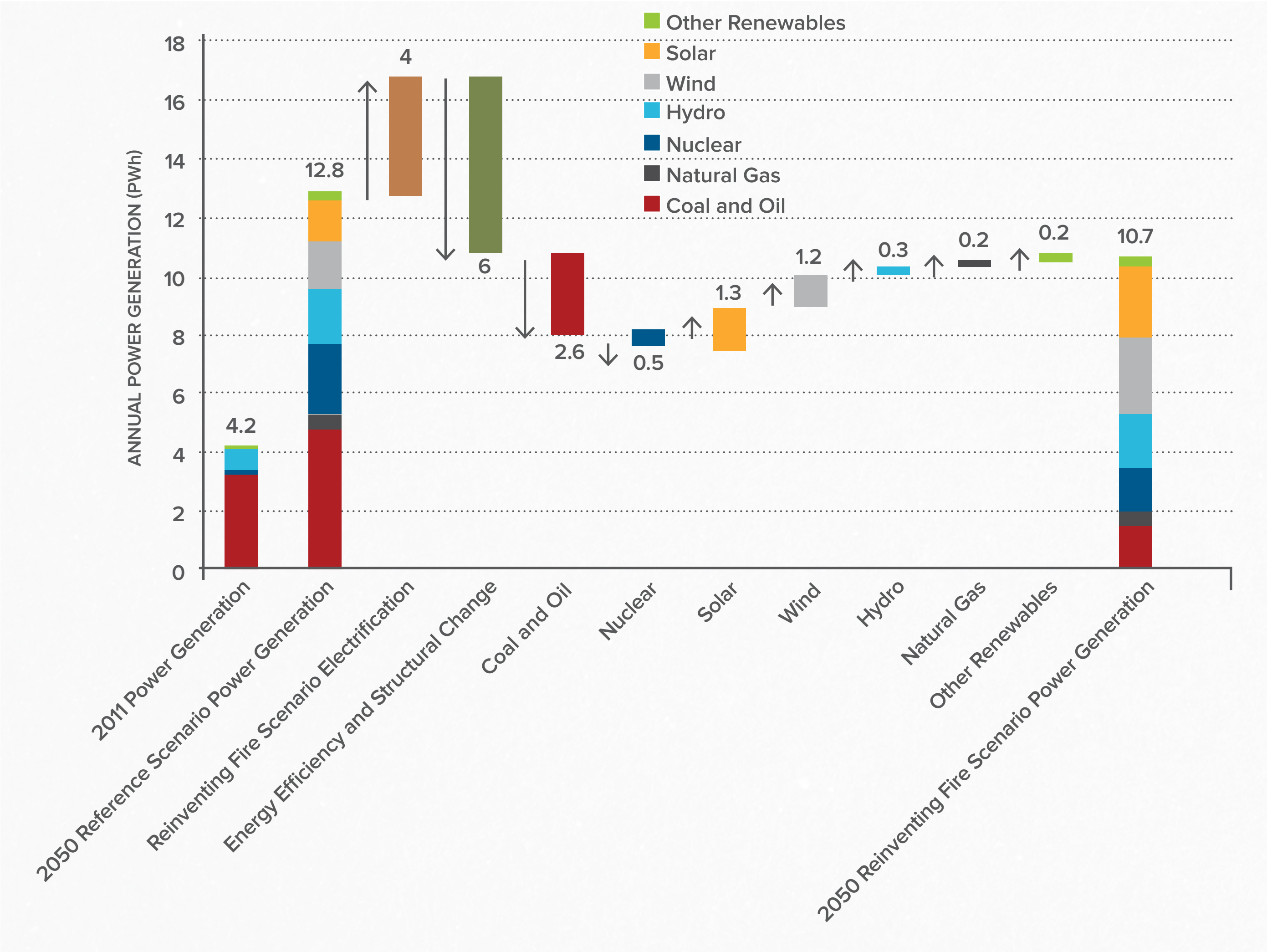


FIGURE 7.7: CHINA'S ELECTRICITY GENERATION MIX (TRENDS)

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

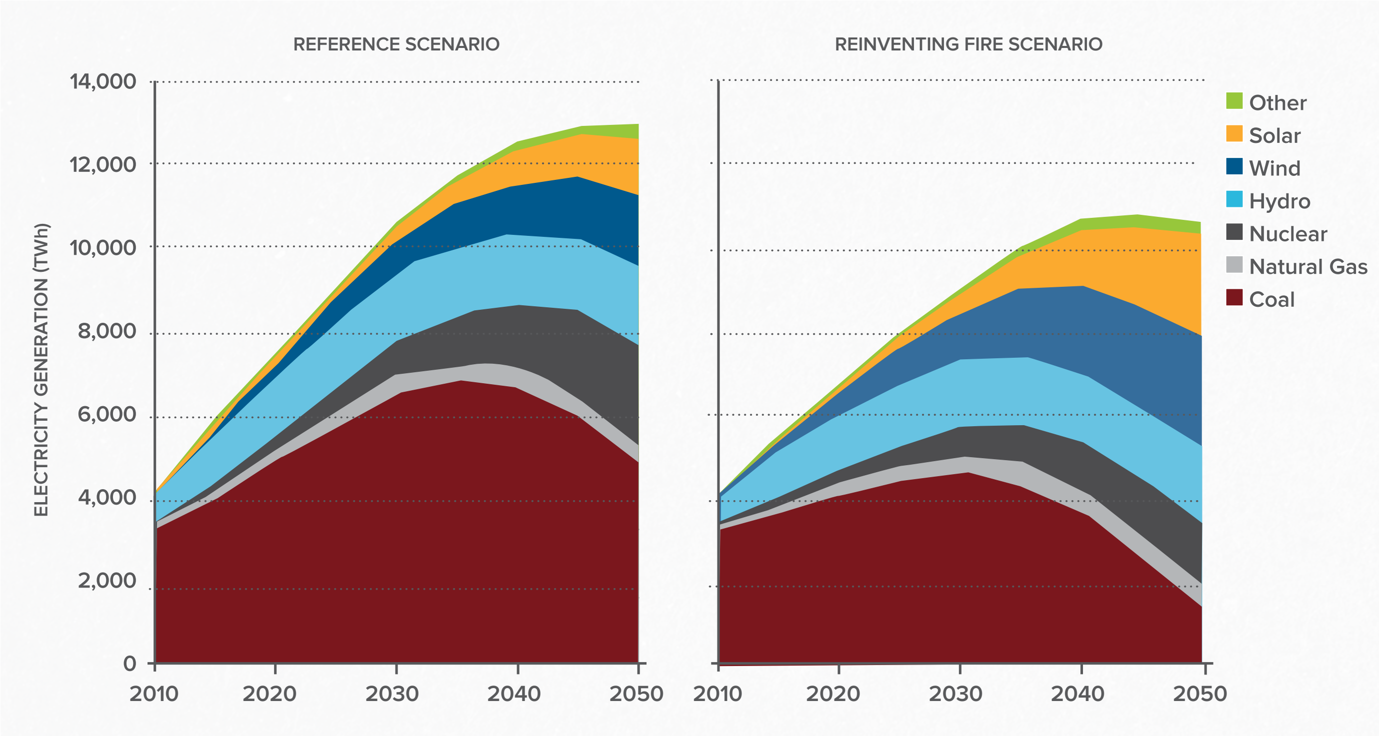


FIGURE 7.8: CHINA'S INSTALLED GENERATING CAPACITY

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

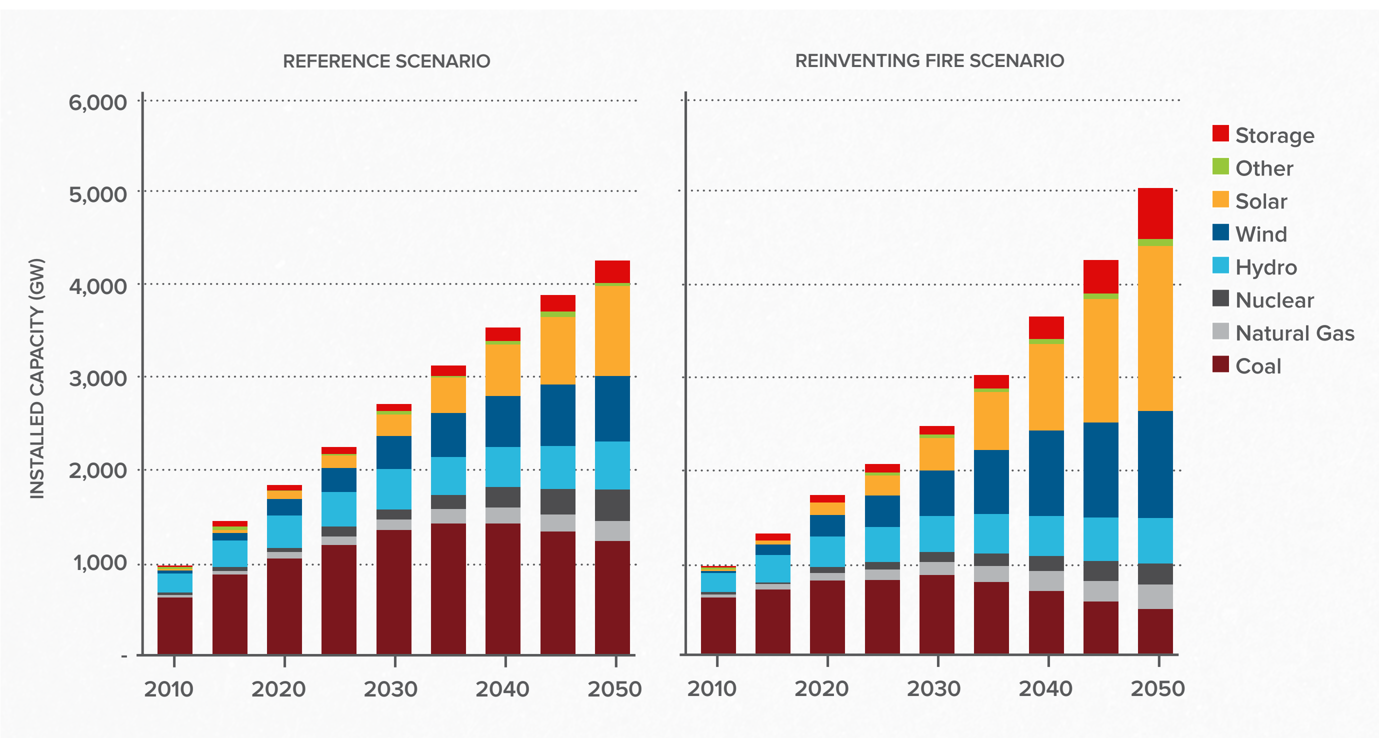
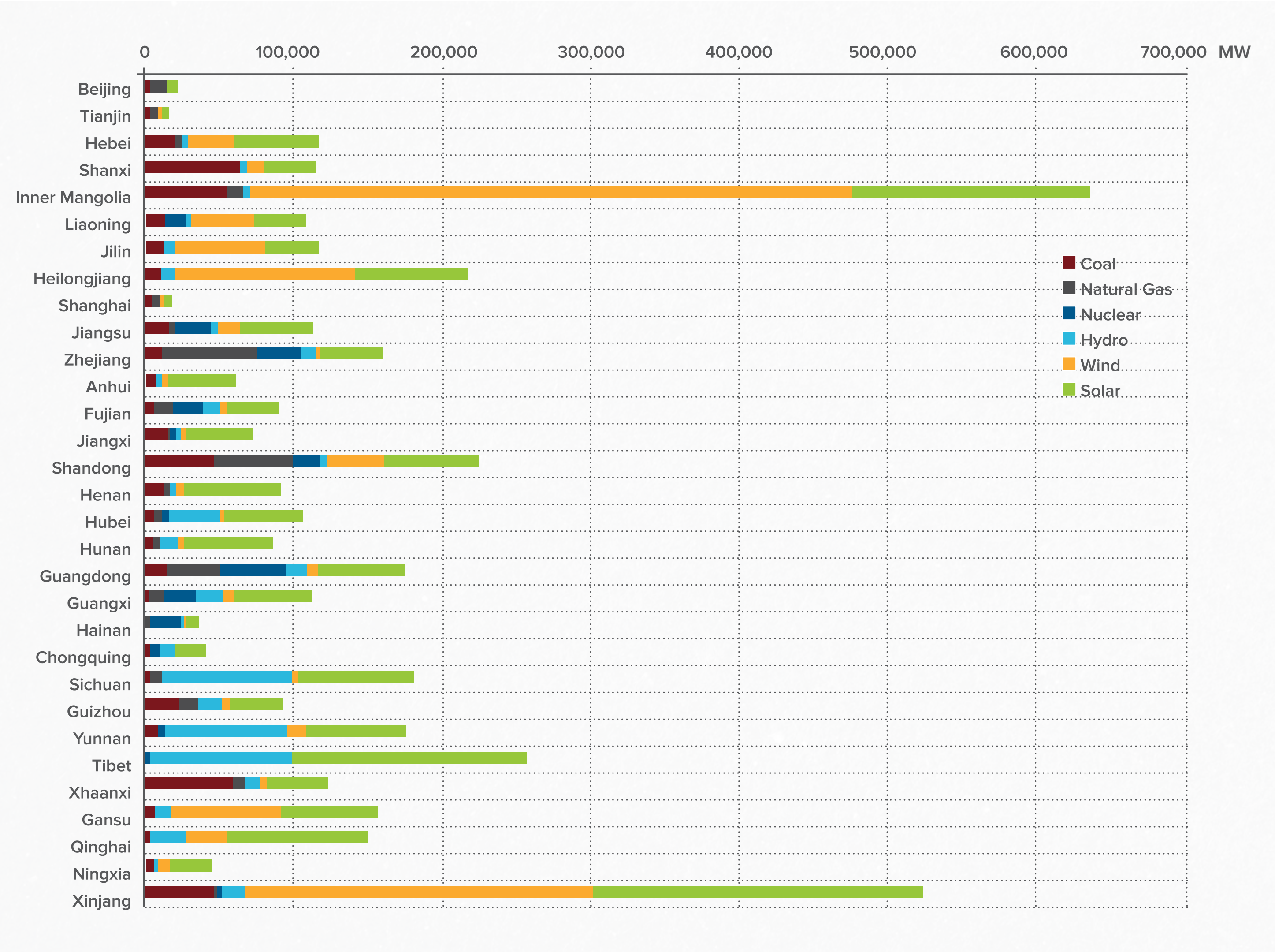


FIGURE 7.9: CHINA'S REINVENTING FIRE SCENARIO INSTALLED CAPACITY BY CITY/REGION

2050



FIGURES 7.9A–7.9F: CHINA'S REINVENTING FIRE SCENARIO INSTALLED CAPACITY BY CITY/REGION PER GENERATION TYPE

2050

(1) Develop efficient and clean coal power resources

In the Reinventing Fire Scenario, coal generation capacity peaks around 2030, 10 years earlier than in the Reference Scenario. This is driven by curbing new coal capacity development and immediately requiring existing coal plants to minimize pollutant emissions. After 2030, non-fossil generation accounts for almost all new installed capacity. Around 2035, electricity demand growth slows down and the LCOE of new renewables (including integration costs) drops below that of existing coal generation. This leads to a reduction in coal generation and capacity. The Reinventing Fire Scenario has 490 GW coal capacity online in 2050, which is 750 GW less than the Reference Scenario. The remaining coal plants operate in a flexible manner to support variable renewable generation.

- **Minimize the construction of new coal power facilities.**
  China is overdeveloping its coal generation fleet. The national average annual operation hours of thermal power plants in 2014 was 4,700 hours, 314 hours lower than in 2013.[12] This fell further to 4,165 hours in 2016.[13] The development of new coal power facilities is minimized in the Reinventing Fire Scenario, while the retirement of old, polluting coal power plants in the east is accelerated in the near term. Employing economically viable measures—end-user energy efficiency, demand response, economic dispatch,[viii] and less renewables curtailment—reduces the need for new coal power plants. Requiring grid companies to undergo a thorough planning process that demonstrates the necessity of new coal power assets also minimizes new coal power facilities and prevents stranded assets.

- **Require all coal power facilities to comply with pollutant emission standards before 2020.** By strengthening and geographically expanding regional pollutant emissions standards for coal power facilities and promoting super-low or near-zero SO_2, NO_x, and particulate emission technologies, China reduces overall emissions of these pollutants from power plants. This helps address the pollution-related health crisis in the near term.

- **Enhance the flexibility and efficiency of coal power facilities by optimizing design; increase the efficiency of coal power facilities operating under low minimum loads.**
  Coal power plants are not typically operated in a flexible manner. When operated flexibly, plants experience efficiency losses, increased emissions, and increased wear and tear.[14] But building or retrofitting a coal plant with flexibility in mind reduces these impacts and can enable a more-efficient coal fleet overall.[15] To realize the Reinventing Fire Scenario, China could require all new facilities to comply with standards for flexibility and existing, efficient plants could be encouraged to shift toward a more-flexible style of operation. This flexibility will be supported by corresponding market and dispatch reforms (discussed in section 7.4.3).

(2) Accelerate the development of hydropower resources

Hydropower is a mature technology that can be deployed economically at scale. For this reason, China will rely upon hydropower as its primary renewable energy asset in the near and medium terms. In the Reinventing Fire Scenario, installed hydropower capacity grows significantly, from 200 GW in 2010 to 400 GW in 2030. Development then slows, reaching 500 GW in 2050.[ix] Such development must be achieved in an environmentally-compatible way. Neither the Reference nor Reinventing Fire Scenario attempts to evaluate the social cost and political implications of ecological preservation, inhabitant resettlement, or drainage-basin management on China's hydropower potential and development.

[viii] *Economic dispatch is a grid operation paradigm where the short-term determination of the optimal output of a number of electricity generation facilities required to meet the system load at the lowest possible cost, subject to transmission and operational constraints.*

[ix] *Reinventing Fire Scenario China Results and Inputs – see Appendix C.*

(3) Develop wind power

China has plentiful wind resources. Wind power will be one of the principal assets developed in China in the Reinventing Fire Scenario, growing from 30 GW of installed capacity in 2010 to 500 GW by 2030 and 1,140 GW by 2050. In the Reference Scenario, only 720 GW of wind energy capacity is installed by 2050. Onshore wind is the primary focus in the near and medium term, with some deployment of offshore wind (including intertidal resources). These developments will be mainly large, utility-scale deployments. In the long term, the focus will be on developing slow-velocity wind resources in northeast, northwest, and mid-north China,[x] continuing to build out resources along the eastern coast and central areas, and a steady increase in offshore wind developments.

(4) Develop solar power resources according to regional availability

In both scenarios, solar power is rapidly deployed, growing from less than 1 GW in 2010 to providing 22% of all generation in 2050 in the Reinventing Fire Scenario. This capacity is divided between concentrating solar power (CSP) and utility-scale PV (for relative shares, see Figure 7.10). In the Reinventing Fire Scenario, national solar power capacity reaches 350 GW by 2030 and 1,800 GW by 2050 vs. 960 GW by 2050 in the Reference Scenario.

(5) Efficiently develop secure nuclear power resources

In the Reinventing Fire Scenario, nuclear power develops close to load centers with limited potential to develop other, non-fossil energy resources (e.g., the eastern coast, which has limited wind and solar potential). Nuclear power plays an essential supporting role in China's low-carbon power system in both scenarios as it provides stable baseload energy. In the Reference Scenario, China builds more nuclear capacity, growing from 11 GW in 2010 to 350 GW in 2050. In the Reinventing Fire Scenario, national nuclear capacity reaches 100 GW by 2030 and 220 GW by 2050. Less nuclear capacity is required in the Reinventing Fire Scenario due to decreased end-use demand through efficiency, and greater resource flexibility that supports the increased integration of variable renewable generation.

(6) Strategically develop natural gas flexibility

Natural gas power plants can ramp easily and can play an important role as the adoption of renewables increases in China. Moreover, combustion of natural gas results in approximately half the CO_2 emissions as the combustion of coal.[16] However, natural gas power is unlikely to have the same prominence in China as in the U.S. given the relative scarcity of domestic natural gas in China (in 2014, China had 155 trillion cubic feet of proven reserves while the U.S. had 338 trillion cubic feet).[17] This could change if China is able to economically exploit its shale gas resources, but the use of significant unconventional gas resources is not explored in this report. In the Reinventing Fire Scenario, natural gas generation capacity reaches 150 GW by 2030 and 270 GW by 2050. There is less deployment in the Reference Scenario, with installed capacity reaching only 210 GW by 2050.

Barriers:

Renewables are not yet cost competitive against traditional thermal assets throughout all of China. China's coal generation capacity is rapidly expanding in spite of China's goals of reducing pollution and limiting CO_2 emissions. Additionally, integrating high levels of variable renewables requires greater flexibility from the whole power system, including non-renewable generating assets.

Solutions:

Limiting Coal Capacity and Generation:

- Ensure that new construction of coal plants is the last alternative to meet demand growth. Other demand and grid measures (detailed in sections 7.4.2.4 and 7.4.3.6), such as demand response (DR), integrated planning, and storage and transmission build out, can balance supply and demand more cost effectively. Generation-side measures, such as increasing capacity factors and plant efficiency, can also reduce the need for

[x] *These three regions are dubbed the "Three Norths" in Chinese.*

new coal plants. Including environmental costs in the plant construction permitting process can also limit additional coal capacity and generation and promote the construction of efficient coal plants. Additionally, older coal power facilities should not be protected from early retirement and any non-compliant plant should shut down.

- Implement stricter emission standards for coal power plants. In 2014, the Chinese government announced a super-low emission requirement for coal power plants in eastern regions.[18] This requires regulatory agencies to monitor emissions in real-time and penalize violators. Extending the super-low emission requirement to the rest of the country will protect the less polluted western regions of China.

- Introduce CO_2 emissions standards or CO_2 emissions reduction targets after super-low emission standards have been achieved. CO_2 emissions can be efficiently controlled via market-based policies, such as carbon pricing or emissions trading systems (ETS) like the one currently being scaled in China. This will incentivize power plants to continuously improve efficiency and adopt lower-carbon technologies.

Improve Generation Flexibility:

- Fully exploit the ramping capability of generation plants. Chinese utilities can use international experience with advanced coal power technology to improve operational flexibility. In the U.S., the ramping capabilities of coal power facilities increased by 33% from optimization and retrofits.[19] Maximizing other sources of ramping capabilities, such as hydro or storage, will also improve the grid's ability to integrate more renewable energy and reduce renewable curtailment. These retrofits will be economically incentivized by some of the market mechanisms proposed in Section 7.5, which increase compensation for flexibility in China's electric power sector.

Support Renewables Generation:

- Continue supporting renewables generation via feed-in-tariffs (FITs). FITs have contributed to the rapid growth of renewables in China but the national FIT program can be improved.[20] Currently, FIT values are not regularly adjusted. As the cost of renewables decline, regular adjustments are necessary to ensure that the government and consumers do not overpay to support renewables. FIT should also be adjusted by geography so that new renewable generation is located where demand is highest and/or where flexibility resources are adequate to accommodate renewables' intermittency and reduce curtailment.

7.4.2 PATHWAY #2: REINVENTING CUSTOMER PARTICIPATION IN THE GRID

Expand the use of efficient, clean, and flexible distributed energy resources

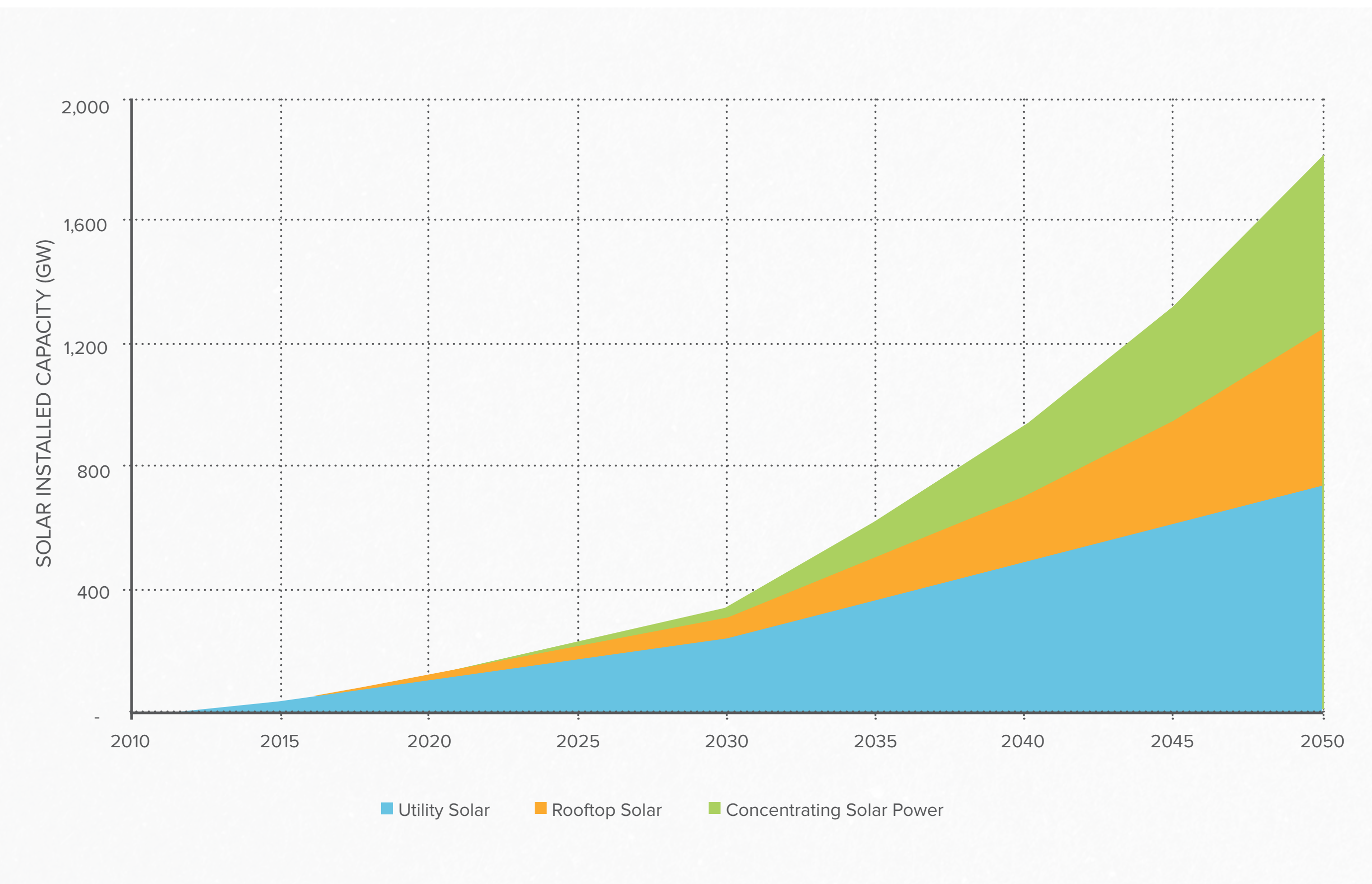
Historically, the electric power grid was managed using supply-side resources. Now customer-side options can play an important role in grid management due to advancements in distributed renewables, low-cost storage, and demand response. Grid operators can utilize energy resources located at customer premises to help meet demand growth and integrate centralized variable-renewable generators by aligning supply and demand on the electricity system. Leveraging these distributed energy resources will result in a more-resilient, lower-cost electricity system.

(1) Aggressively develop distributed PV power resources

Due to the rapid decline in solar costs by 2050 (levelized module costs are projected to be half of what they were in 2014), distributed PV reaches 504 GW by 2050 in the Reinventing Fire Scenario, contributing 28% percent of total solar generation capacity (Figure 7.10).

FIGURE 7.10: CHINA'S REINVENTING FIRE SCENARIO INSTALLED SOLAR CAPACITY BY TYPE

2010–2050



CASE STUDY 7.1: SOLAR COMMUNITIES IN LANCASTER, CALIFORNIA (U.S.)[21]

Lancaster, California, is on its way to becoming a net-zero-energy city by implementing aggressive distributed PV policies and programs. Some highlights include:

- The City Council voted in 2014 to adopt a residential solar mandate, making Lancaster the first city in the U.S. to require all new residential construction include solar power.
- The city launched Lancaster Choice Energy, its own community choice aggregator (similar to a municipal utility) in May 2014. This type of setup allows cities and counties to aggregate the buying power of individual customers (customers must opt in) and secure alternative-energy supply contracts on a community-wide basis.
- Solar Lancaster, launched in 2010 in partnership with SolarCity, offers affordable solar financing to homeowners, business owners, and nonprofit organizations. The program also offers customers discounted solar pricing and custom solar system designs and monitoring.
- The city has been successful, procuring and producing 54.4% of its consumed electricity via renewable sources at the end of 2014. Five city facilities, including Lancaster Municipal Stadium, City Hall, and the Lancaster Performing Arts Center, have signed power purchase agreements to off-take solar energy from a 1.45-megawatt project. The project is projected to save the city an estimated $6 million over 15 years.

(2) Extensively develop demand response

By having customers shift their energy use from peak demand periods to times when energy is readily available, China can increase its dispatch efficiency and reduce the amount of capital investment necessary for resource adequacy. Significant demand response (DR) potential exists (over 11% of peak demand reduction and an estimated 34 GW in the Reinventing Fire Scenario in 2050) to help balance the grid by adjusting customer demand.

Capturing the full 11% of peak demand reduction and estimated 34 GW of DR requires enhanced information and communications technology. Smart grid deployment allows grid companies to relay communications directly to customers, coordinating home and industrial appliances with the needs of the grid. By 2050 in the Reinventing Fire Scenario, many household appliances—including air conditioners, refrigerators, washing machines, hot water heaters, and other, smaller appliances—will connect to the smart grid and respond automatically to real-time signals.

As DR technology improves, appliances can also provide ancillary services beyond simple peak reduction and coordinate loads in order to smooth out variations in rooftop solar.

CASE STUDY 7.2: THE POWER OF DEMAND RESPONSE IN THE U.S.

PJM Interconnection, the largest electricity market in the U.S., has used market mechanisms since 2007 to incentivize end users to provide demand response (DR). After a significant redesign of their market rules for DR, PJM procured 13,306 MW for delivery in 2011–2012, or 10.5% of their 2010 peak load.[22] PJM reached this scale of DR resources largely due to service providers aggregating numerous end users. These service providers participate in capacity and energy markets on the customers' behalf and provide them with a share of the earnings. Utilizing DR is often cheaper than operating peaking plants and is even more cost effective if it defers building new peaking generation or improves grid stability. Estimates show that a 3% peak-load reduction in PJM's Mid-Atlantic states could reduce the electricity market price by an average of 5–8%.[23] To achieve these potential savings, grid operators are motivated to procure large amounts of DR. The PJM Interconnection provided around $700 million in revenue to DR providers in 2014, representing a large opportunity for new entrants to the electricity provision system.[24]

(3) Develop EV charging platforms to integrate EVs as a grid resource

In the Reinventing Fire Scenario, 80% of light-duty vehicle kilometers traveled are electric, demanding over 289 TWh of electricity annually (see Transportation chapter).[xi] When these vehicles are connected to the grid, they can effectively operate as grid-connected battery systems and can supply roughly one-quarter of all grid-connected chemical storage capacity in 2050.[xii] If properly coordinated, EVs become a grid asset instead of a grid liability. In the Reinventing Fire Scenario, 60% of EVs will participate in smart charging, which means their batteries charge when there is a surplus of wind and solar energy on the grid. In addition, 50% of smart charging vehicles will perform vehicle-to-grid (V2G) services, whereby EVs, when plugged in, discharge electricity to help keep the grid in balance during small misalignments in electric supply and demand.

To enable this vision, smart charging stations will be available across all Chinese cities. Residential, commercial, and industrial buildings will need to be equipped with smart charging systems. By having widely available charging infrastructure, EVs become a more viable transit option and give grid operators the ability to regionally balance supply and demand.

Barriers

Institutionally, China lacks a distinct focus on the development of demand side resources (including distributed generation, demand response, and distributed storage). The design of wholesale and retail electricity pricing does not fully reflect real-time generation and transmission costs, resulting in inadequate incentives for grid companies or customers to develop demand-side resources or change their behavior. The lack of intelligent end-user appliances prevents customer loads from responding to signals sent from the grid. EVs will soon be capable of both accepting power from and discharging power to

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[xi] A light-duty vehicle is a Chinese classification for vehicles intended to carry passengers and with curb weight of no more than 3,500 kg and fewer than nine seats (i.e., passenger vehicles).

[xii] Chemical storage capacity refers to the instantaneous power output of any energy storage device interconnected to the grid that converts electricity into chemical potential for storage, then converts that potential back into electricity (i.e., batteries).

CASE STUDY 7.3: ELECTRIC VEHICLES HELP THE GRID

By 2050, passenger electric vehicles (EVs) alone will demand 3% of China's electricity. If this growth is not effectively coordinated with the grid, charging EVs could incur substantial costs. By using information technology to coordinate when EVs charge their batteries (also known as smart charging), a study in PJM's territory showed smart charging could reduce grid energy costs by 45% compared to unmanaged charging, representing an estimated a $350 million savings annually for the grid.[25]

Smart charging can help reduce the cost of EVs as well, spurring adoption. A study conducted by the U.S. Department of Defense investigated V2G technology, which would allow EVs to communicate with the grid in real time, charging or discharging power as needed. The study found that an EV sedan in Southern California Edison's territory could generate $210 per month in 2011 by participating in frequency regulation markets. This revenue could reduce monthly lease fees for an EV sedan by an estimated 72%, which would motivate more consumers to adopt electric vehicles.[26]

Another pilot project, initiated in 2013 at Los Angeles Air Force Base, involved 40 EVs, of which half participated in a V2G program. The pilot project found that EVs providing frequency regulation services to the California Independent System Operator could expect a monthly income of $102–122.[27]

TABLE 7.1: REINVENTING FIRE SCENARIO DEMAND-SIDE RESOURCES QUANTITY AND BENEFITS

<table>
<tr><th>DEMAND-SIDE RESOURCES</th><th>QUANTITY</th><th>BENEFITS</th></tr>
<tr><td>Distributed PV</td><td>• 504 GW (12% of total generating capacity in 2050 in Reinventing Fire Scenario)</td><td>• Peak solar availability aligns with periods of high demand
• Increases grid resiliency
• Reduces capital costs by deferring some grid upgrades and new centralized generator installation in the short term[xiii,28]</td></tr>
<tr><td>Demand Response (DR)</td><td>• Reduces the need for nearly 34 GW of fossil fuel capacity in 2050 (roughly 1% of total capacity in 2050 in the Reinventing Fire Scenario)</td><td rowspan="2">• Reduces capital costs by deferring grid upgrades and new centralized generator installation[29]
• Reduces system operating costs by nearly 140 billion RMB annually[30]
• Increases the utilization of existing assets[31]
• Reduces the integration costs of wind and solar[32]
• Reduces wind and solar curtailment[33]</td></tr>
<tr><td>Electric Vehicles (EVs)</td><td>• Equivalent to 79 GW energy storage that connected to the grid[xiv]</td></tr>
</table>

[xiii] For example, the Western Wind and Solar Integration Study estimated cost savings of $310,000 to $450,000 per MW annually for the high wind penetration case when using demand response to balance the system for the small number of hours that extreme events occurred during the course of the year rather than maintaining increased spinning reserves for the entire year (GE 2010).

[xiv] Reinventing Fire China transportation sector report.

CASE STUDY 7.4: DEMAND-SIDE RESOURCES IN NEW YORK[34]

By initiating a regulatory change process called Reforming the Energy Vision, New York State is trying to allow demand-side resources, such as distributed PV, demand response, and electric vehicles, to participate equitably in the power markets and enhance the efficiency and cost effectiveness of the system. In New York, peak load grows 0.83% annually. Building additional power plants requires additional investment in dispatchable generators (typically natural gas) and results in lower utilization of New York's generation fleet. New York State determined that using demand-side resources to reduce the top 100 hours per year of demand could defer system upgrades and reduce energy costs, resulting in an estimated annual savings of $1.2–1.7 billion. The New York Public Service Commission estimated that the annual benefit of merely increasing system utilization from 55% (the current rate) to 56% could be as high as $150–219 million.

the grid, thus increasing system flexibility. However, little support for integration of EVs with the grid has materialized.

Solutions

Distributed generation (DG):

- Take steps to implement existing DG policy, ensuring distributed PV power is effectively integrated onto the grid.[xv]
- Further promote and utilize smart meters to provide more accurate measuring and payment for DG.
- Define a clear interconnection standard for distributed generation integration, ensuring equipment interoperability and potentially lowering equipment costs.
- Promote the integration of PV into all newly constructed buildings to fully utilize available rooftop space.
- Apply a dynamic tariff for distributed generation that varies by time of generation, which improves the interaction between distributed generation and the grid.

Demand response potential for end-user appliances:

- Encourage appliance manufacturers to actively develop end-user technology (such as household appliances or industrial equipment) that communicates with the grid. Government-supported standards-setting bodies should actively work with the power sector, the ICT industry, and manufacturers to develop a compatible, interoperable communication protocol.
- Provide incentives for household- or enterprise-level demonstration projects to pilot smart appliances that promote advanced DR technology.
- Apply dynamic tariffs for end users. Replace conventional peak and off-peak pricing schemes and block rates with a dynamic tariff system that adjusts end-user rates according to real-time supply and demand.
- Procure firm DR resources. Government requirements for utilities to procure demand-

[xv] *China released a set of policies supporting and regulating distributed PV industry in 2014, including: National Energy Administration, Further implementing distributed PV generation, Facilitating demonstration and deployment zone of distributed PV generation, etc.*

side resources to fulfill resource adequacy requirements will help procure firm resources that complement indirect influence on customer demand through dynamic pricing. For example, utility companies can substitute the construction of new gas-fired peaking plants with automated DR from commercial air conditioning systems or aggregated EVs. In the U.S., utilities secure firm demand response resources by paying service fees to end-users or by allowing demand-side resources to bid into markets and compete for capacity and energy payments.[35]

Distributed energy storage resources (including EVs and distributed battery systems):

- Develop a software platform for EV and distributed battery power management. This will coordinate EV and battery charging and discharging with the real-time balance of supply and demand.
- Introduce smart EV demonstration projects to prove technical feasibility and to develop secure solutions for EV charging and discharging.
- Introduce an EV charging tariff nationwide to incentivize EV owners to practice smart charging and participate in V2G programs.
- Establish a hardware standard for EV charging stations, including a standard interface for charging management and billing. This will help scale EV adoption, facilitate grid integration, and avoid the inefficiencies of multiple, competing EV charging platforms.

7.4.3 PATHWAY #3: DEVELOP THE INFRASTRUCTURE AND BUSINESS MODEL FOR A CLEAN GRID

Integrate utility-scale and distributed energy resources into China's grid and reform power transmission and distribution

China's electric grid needs to be more interconnected, intelligent, and flexible to properly integrate and coordinate distributed energy resources, utility-scale renewables, and traditional dispatchable resources. Technology improvements can address some of these needs. But for a modern grid platform that unifies both distributed and centralized assets, business reforms for grid dispatch and compensation are necessary. This could greatly reduce the required generating capacity, improve grid stability, and reduce system costs.

(1) Improve grid interconnectivity

China's grid comprises multiple, poorly interconnected regions. The three northern regional power grids do not have the transmission capacity to integrate large-scale wind power and connect it to eastern demand centers.[36] China is building new high-voltage

CASE STUDY 7.5: REDUCING RENEWABLE POWER VARIABILITY IN THE U.S.[37]

Wind and solar power are inherently variable. By spreading these variable renewable energy generators over a wide geographical area, the overall variability significantly decreases. Using data from wind generators throughout the American Midwest, the U.S. National Renewable Energy Laboratory (NREL) and the International Energy Agency (IEA) assessed the impact of interconnecting geographically diverse wind generators.

They found that integrating wind farms over a wide geography cut average hourly generation variability by half. This means that both the severity and the frequency of swings in power generation are cut and there is less need for new ramping capacity to firm renewable variability. Although interconnection can smooth wind variation, once wind penetration reaches of around 20% (according to the IEA and NREL study), more-substantive changes in system operational practices are typically necessary.

transmission lines between these regions that will allow larger balancing areas, improve management of variable renewable generation, and reduce curtailment. Expanding balancing areas allows grid operators to optimize resource allocation from a national perspective, resulting in more-efficient dispatch and better capacity utilization.[38]

In the Reinventing Fire Scenario there are three important transmission corridors that will help facilitate interconnection of remote renewable generators. These electricity superhighways will carry high volumes of electricity (they are interregional transmission lines with over 100 GW of capacity) to connect eastern and central China, central and northwestern China, and northern and eastern China. These corridors will be important in the Reference Scenario as well, but will be less developed since there will be less remote renewable generation.

(2) Increase grid intelligence

Beyond improved physically interconnectivity, the grid's ability to collect, transfer, and process information needs to improve. Using advanced information and communications technology (ICT), the power sector will become highly integrated, self-healing, interactive, and optimized. The grid platform will unify centralized and distributed resources and electricity information and services will be easily exchanged. This platform requires a flexible communication standard, a comprehensive sensor network, an automated power system that responds in real time to control signals, and an expansive information pathway with bi-directional communication between centralized generators and customers.

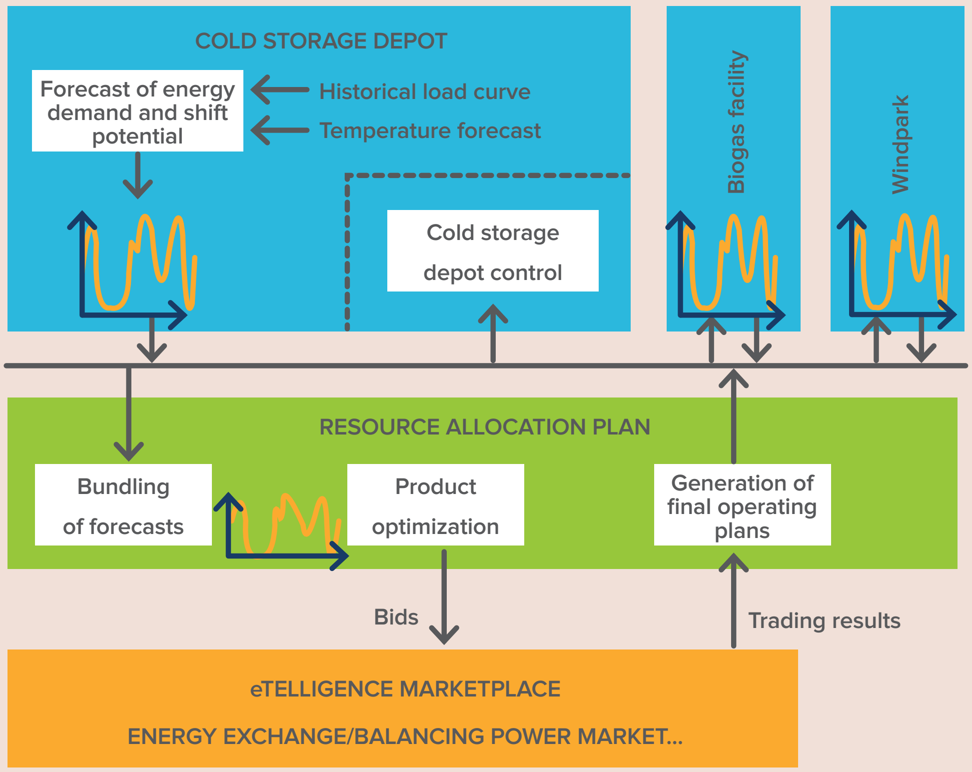
- **Centralized generators** will become increasingly automated and will be controlled by information systems that evaluate the most-efficient use of resources in real time to meet demand. These information systems will integrate weather predictions and real time data to coordinate centralized, grid-scale assets.

- **Customers'** behavior and demand will be coordinated by time-of-use (TOU) tariffs or real-time utility signals (informing customers how they can voluntarily change their consumption). The grid does not yet have the necessary ICT capabilities required to enable customer participation on this scale. ICT investment should be a primary focus of China's power sector, and should utilize the extensive development of China's digital communication infrastructure.

CASE STUDY 7.6: USING VIRTUAL POWER PLANTS IN GERMANY

The eTelligence project in Cuxhaven, Germany, aggregates distributed generators along with consumer demand response (DR) capacity (Figure 7.11). Collectively, these assets are called a virtual power plant (VPP). VPPs help deal with renewable power's variability by combining diverse resources (rooftop PV from a wide geographic region, wind farms with DR, and distributed storage). With coordinated resources, fluctuations from wind and solar energy can be balanced by automating DR (from large, demand-elastic facilities like refrigerated warehouses) or with various forms of storage. By aligning usage with the availability of cheap energy in this fashion, VPPs can help lower energy costs for participants by 6–8%.[39] This balancing also allows VPPs to react to forecasting errors and minimize supply network deviations. In a field test, VPPs adhered to forecasted renewable outputs with 15% more accuracy than centralized renewable assets did, without VPP coordination. This makes VPPs more affordable than other centralized renewable assets, which have to pay other fossil-fuel plants to provide balancing for their output. The VPP sector's annual worldwide revenue could reach an estimated $5.3 billion by 2023, as VPP capacity more than quintuples from 4,800 MW in 2014 to nearly 28,000 MW.[40,41]

FIGURE 7.11: eTELLIGENCE VIRTUAL POWER PLANT OPERATION SCHEMATIC



(3) Enhance grid flexibility

Grid assets need to be far more flexible to accommodate the rapid deployment of variable renewable generation technologies. Flexibility accommodates variability in renewable generation and customer demand, improves grid stability, and reduces the need for expensive, under-utilized reserve capacity.[42] Therefore, the Reinventing Fire Scenario requires more flexible capacity (by absolute value and proportion of total capacity) than the Reference Scenario. The Reinventing Fire Scenario has 1.8 TW of intra-hour ramping capacity, not including DR and EV potential. If these resources are included as dispatchable flexibility resources, system operators have up to 2.0 TW of intra-hour ramping capacity. Concentrated solar power (CSP) stored in molten salt, chemical storage, and hydro constitute the three largest sources of intra-hour flexibility (Figure 7.12). Coal and natural gas generation, along with DER, provide substantial flexible capacity in 2050. Each of these assets can deliver intra-hour changes in output with varying speed, accuracy, and magnitude of delivery. Each of these attributes is valuable in maintaining the grid, therefore assets will be dispatched based on the needs of the grid and the assets' ability to deliver based on these metrics.

Additionally, transmission and interregional balancing in China is currently planned on a day-ahead basis.[43] Shifting to real-time balancing allows the grid to better operate these flexible assets, while broader interconnection and wider balancing areas decrease the amount of dispatchable, flexible assets needed online to maintain grid stability.

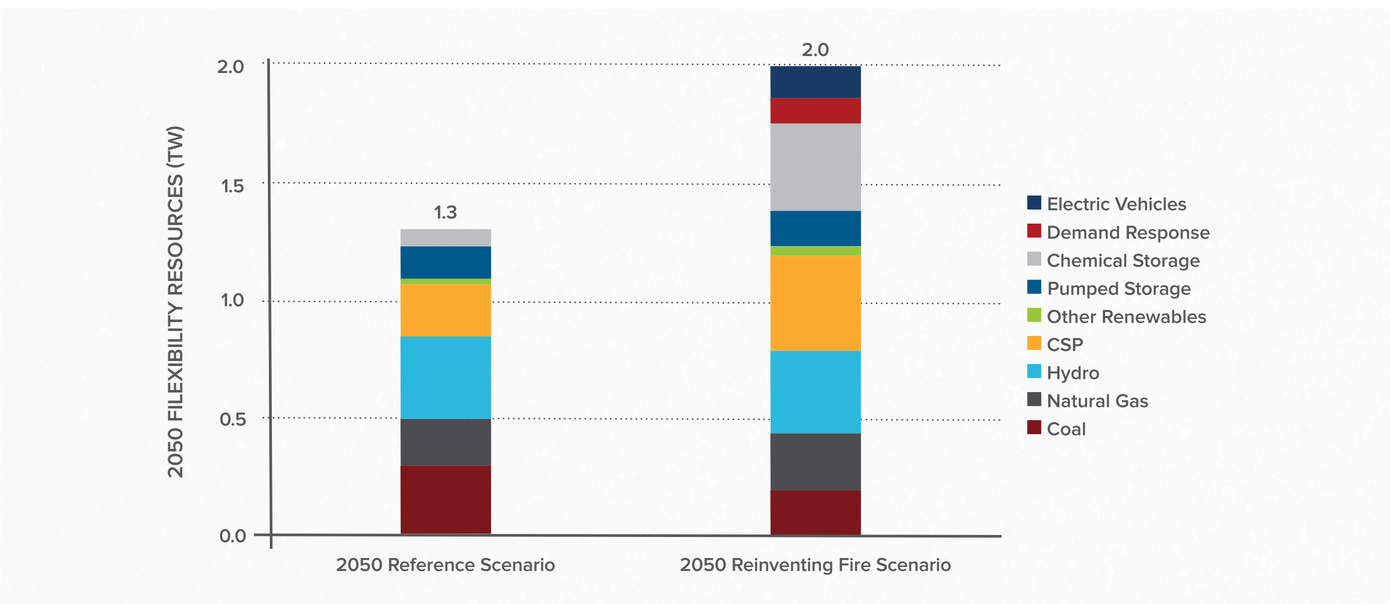
(4) Reform wholesale pricing and dispatch rules

China's current dispatch protocol is not designed for high renewable penetration. China's 2015 "Deepening Reform of the Power Sector,"[44] aims to shift the power sector towards lower-carbon generators while keeping costs low. This policy has not been fully specified, but international best practices suggest several key reforms to successfully increase renewables penetration while lowering costs. These reforms include:

- Implement two-tier pricing for generation
- Dispatch generators based on their marginal cost

FIGURE 7.12: MAXIMUM INSTALLED CAPACITY OF INTRA-HOUR FLEXIBILITY RESOURCES

2050, REFERENCE VS. REINVENTING FIRE SCENARIOS



- Consider locational aspects of transmission and system losses
- Internalize the cost of pollution

In China, generating assets are compensated only for the amount of electricity produced, though they may provide other services, such as reserve capacity, load following, or ancillary services. Since they are only compensated for electricity generation, each asset is assigned a number of operating hours to ensure fixed costs are covered. This compensation method favors generators that operate a high number of hours per year. Flexibility assets (those that operate for a small yet critical number of hours) may not be fully compensated for their service and often struggle to cover their costs.

China can address this problem by adopting a two-tier pricing system that separates fixed and capital costs from variable operating costs. In a two-tier scheme, utilities directly pay to cover dispatchable generators' fixed and capital costs (a capacity payment). This "holds" generating capacity for when it is needed. When generators produce electricity, they are also paid for the energy produced (an energy payment). Together, these two types of payments are roughly equal to the total amount paid to all generators in the existing paradigm. This alternative pricing system pays generators for the true service they provide: reliability in the form of available capacity and electricity generated.

By paying separately for the energy created, grid operators can operate assets to minimize costs to the system. Since older assets have often paid off their capital costs, it does not make sense to prioritize dispatch based on an LCOE, but rather the marginal (operating) cost of the asset. If dispatching is based on LCOE, coal may be prioritized in dispatching even if wind farms are producing energy (at zero additional cost), because coal's LCOE is currently cheaper than wind's. Instead, by evaluating the marginal cost, the grid operator would utilize the available wind energy, and not pay for the fuel and labor to generate the same number of kWhs with a coal plant. Prioritizing dispatch to the lowest-marginal-cost generators reduces system-wide generation costs by ensuring the most-efficient plants generate the most power.

This marginal-cost-based, merit-order dispatch can be further improved by including a locational component to the pricing. This system, known as locational marginal pricing (LMP), factors in the electrical losses. Even if one generator is more efficient than another, if the transmission pathway is heavily congested, a slightly less-efficient generator that is better located with less congestion may be more efficient for the entire system. Taking this into account helps drive down both costs on the entire grid (as seen in the U.S., New Zealand, and Singapore) and project developer's investment in transmission to connect their geographically remote renewables with adequate transmission lines.

CASE STUDY 7.7: INCORPORATING A HIGH LEVEL OF RENEWABLE POWER IN THE U.S.[45]

The U.S. National Renewable Energy Laboratory (NREL) found that by improving power dispatch, the Western Electricity Coordinating Council (WECC) could significantly reduce its operating costs under a 35% renewable-penetration scenario. After WECC shortened its dispatch interval from one hour to half an hour, the demand for combined-cycle power-plant load-following services decreased by 50%, enhancing both generation efficiency and O&M costs.[xvi] When used with accurate weather and power-demand forecasting, efficiency gains increase. Day-ahead forecasting helped WECC reduce operating costs by up to $5 billion annually. Additionally, expanding balancing areas to allow authorities to share resources for spinning reserves saves WECC up to $2 billion annually.

[xvi] *Load following is when a power plant adjusts its power output as demand for electricity fluctuates throughout the day.*

Merit-order dispatch, when coupled with properly assessed penalties for polluting generators, can effectively optimize emissions from fossil generators and manage pollution. This helps power plants internalize the real environmental and health impacts caused by pollution. It will drive grid companies to use clean generation whenever practicable and use fossil fuel plants increasingly for system reliability. Two-tier pricing coupled with economic dispatch achieves two simultaneous benefits: emissions reductions and lower power costs.

(5) Reform dispatch at different timescales

Balancing supply and demand requires procuring and dispatching resources over a series of differing timescales. System planning involves acquiring generation and demand-side capacity 1–10 years in advance and operational planning occurs 6–12 months in advance. Economic scheduling of generators happens one day ahead based on demand and renewable forecasts. Finally, within each day, real-time corrections are made on various timescales (typically 15 minutes or less). A well-run power system requires planning and balancing at each timescale.[46]

An efficient system has diverse technologies operated by numerous service providers, delivering electricity services on different timescales. Take flexibility as an example: natural gas plants, coal plant spinning reserves, DR, and grid and distributed storage can all provide flexibility but are not all suited to the exact same timeframe. Ideally, the grid operator selects the most cost-effective and system-appropriate service provider and offers fair compensation.

While the principles of market and price reform discussed earlier hold for each timescale, market structures differ by timescale and service. For example, system planning may use auctions to acquire generation or demand-side capacity five years in the future. In contrast, ancillary services at sub-fifteen-minute increments may involve dispatching contractually agreed upon resources, such as direct load control of homeowner smart appliances. Both scenarios still utilize capacity and real-time pricing established by market auctions. Providing such service is generally more complicated and critical at shorter timeframes and compensation is thus higher per kWh of service delivered.[47]

Barriers

China's electric grid is designed for single-direction electricity flow from generators to customers. It lacks advanced systems that enable two-way communications between customers and generators and real-time load/generation coordination. Additionally, the national grid is fragmented into several regions with little interconnection or communication. Finally, grid companies make their profits by selling electricity and have no incentive to procure efficiency or DR. This revenue model inhibits effective renewables integration and demand-side management.

Solutions

To improve the grid's power system operation:

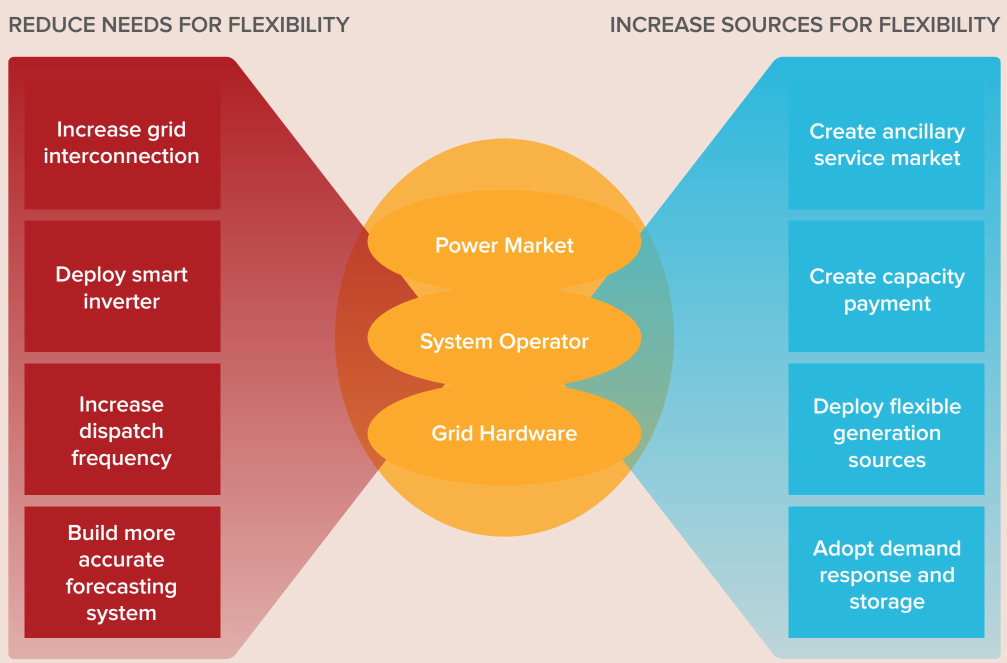
- Research and develop ultra-high-voltage (UHV) power transmission technologies. This should include support for new technology development, demonstration projects, and financial support (e.g., incentives or loan guarantees) for early, full-scale implementation.
- Restructure how balancing responsibility is shared across China. Require balancing to be performed at higher levels and over larger geographies that correspond to actual grid assets; this will achieve efficient asset utilization. Then allow smaller perturbations to be managed by localized grid companies and entities.
- Require grid companies to bear a greater share of renewable energy curtailment costs so that they are incentivized to reduce curtailment and invest in renewables integration.
- Ensure generators and grid companies share grid-congestion costs. Implement a hedging mechanism (such as Financial Transmission Rights or FTR) between generators and grid companies to provide economic incentives to alleviate congestion points on the grid.[48]

CASE STUDY 7.8: INCREASING RENEWABLE PENETRATION IN GERMANY[49]

Germany increased its share of renewable energy by employing a two-pronged approach: first, minimizing the need for flexible capacity, and then meeting the remaining need for flexibility with improved operations and more flexible generation and storage assets. To reduce the need for flexibility, Germany substantially interconnected its grid with the rest of Europe. The German grid was able to support 15% more renewable capacity by increasing grid interconnection alone. In addition, Germany was able to cut the costs incurred by firming renewables by shifting dispatch timeframes from one hour to 15 minutes, in conjunction with more-accurate weather and demand forecasts.

To increase the amount of flexibility resources on the grid, Germany created markets that pay generators directly for load-following services. Additionally, Germany provides capacity payments to reserve generators specifically for providing flexibility services, which helps generators cover their opportunity costs and forego providing bulk energy services in favor of providing flexibility service (and operating fewer hours). Germany also encourages the deployment of new, flexible technologies such as distributed combined heat and power (CHP), demand response, bi-directional transformers, and energy storage. Germany's existing facilities can ramp more than 1,800 MW within one hour (over 1% of all of Germany's installed capacity).[50] Through all the methods explained above (Figure 7.13), Germany increased its renewable penetration on the electricity system from 9% in 2007 to almost 30% in 2015.

FIGURE 7.13: KEY TECHNOLOGY DRIVERS THAT ENABLE HIGH-PENETRATION RENEWABLES IN GERMANY



- Regulate transmission and distribution tariffs to ensure adequate cost recovery without profiteering. These tariffs should be frequently reviewed to ensure costs are appropriate to cover power sector costs plus a reasonable return, while protecting end users from unfairly high electricity prices.

- Require distribution grid companies to achieve greater reliability standards and establish resiliency standards. This should require distribution grid companies to deploy grid assets that are able to handle two-way flows of electricity, respond automatically in emergency situations, and requires sources of resiliency on the local level (e.g., distributed battery systems). This will simultaneously increase resiliency while allowing high penetrations of distributed generation and storage.

To improve power sector information systems:

- Require greater data reporting and monitoring requirements to ensure compliance and high-quality operational data. Some energy data should be publicly available to allow for greater research into power system optimization and to spur the development of China's rapidly growing smart grid and cleantech industries.

- Create a standard-setting body to develop a common data and communication standard that provides for comprehensive interoperability across generators, grid assets, and distributed energy resources.

- Increase the time granularity of dispatch (to a sub-15-minute timescale) to enable compensation to generators that correct for divergences in scheduled power generation.

- Support research and development of better demand- and weather-forecast systems. Ensure grid companies pay higher costs for intra-day corrections by generators. These mechanisms will incentivize improved day-ahead predictions from both grid companies and generators.

To improve power sector compensation:

- Decouple distribution grid company profits from volumetric electricity sales to more accurately reflect the true cost of service.

- Shift wholesale electricity prices away from the current system of pre-set, volumetric prices for all generators towards a two-tier pricing scheme. Phase out fixed generation hours and annual contracts. Implemented a two-tier pricing system that pays to hold capacity (covering the fixed costs of those generators), and then pays to dispatch generators (covering operating costs).

- Create reforms to prioritize dispatch based on the marginal cost to operate and internalize any grid-congestion costs and environmental costs.

- Directly remunerate for ancillary services. This will allow the grid to attract more flexibility resources (including peaking, ramping, and power-quality services).

- Define ancillary services clearly, specifying required response times and accuracy metrics that grid assets will be assessed on. Establish standards for accuracy and responsiveness that prohibit unsuitable assets from receiving capacity payments for these services. Upon dispatch, use these metrics for responsiveness and accuracy alongside other cost and locational considerations to determine the appropriate asset to provide these ancillary services.

- Establish clear renewable interconnection standards that do not place an undue burden on generators. Ease ancillary service requirements assigned to individual generators, allowing generators to supply ancillary services on the behalf of other generators, which is important in a high-renewables system.

7.4.4 PATHWAY #4: PROMOTE WHOLE-SYSTEM PLANNING AND INTEGRATION

Integrate solutions across electricity supply, demand, and the grid through planning reforms

Certain measures necessary to realize the Reinventing Fire China scenario cut across the three pathways considered above. Barriers and solutions to these crosscutting measures are discussed here.

Barriers

The current power planning system is not well aligned with the national goals of efficiency and reduced emissions. The planning and goal-setting process does not integrate either air-pollution and CO_2 reduction goals or energy-efficiency targets. Additionally, current planning involves multiple, independent government agencies, resulting in poorly integrated assets and system-wide inefficiencies. Planning agencies are not required to perform cost-benefit analyses that consider generation alternatives such as efficiency or transmission build-out when establishing resource-adequacy requirements. Furthermore, planning assumptions use simplistic demand projections that fail to reflect China's slowing growth and changes in load profiles as more air conditioners and EVs connect to the grid. Finally, the impacts of comprehensive carbon regulations, such as the carbon cap-and-trade pilots, are not factored into the planning process.

Solutions

- Require power system planning to be performed at the national level, using an integrated resource planning (IRP) process. Incorporate other planning entities into this process to contribute local perspectives and enable local jurisdictions to develop subsidiary and compliant plans in line with the national IRP process.
- Require the planning process to consider generation, grid, and demand-side planning equitably. Demand-side resources, such as energy efficiency and demand response, should receive priority and fair compensation as firm capacity where economic (effectively being paid to help defer new generation).
- Institute a review process for IRP where grid companies are required to submit integrated resource plans, with complete cost-benefit analysis, for review before permits are awarded to new generators. These documents should be made available to the public to encourage private-market innovation.
- Utilize renewable portfolio standards (RPS) to ensure coal power capacity peaks in accordance with government commitments. China's current national RPS program requires a certain percentage of non-hydro renewable power in generating companies' and grid companies' portfolios. The first policy was announced in 2007, but the policy has not been fully implemented. Further announcements regarding provincial and grid-company standards for renewable energy are expected in 2016.[51]
- Institute long-term capacity and forward energy contracts that are linked to RPS, national air quality emissions-reductions goals, and international agreements. By providing contracts that specify the type of assets eligible (e.g., flexible capacity or non-fossil capacity), China[52] can guide the retirement and construction of its generation fleet and transmission and distribution assets.
- Internalize environmental costs into resource planning using emissions taxes or cap-and-trade systems on CO_2 emissions and other pollutants. These mechanisms are internationally established and have been piloted in China. Expanding these pilots will increase their impact.
- Establish more-aggressive national standards and criteria (instead of multiple localized ones) for resources such as safety, reliability, ancillary services, and resiliency. These standards should consider the future evolution of the power system that has high renewable penetration and many individual actors participating from the customer side.

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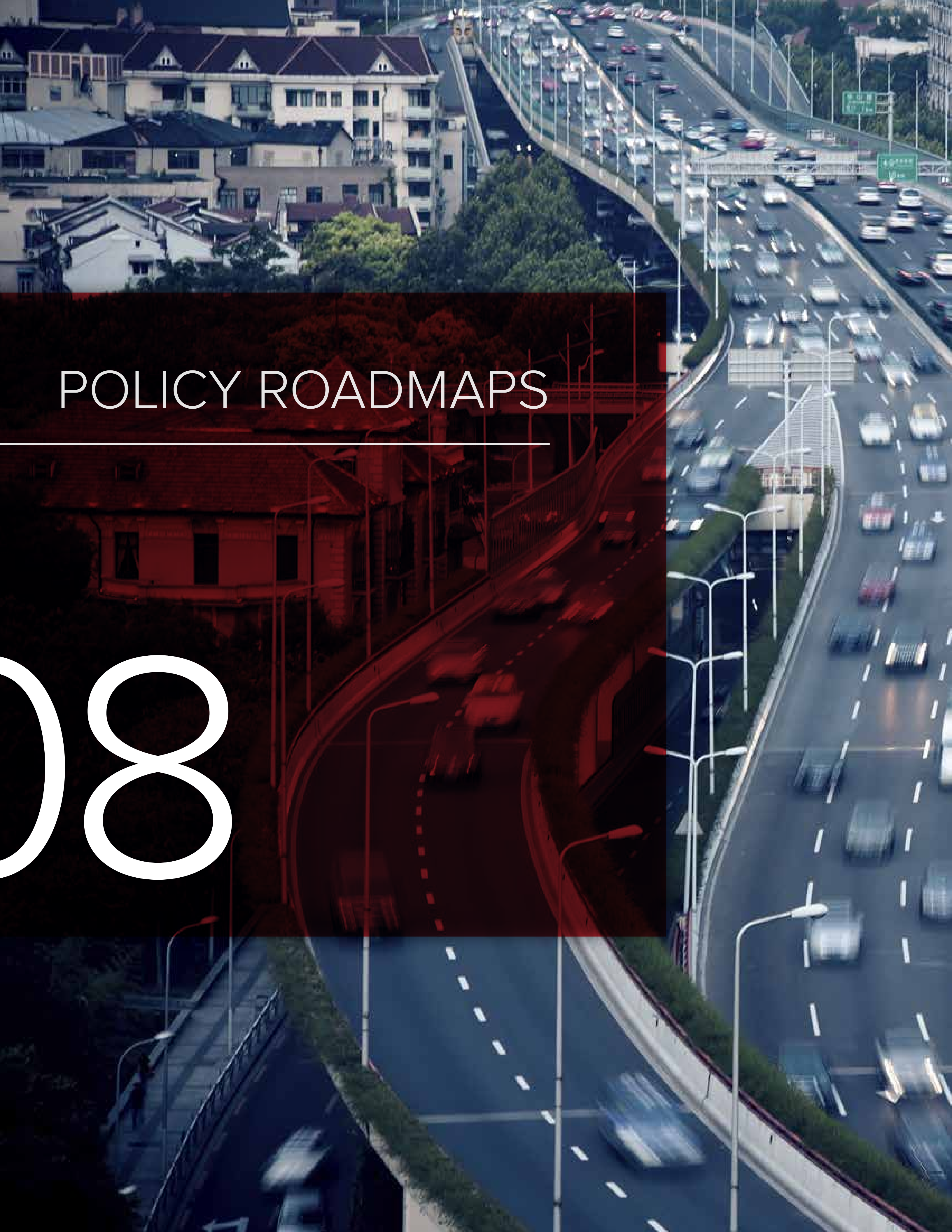
POLICY ROADMAPS

08



POLICY ROADMAPS

8.1 REINVENTING FIRE ROADMAPS

The results from Reinventing Fire: China were used to create integrated and sector-specific roadmaps that identify targets and timelines. The roadmaps mark future development indicators, focus on decade-long time horizons, indicate major milestones, and aim to provide targeted decision-making references to relevant governmental departments designing mid- to long-term energy production and consumption development strategies.

If these roadmaps are diligently pursued and realized, China can "reinvent fire," creating a new production and consumption network where energy use is highly efficient, energy production is clean and low-carbon, energy technology is world leading, and the economic benefit is significant. This will contribute to building a beautiful China and will help address global climate change.

At an integrated level, Reinventing Fire: China tracks progress across three stages:

(1) 2010 to 2020: Declare a war on pollution, restructure industrialization

This stage is critical for China to achieve its first 100-year goal and establish a moderately prosperous society. The driving force of economic development gradually shifts from heavy and material-intensive industries towards services and high-end manufacturing. Resources and environmental quality remain constrained, and pollution remains a serious issue. Developing the economy, improving living conditions, and controlling environmental pollution are the core tasks of this period.

To promote Reinventing Fire during this period, the industrial sector will combat excess capacity of high-energy-consuming industries, enhance energy savings, and further develop energy management. By strengthening energy-saving and environmental protection requirements for new developments during rapid growth in the buildings and transportation sectors, China can avoid locking in future energy waste.

Milestones of this period include:

- Urbanization increases from 50% in 2010 to 60% in 2020.
- China's GDP per capita aims to increase from $4,400 to about $8,400.
- Coal consumption peaks in 2020, falling from 70% of total energy to 60% or less.
- 2020 national sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions will decrease about a quarter from the 2010 level as the effectiveness from energy-savings measures in industry take hold.
- SO_2 emissions peak in the power sector in 2020 from stricter pollution control measures.

(2) 2020 to 2030: Peak CO_2 emissions by 2030 and move towards post-industrialization

During this stage, China's GDP will surpass the U.S. and become the largest in the world. China's economy takes on post-industrial characteristics, and the share of services and high-end manufacturing sector continues to grow. SO_2, NO_x, and other pollution issues subside, and efforts to peak CO_2 are reinforced. Domestic demands to address climate change become increasingly urgent as China uses the CO_2 emission peak target to promote low-carbon and clean energy systems.

The milestones of Reinventing Fire during this period include:

- GDP per capita increases from about $8,400 to about $14,300.[i]
- Urbanization rates rise from 60% in 2020 to 68% in 2030 and the pace of urbanization slows.
- Energy consumption of the industry sector peaks before 2025, signaling that China's industry-

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[i] *Achieving this level would put China on par with high-income countries, according to the World Bank's standards.*

based energy consumption structure has adjusted and rebalanced.

- National CO_2 emissions peak in 2025; the share of non-fossil energy in primary energy consumption reaches 28% using PPCC in 2030; CO_2 emissions per GDP intensity decrease 70% from 2005 levels, indicating that China has begun to curb the growth of global greenhouse gas emissions.

- China's oil demand peaks around 2030; oil demand reaches 820 million tons (about 300 million tons higher than 2015 demand). This helps limit China's import requirements to 70% of total oil demand and concerns over oil supply security are somewhat eased. SO_2 emissions drop from 15 million tons in 2020 to 9 million tons in 2030 and NO_x emissions drop from 14 million tons in 2020 to 7 million tons in 2030.

(3) 2030 to 2050: Achieve a high share of non-fossil energy and further develop green and intelligent growth strategies

This stage is a decisive period for China to realize its second 100-year goal and reach a moderately developed country by 2050. Greenhouse gas emissions have peaked, but pressure remains to reduce overall emissions. Low-carbon technologies such as wind power, solar power, and energy storage will be fully commercialized. The mutual integration and promotion between intelligent technology and low-carbon technology creates a new generation of energy savings.

The levelized cost of electricity from renewable energy sources such as wind power and solar power falls well below that of coal-fired power and many coal-fired power plants built from 2000 to 2010 will reach 40 years of operation and will retire at this stage. The remaining coal plants will serve as a flexible ancillary service to the grid. The average share of non-fossil energy in national electricity generation by 2050 will exceed 80%, with many districts or communities utilizing electricity that is 100% supplied by nonfossil energy.

Milestones of this period include:

- China's per-capita GDP increases from approximately $14,300 to around $29,900 as the country fully transitions to a post-industrial society.

- Economic growth slows and the population peaks.

- Urbanization, while slowing, increases from 68% in 2030 to around 78% in 2050.

- Total CO_2 emissions decline from 9.5 billion tons in 2030 to 4.6 billion tons in 2050; CO_2 emissions intensity per unit of GDP falls 93% compared with 2005.

- Installed capacity of coal-fired power plants falls by nearly half, from 858 GW in 2030 to 489 GW by 2050.

- China peaks primary energy consumption around 2035. Building sector energy consumption and transport sector energy consumption all peak before 2040.

- In 2050, nonfossil fuels account for 55% of primary energy consumption (China's Power Plant Coal Consumption conversion standard) and nonfossil electricity accounts for 82% of electricity generation.

- SO_2 emissions drop from less than 10 million tons in 2030 to around 3 million tons in 2050.

Summary

Of the three development stages of Reinventing Fire, the first two stages are a transformation period (2010–2030). During these two stages, energy savings and energy-efficiency improvements play a leading role, while new energy and renewable energy grow rapidly. After 2030, the third stage harvests the work from the previous two decades. During this stage, renewable energy growth in the power market is significant.

The first two stages of development will be challenging. When the government designs national long-term development strategies, it must highlight the reinforcing effects of energy-savings, environmental protection, CO_2 emission reductions, and establish strict incentives and restraint mechanisms to promote energy savings and new energy development. If strong efforts are not carried out during the first two stages, China will not realize the full benefits of Reinventing Fire in the final stage of the transformation.

8.2 REINVENTING FIRE ROADMAP: INDUSTRY SECTOR

Reinventing the industrial sector is a complex and long-term task. The development pathway and energy consumption pattern of the industrial sector can be comprehensively restructured and the transformation can be driven by methods such as structural change, demand reduction, efficiency improvement, and decarbonization of energy supply. Reinventing Fire in the industrial sector follows three stages:

(1) 2010 to 2020: Peak industrial energy consumption early by controlling capacity and utilizing existing stocks

In this stage, the industrial sector focuses on improving the quality and efficiency of energy-intensive industry. The approaches include **controlling capacity levels, improving energy efficiency, emphasizing environmental protection, and improving product quality**. The share of industrial GDP in China's total GDP will begin to decrease as secondary industry develops rapidly.

Milestones of this period include:

- The value-added share of manufacturing will drop to 36.5% by 2020, while tertiary industry will represent 50% of total value added.
- The share of industrial value added in gross output will significantly increase from 26% in 2010 to 32% in 2020.
- Export and import balance are optimized, the export of energy-intensive products decreases, and the import of raw materials increases; as a result, the embodied energy of exports decreases from more than 400 Mtce in 2010 to less than 200 Mtce by 2020.
- As the circular economy of the industry sector is established, the recycling rates of steel, aluminum, paper, and other material increase significantly to 22%, 32%, and 69% respectively by 2020, increasing 8%–13% compared to 2010 levels.

(2) 2020 to 2030: Scale eco-industrial parks and composite industry plants

The primary goals of this stage are **structural shift, capacity replacement, and system optimization**. With a significant structural shift, high-value-added industry replaces traditional industry and becomes the main driving force of industrial development.

Milestones of this period include:

- Four high-value-added industries including medicine, machinery, electronics, and transportation equipment manufacturing grow to represent more than 50% collectively of total industrial GDP, reaching 55% in 2030.
- New capacity is constructed incorporating integrative design and systemic energy-efficiency measures. This is important because the capacity installed after 2000—especially after 2010—accounts for more than 50% of the total remaining capacity after 2030.
- Energy and material consumption and pollutant emissions per unit of value added of key industries attain global best practice.

(3) 2030 to 2050: Revolutionize energy consumption in industry through intelligent, digital, and networked production systems

During this period, intelligent, digital, and networked production systems are established across industries and enterprises.

Milestones of this period include:

- Automated control is applied for more than 80% of key processes.
- High-value-added industries account for two-thirds of total industrial GDP.
- Labor productivity of the industry sector increases six times and the share of industrial value-added in total gross output increases to more than 40%.
- Recycling systems cover every major city in China and the treatment rate of industrial and residential wastes reaches 100%.
- The share of coal consumption in total industrial energy consumption decreases to 22%, the share of natural gas consumption increases to 11%, and the electrification rate increases to 39%.

8.3 REINVENTING FIRE ROADMAP: BUILDINGS SECTOR

Reinventing Fire aims to transform the development pattern of the buildings industry in both urban and rural areas. The pathways include rational control of growth in floor space, promotion of ultra-low-energy buildings, improvement of efficiency in building energy systems and equipment, and optimization of building end-use structure. Fundamental reforms are needed in building energy consumption patterns to reduce energy consumption growth. Reinventing Fire in the buildings sector follows three stages:

(1) 2010-2020: Establish energy-savings policies and improve both rural and urban planning

In this stage, the focus of Reinventing Fire in the buildings sector is transforming construction practices in both urban and rural areas to establish the foundation for future energy savings. Building floor area limits should be set while strengthening the management of building demolition; this will help control the extensive expansion of city planning and haphazard growth of building floor area.

Milestones of this period include:

- By 2020, the building floor area per capita in urban areas should not exceed 32 m^2.
- By 2020, a standard for energy consumption caps, ultra-low-energy building design standards, and construction requirements are released.

(2) 2020 to 2040: Focus on constructing ultra-low-energy buildings

This stage is focused on the construction of ultra-low energy buildings. The concept of integrated design, passive houses, near-zero-energy buildings in rural areas, and ultra-low-energy public buildings are all promoted. Building retrofits, especially deep retrofits, accelerate. Ultra-high-efficiency energy-use systems and equipment are promoted. Buildings integrate renewable energy, supporting the improvement of electrification in the building sector. Utilization of low-quality industrial waste heat is also promoted. Smart building systems are developed, while the growth of floor space is controlled. Prefabrication becomes more common.

Milestones of this period include:

- By 2040, ultra-low-energy buildings make up 60% of the new urban buildings and public buildings.
- The percentage of ultra-low-energy buildings among new urban and public buildings built in 2010–2040 will be 38% and 33%, respectively.
- Among urban and public buildings, 67% undergo deep retrofits.
- End-use energy consumption in building sectors peak by 2040.

(3) 2040 to 2050: Formation of highly- efficient, clean, and smart energy use in buildings

This stage focuses on ultra-low-energy retrofits and deepening the measures in Reinventing Fire, creating a highly-efficient, clean, and smart energy use in buildings.

Milestones of this period include:

- By 2050, energy efficiency in the building sector improves significantly and all new construction is ultra-low energy; ultra-low-energy buildings achieve 60% share among all new urban and public buildings.
- Ultra-high-efficiency energy-use systems and equipment are widely applied with smart controls applied in most buildings.
- Building systems are engineered modularly; building industrialization of urban structures achieves 100% through use of pre-fabricated systems and components.
- End-use energy consumption in the buildings sector will be clean and low-carbon, with renewable energy being widely deployed in buildings. Building energy use achieves 66% electrification rate by 2050.
- Coal consumption will account for only 2% of building energy use in 2050.

8.4 REINVENTING FIRE ROADMAP: TRANSPORTATION SECTOR

The goal of Reinventing Fire in the transportation sector is to create a highly-efficient, clean, green, low-carbon, convenient, comfortable, and competitive modern transportation system. Reinventing Fire decouples energy consumption from oil consumption, transportation service, and carbon emissions. A transportation development roadmap for China needs development goals and outputs by period, industry, and region to provide effective policies and regulations. Reinventing Fire in the transportation sector follows three stages:

(1) 2010 to 2020: Accelerate the construction of energy-efficient transportation infrastructure and decrease private-vehicle travel demand; demonstrate and deploy new transportation modes and innovative management models to improve energy efficiency

Before 2020, urbanization accelerates. Reinventing Fire helps seize the opportunity to revolutionize transportation in the course of this development to

comprehensively improve transportation operational efficiency and quality. This is accomplished by accelerating the construction of high-speed rails and subways and providing support for urban and rural residents to choose highly efficient, rapid, and energy efficient transportation modes.

Milestones of this period include:

- By 2020, China's high-speed railway spans 25,000 kilometers. Beijing, Shanghai, and Guangzhou have widely-connected public transportation networks.
- Subway systems and bus rapid transit (BRT) systems start to scale in main provincial capital cities.
- China uses multiple methods to actively demonstrate new energy vehicles and strives to reach 5 million new energy vehicles sales by the year of 2020 (including 1.5 million fully electrified vehicles).
- By optimizing city structure and layout, improving the convenience of non-motorized vehicles, and increasing parking and congestion fees, the distance travelled by private vehicles decreases from 12,000 kilometers to 8,000 kilometers in 2020.

(2) 2020 to 2035: Peak oil consumption, diversify the energy structure, and complete China's transportation system with emphasis on railway and public transportation

By 2035, a comprehensive, energy-efficient, and environmentally friendly transportation system, including a rail-based intercity passenger system, is in place.

Milestones of this period include:

- By 2035, passenger rail demand accounts for 33% of overall passenger transport demand, while freight rail demand accounts for 20% of overall freight transport demand.

- City transportation systems focus on subways and public buses with public transportation accounting for 60% of urban passenger mobility.

- 80% of the newly-added taxis are electric vehicles or plug-in hybrid vehicles and over 30% of private vehicles are electrified.

- In 2035, the percentage of oil consumption decreases to 76% of the transportation total, the share of electricity increases to 8%, and oil consumption peaks in 2030.

- End-use energy consumption and CO_2 emissions both peak in 2035.

(3) 2035 to 2050: Create an efficient, clean, green, low-carbon, convenient, comfortable, and modern transportation system and mitigate China's high dependence on oil

In this period, energy consumption will be clean and diversified, with significantly lower oil dependency. The transportation infrastructure is a connected network and information technology improves operational organization and efficiency. Transportation modes are linked together seamlessly.

Milestones of this period include:

- Despite private-vehicle ownership increasing to over 300 million vehicles, travel distances decrease significantly due to better urban public transportation as well as smart growth.

- Electric vehicles serve as an important source of energy storage and are connected and employed as a demand-side resource.

- Oil accounts for only 50% of final transportation energy consumption, helping mitigate dependence on foreign oil.

8.5 REINVENTING FIRE ROADMAP: ELECTRIC POWER SECTOR

The electric power sector is the core of a modern energy system. Achieving the Reinventing Fire transformation in the power sector requires technology upgrades, structural optimization, and institutional innovation. The Chinese power sector can become clean, low-carbon, secure, diversified, economic, and efficient. There are three steps to realize Reinventing Fire in the power sector: optimize centralized generation resources; leverage distributed generation, demand response, distributed storage resources; and improve the integration capabilities of the grid. The Reinventing Fire strategy envisions transformations in every link of the power industry chain, including generation resource development, generation integration, transmission planning, grid structure, electricity transmission, dispatch, distributed generation, and demand-side management.

(1) 2010 to 2025: Peak pollution emissions by retrofitting coal plants

The task of this phase is to peak regional pollutants such as SO_2, NO_x, and dust while meeting the rapid growth in electricity demand. This period sets up future energy savings by strictly controlling the total installed capacity of coal-fired power plants, retrofitting plants to improve energy efficiency and achieve ultra-low pollutant emissions, and scale renewable energy development.

Milestones of this period include:

On the generation side (see Table 8.1):

- The installed capacity of coal-fired electricity generation is below 900 GW by 2025.

- The installed capacity of nuclear power increases from 11 GW in 2010 to about 80 GW in 2025.

- Hydropower installed capacity increases from 200 GW in 2010 to 370 GW in 2025.

- Wind installed capacity increases from 30 GW in 2010 to 360 GW in 2025.

TABLE 8.1: CHINA'S REINVENTING FIRE SCENARIO ELECTRIC GENERATION CAPACITY FOR SELECT YEARS

	2025	2035	2050
COAL	<900	790	490
NUCLEAR	80	130	220
HYDRO	370	420	500
WIND	360	710	1,140
UTILITY-SCALE SOLAR	190	480	1,300
NATURAL GAS	120	180	270

- Utility-scale solar (including CSP) generation installed capacity increases from less than 1 GW in 2010 to 190 GW in 2025.
- Natural gas generation installed capacity increases from 30 GW in 2010 to 120 GW by 2025.

On the demand side:

- Energy management services companies provide professional demand-response services to big electricity consumers, helping to minimize the construction of new centralized dispatchable generators.
- Demonstration projects to utilize electric vehicles as energy storage are piloted in communities.
- Distributed photovoltaic installed capacity increases from less than 1 GW in 2010 to 41 GW in 2025.

On the grid side:

- Grid interconnection capacity significantly increases as several long-distance, high-capacity transmission channels are built.
- Pilots for an intelligent grid begin and an initial framework for a flexible marketplace is established.
- Energy-efficient dispatch or green dispatch and renewable portfolio standards are piloted at a large scale.
- Utilities experiment with more-flexible electricity rates such as dynamic pricing.
- Thanks to those efforts, SO_2 emissions from the electricity sector peak in 2020 and NO_x emissions peak in 2025.

(2) 2025 to 2035: Peak CO_2 emissions from the power sector by further developing renewable power generation

Decarbonization is the key theme for this stage of development in the power sector. The main task of the stage is to peak CO_2 emissions early while meeting growth in electricity demand. To achieve this goal, first coal generation shifts from being used primarily as base load to load following and coal-fired power plants utilize ultra-low-emission technologies.

Second, the development of new and renewable energy is accelerated. Third, demand response is utilized to address fluctuations in both supply and demand. Finally, dispatch and system planning protocols are reformed to better coordinate the development of renewable energy and coal-fired.

Milestones of this period include:

On the demand side:

- Demand response combined with smart appliances and is aggregated and operated by grid companies to help integrate renewable generation.
- Distributed photovoltaic installed capacity increases from 40 GW in 2025 to about 140 GW in 2035.

On the grid side:

- The flexibility of transmission assets and operations steadily improve and innovative modes combining centralized and distributed grid systems emerge.
- The power dispatch market offers payments for capacity, energy, and ancillary services and dynamic pricing is expanded on the retail side.
- CO_2 emissions in the power sector peak around 2030.
- SO_2 and NO_x emissions decrease by roughly 20% compared to 2025 levels.

(3) 2035 to 2050: Cut CO_2 emissions substantially by transforming coal power and rapidly developing wind and solar power

The main task of this stage is to substantially cut CO_2 emissions in the power sector while meeting electricity demand for the entire society. This stage is characterized by the gradual decommissioning of coal-fired plants, the gradual increase of new and renewable energy, and active use of the internet and new smart technologies to enhance the automated and flexible operation of the power system.

Milestones of this period include:

On the demand side:

- Demand response services are deployed universally and intelligent home appliances are ubiquitous.
- Electric vehicle storage will be a major component of the grid storage service.
- Distributed photovoltaic installed capacity increases from 140 GW in 2035 to about 500 GW in 2050.

On the grid side:

- A more-mature flexible service market is established.
- Power dispatch markets are more sophisticated and operate on shorter time scales.
- The grid is increasingly intelligent and supports dynamic interactions between generation and demand.
- 82% of electricity is generated by non-fossil fuel sources in 2050, and renewable energy accounts for 68% of all electricity generation in 2050.
- CO_2 emissions in the power sector decrease from the peak of 2.8 billion tons in 2030 to 1.2 billion tons in 2050, roughly 40% less CO_2 emissions than in 2010.

09

SOLUTIONS & POLICY RECOMMENDATIONS

SOLUTIONS & POLICY RECOMMENDATIONS

Reinventing Fire is technologically, economically, and socially feasible for China, but it will not be realized without a concerted set of policy actions accompanied by market-based solutions. The following recommendations were designed to overcome foreseen barriers and realize the full potential of Reinventing Fire. This set of recommendations is not exhaustive, but was developed to provide policy makers with top-level guidance on important interventions to achieve national goals and the Reinventing Fire vision.

9.1 CLARIFY STRATEGIC GOALS OF REINVENTING FIRE AND ENSURE EARLY IMPLEMENTATION

The roadmaps presented in Chapter 8 encompass technology and development pathways and represent a revolution of similar scale to China's Reform and Opening Policy, but with policies focused on technology, design, business models, and markets. To achieve the objective of Reinventing Fire: China, actions are needed to accelerate the transformation of traditional energy development, production utilization methods, technical systems, and institutional systems. For these reasons, there are two important pieces of guidance for policymakers to consider:

Implement actions early to avoid the lock-in effects of poor energy choices and set the country on a path to harvest smart investments.

- Incorporate the Reinventing Fire strategy during the 13th Five-Year Plan period into economic and social development, urbanization, energy, and other planning policies.
- Measure progress against Reinventing Fire milestones.

Coordinate relationships between short-term and long-term planning and between government and markets to ensure the full scope of the opportunity is addressed.

- Establish long-term investments in energy resources and optimize policy mechanisms to support capture of their economic, environmental, and social benefits.
- Improve market and institutional environments to allow for the adoption of mature renewables and efficiency technologies, while promoting their ongoing improvements in cost, performance, and integration.

9.2 PROMOTE THE ENERGY EFFICIENCY REVOLUTION AND BUILD A NEW URBAN-RURAL ENERGY CONSUMPTION PATTERN THAT PRIORITIZES ENERGY SAVING

Significantly improving energy efficiency and reducing unreasonable energy demand are prerequisites to reinventing the production and consumption of energy. Rebuilding the urban development model is important to reduce demand growth in the industry, buildings, and transportation sectors.

Promote smart growth in all areas of the economy.

- Optimize city siting and design and accelerate the development of compact cities, prioritizing the concepts of energy conservation, smart growth, and new urbanism.
- Promote very low energy consumption buildings, public transportation, electric vehicles, smart grid, and distributed energy systems.
- Increase China's urban and rural living comfort levels alongside low-carbon development measures.

Accelerate the structural shift of industry.

- Develop tertiary industry and advanced manufacturing while promoting significant improvements in energy efficiency and increasing the value add of traditional industries.
- Enhance the quality and performance of industrial raw materials.
- Promote the circular economy in industry.
- Implement compatible development between composite factories (such as of cement or iron and steel) and urbanization.

Strengthen standards and promote low-energy buildings.

- Promote ultra-low-energy buildings for all new construction.
- Strengthen urban and rural construction planning and management and guide the rational distribution and orderly development of new construction.
- Introduce and implement more-stringent building energy efficiency design codes and clarify building energy consumption quota codes.
- Regularly increase the stringency of energy efficiency standards for household appliances, office equipment, and other building energy end uses.
- Improve energy saving policies that use actual energy consumption to control targets.
- Encourage the integration of renewable energy in buildings. In areas with favorable insolation, mandate the use of solar water heaters.
- Develop distributed energy and microgrid systems.
- Develop incentive policies to promote the adoption of high-efficiency biomass energy for heating and cooking in rural areas.

Focus on efficient modes of transportation.

- Build a comprehensive, energy-efficient system with rail as the backbone.
- Employ public transportation as the backbone for mobility in urban areas to reduce traffic congestion and local air pollution.
- Enhance the convenience, comfort, and competitiveness of public transport systems.
- Significantly increase the fuel economy standards of trucks and cars.
- Promote the accelerated adoption of highly-energy-efficient vehicles.
- Increase research and development (R&D) in electric vehicles and hybrid vehicles. Promote scientific advance in technology to support breakthroughs in the areas of battery life, mileage, reliability, service life, and power grid energy storage.
- Accelerate charging station planning and roll out.
- Promote cooperation between electric vehicle development and the grid.
- Encourage the development of alternative oil products such as natural gas and liquid biofuels. Strengthen R&D for hydrogen fuel vehicles.
- Improve differential incentive policies and transport management policies.

9.3 PROMOTE A LOW-CARBON ENERGY SYSTEM BY FOCUSING ON ELECTRICITY SUPPLY

Reinventing Fire incorporates high levels of electrification with aggressive renewable energy development targets, while promoting the transition from centralized to distributed power supplies. Compared to the traditional coal-based supply system, the Reinventing Fire Scenario increases energy system utilization through the symphonic dispatch of hydropower, wind power, solar power, and other renewable electricity at large scale (which reduces losses during the energy transformation process). Multiple related policies are required to make this transition successfully.

Limit new coal-fired power plant construction and mitigate emissions from existing coal-fired plants.

- Strictly limit the construction of new coal-fired power plants.
- Accelerate the retirement of coal-fired units in eastern regions and eliminate inefficient, distributed coal-fired boilers and furnaces.
- Strengthen the constraints on pollutants, CO_2, and other emissions from coal-fired power plants and significantly improve energy efficiency of coal-fired units.
- Strengthen R&D to promote effective participation of coal-fired units in peak load regulation.
- Limit installed capacity of coal-fired units below roughly 1 terawatt (TW) in 2030 and 550 gigawatt (GW) in 2050.
- Rapidly develop low-carbon energy sources.
- Promote the accelerated development of clean low-carbon energy.
- Coordinate the development of wind power to match wind power resources with the transmission capacity of the grid.
- Promote solar energy resource development and encourage distributed solar photovoltaic, solar power generation, and solar thermal utilization.
- Accelerate the development of hydropower resources and comprehensively address the challenges of environmental protection, resettlement, and watershed planning.
- Develop nuclear power safely and efficiently, prioritizing sites near load centers along the coast.
- Accelerate the development of gas-fired power generation to enhance grid flexibility, supporting peak adjustment and the integration of distributed energy.
- Promote the utilization of waste, straw, and biomass generation based on local conditions.

Enhance the grid's ability to deliver services as renewable power capacity increases.

- Enhance power forecast planning; strengthen the linkages between the supply side, power grids, and the demand side; and enhance the ability of frequency and peak load modulation and energy storage.
- Strengthen power grid construction and enhance the interconnection capacity of regional grids.
- Establish a service market for grid flexibility to attract participants in peak load adjustment services through a market platform.
- Develop energy-saving and demand-response potential on the demand side to reduce the need for new generating capacity.
- Optimize the dispatch scheduling process and encourage the participation of flexible power supply (coal-fired units, gas turbines, pumped storage, chemical storage, capacitor energy storage) in peak load optimization.

9.4 ACCELERATE TECHNOLOGICAL INNOVATION TO REALIZE AN INTEGRATED SYSTEM OF INFRASTRUCTURE

By 2050, industrial output will increase by several times and the urban population will grow by about 400 million. By then, many new cities will have emerged. Nationally, infrastructure across the industry, buildings, transportation, and power sectors will have been upgraded, representing a great potential to accelerate the popularization of advanced and mature technologies and promote efficient and clean technology integration.

Increase domestic R&D in energy technology and improve manufacturing.

- Increase investments in science and technology, improve research in energy-related fields, and increase the cost-competitiveness of ultra-low-energy buildings, electric vehicles, renewable power, and high-efficiency equipment and products.

- Strengthen the research, development, demonstration, and deployment of advanced coal-fired units, gas turbines, nuclear power equipment, renewable power generation equipment, and next-generation power grid components to improve domestic manufacturing capacity.

Promote integrated design.

- Promote integrative design in automobiles, buildings, factories, industrial parks and zones, and cities to achieve efficient and optimized use of energy from the source.

- Break regional, industry, and enterprise boundaries to encourage resource integration.

- Integrate the entire process of product design, production, and consumption through policy and markets where practicable.

- Promote compact urban development and urban groups, encourage mixed-use land development, and achieve the integration and development of composite factories, public transportation, and green buildings.

Effectively utilize technology and markets to further harness integrative design.

- Promote the development of intelligent and connected technologies to support solution integration.
- Accelerate the development of smart grids and microgrids, promote two-way adjustments between power grid and photovoltaic-integrated buildings, home appliances, and electric vehicles; and strengthen peak load flexibility of electricity grids.
- Improve pricing mechanisms, encourage business model innovation, and develop an electricity storage service market (including electric vehicles).

9.5 ACCELERATE INSTITUTIONAL AND MECHANISM REFORMS TO RELEASE SYSTEM AND ECOLOGICAL BENEFITS

Strong governance and market reform can promote new forms of industry, technological innovation, and business models; together these can become a driving force for productivity. Deepening the reforms in government supervision and monitoring, energy pricing and markets, railways, power scheduling, and other key sectors can release significant energy savings while promoting the accelerated development of advanced service industries, high-end manufacturing, renewable energy, clean technology, green finance, modern logistics, energy and environmental performance contracting, and other emerging industries. These industries will create new employment opportunities and become a driving force for economic development.

Shift the government's focus to energy targets.

- Value modern and efficient energy services and ecological health as among the most important public goods; measure their progress to create standards for evaluating government performance and governance capability.

- Improve the energy laws, regulations, and standards to promote the industry-wide standard development of energy efficiency first. The government should play a leading role in energy system planning and optimization. Local protectionism and technical monopolies should be avoided.

- Strengthen supervision and management, improve the regulatory and legal systems, promote the role of the public, media, and third parties to exercise their right of supervision according to laws, and ensure effective implementation of energy-saving and environmental protection regulations and standards.

Improve pricing mechanisms, markets, and taxes while encouraging new business models.

- Reform energy prices, including electricity, petroleum, and natural gas.

- Deepen energy market reforms and establish a unified, open, effective, and competitive market system.

- Rationalize pricing mechanisms, including but not limited to capital, labor, land, resources, and the environment.

- Establish fair market competition that truly reflects supply and demand, degree of scarcity, and environmental externalities.

- Reform the resource tax, remove subsidies for fossil fuels, accelerate the introduction of environmental tax and carbon tax, and establish a green, low-carbon price and taxation system.

- Decentralize and streamline governance processes; encourage pilots and promote innovation of new technologies and new business models.

- Reform the electricity sector and transportation sectors.

- Deepen electricity system reform and liberalize generation, distribution, and other competitive areas.

- Promote institutional reforms of grid construction and operation and gradually establish an electricity transmission grid that is accessible, reliable, and flexible.

- Adjust profit models, decoupling profits and sales from production for grid companies.

- Accelerate market reforms for rail and expand financing sources.

- Increase the proportion of intermodal transportation and create policies that incentivize the use of railways before other options.

- Deepen institutional reform of public transport systems by promoting integrated planning of public transport and urban land-use and establishing a management model integrated with planning, construction, and operation.

9.6 EXPAND INTERNATIONAL COLLABORATION TO REALIZE MUTUAL BENEFITS AND WIN-WIN COLLABORATION

The tenets that underlie Reinventing Fire are globally applicable. Reinventing Fire: China draws on a wide range of advanced domestic and international concepts, mature technologies, policy experience, and best practices. But its implementation will require cooperation and international support to promote the transition of global investment and financing systems, trade systems, science and technology systems, and industrial development.

Strengthen international and cross-border collaborations in clean energy.

- Strengthen collaboration in green, low-carbon resource development.
- Encourage regional grid interconnection and increase green and low-carbon energy supply and imports.
- Promote overseas development of China's energy enterprises, strengthen international cooperation, further expand domestic markets, and create a favorable external and internal environment for improving the technological level and competitiveness of low-carbon energy industries.
- Promote global collaboration in energy efficiency and renewable energy, strengthen joint R&D, and promote best practices.
- Encourage the transfer of advanced technologies from developed countries to developing countries and technology transfer among developing countries, while protecting intellectual property.
- Eliminate green trade barriers, increase the supply and demand for energy-efficient advanced technology products, promote trade liberalization of energy-saving and renewable-energy-related products and services, and promote the accelerated adoption and application of energy-efficient and renewable energy technologies and products around the world.

APPENDIX A:
SCENARIO & SECTOR ASSUMPTIONS

A

APPENDIX A

TABLE A.1: MODEL ASSUMPTIONS

	REFERENCE SCENARIO	REINVENTING FIRE SCENARIO
GDP	Achieve national "three step" strategic goals GDP annual growth: 2015–2020 : 7% 2020–2030 : 5.5% 2030–2050 : 3%	Same as the Reference Scenario
Population	The population peaks around 2030 at 1.46 billion; by 2050 the population falls to around 1.37 billion	Same as the Reference Scenario
Per Capita GDP	Reaches $32,000 in 2050 (in constant 2010 dollars)	Same as the Reference Scenario
Industrial Structure	The economic structure is optimized. By 2030, the Service sector is a major component of the economy while the manufacturing sector is focused on heavy industry.	The economic structure is further optimized. By 2050, China reaches the level seen in today's developed countries. Emerging industries and service sector is rapidly developed and the information economy plays an important role.
Urbanization	2020: 60% 2030: 68% 2050: 78%	Same as the Reference Scenario
Imports and Exports	In 2030, the proportion of exports of primary products begins to significantly fall, as energy-intensive products are used to meet domestic demand.	In 2020, the proportion of exports of primary products begins to fall. Energy-intensive products are used to meet domestic demand. Imports of energy-intensive products increase; exports of high-valued-added products increase.
Domestic Environmental Problems	While the environment is more of a focus, pollution remains a serious problem (Kuznetz curve).	China enforces current pollution controls on all point source criteria pollutants and expands these requirements to all stationary point sources by 2020.
Energy Technologies	By 2040, advanced energy technologies are widely used; by 2050, technical efficiency is 30%–40% higher than current levels.	In 2020 advanced energy technologies are widely used and Chinese industry and technologies reach world advanced levels. By 2050, China reaches world leading levels and technical efficiency improves 50% from current levels.
Peak Steel Production	By 2020, steel production peaks at around 850 million tons.	By 2020, steel production peaks at around 680 million tons.
Living Standards	Energy-efficient buildings and home appliances are universal. Residential energy use will be commoditized in rural areas.	Ultra-low-energy buildings and advanced energy-efficient home appliances are universal. Low-carbon, clean energy sources are ubiquitous in rural areas.

	REFERENCE SCENARIO	REINVENTING FIRE SCENARIO
Transportation Development	Rapid development makes public transportation more convenient, and rail transportation will be improved in big cities.	With rapid development, public transportation network becomes extensive, helping to protect the environment. Rail transit is improved. In 2020, rail is fully utilized. Starting from 2020, Internet of Things (IOT) will be fully utilized.
Transportation Technologies	By 2050, there is a 20%–40% improvement in fuel economy.	By 2050, there is a 30%–60% improvement in fuel economy.
Private Vehicles – Percent Electrified	Around 30%.	100%.
Solar, Wind and Other Power	By 2050, solar power costs 0.39 RMB/kWh; onshore wind farms are ubiquitous.	By 2050, solar power costs 0.27 RMB/kWh. Onshore wind is ubiquitous and large offshore wind farms are constructed.
Nuclear Power Development	By 2020, nuclear power provides 53.15 million kW; in 2050 installed capacity reaches 350 million kW. The rapid growth in demand for electricity requires rapid development of nuclear power. By 2030, China will use fourth generation nuclear technology as the country enters a large-scale development phase.	By 2020 nuclear provides 52 million kW; by 2050 installed capacity reaches 220 million kW. Coupling the falling costs for renewable energy with dampened end-user demand for electricity, nuclear power is developed at a slower and more sustained pace.
Coal	Super-critical and ultra-super-critical technologies.	By 2030 China will use super-critical and ultra-super-critical technologies, after it will start to use IGCC.
Hydro	By 2050, installed capacity will reach around 500 million kW.	Same as the Reference Scenario

TABLE A.2: INDUSTRY ASSUMPTIONS

	2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
STRUCTURAL SHIFT			
Total industry value added	11 trillion RMB (2005)	80 trillion RMB (2005)	66 trillion RMB (2005)
Share of low-value-added, energy-intensive industry (value-added basis)	30%	25%	20%
Import/Export	2010 ratios	Reduced exports of energy-intensive products relative to 2010	Further reductions in the export of energy-intensive products relative to the Reference Scenario
PRODUCTION DEMAND REDUCTION			
Building lifetime	N/A	See Table A.3 Building Assumptions	See Table A.3 Building Assumptions
Infrastructure lifetime	N/A	Same proportional increase as the Reference Scenario building lifetime	Same proportional increase as the Reinventing Fire Scenario building lifetime
Recycling	Share of electric arc-furnace (EAF) in iron and steel: 12.4% Share of recycled aluminum: 20.2% Recycled copper: 38.5%	Share of EAF in iron and steel: 30.2% Share of recycled aluminum: 41.2% Recycled copper: 55%	Share of EAF in iron and steel: 41.5% Share of recycled aluminum: 58.1% Recycled copper: 62%
ENERGY EFFICIENCY IMPROVEMENT			
Energy intensity (EI) values for subsector modeled on physical basis	EI based on government statistical data	EI improves to 2015 advanced levels	EI improves to meet or slightly exceeds 2015 advanced economies' levels
EI values for subsector modeled on value-added basis	EI based on government statistical data	EI improves to value between average of advanced companies and least efficient of advanced countries	EI improves to meet or slightly exceeds 2015 advanced economies' levels
DECARBONIZATION			
Fuel mix	Coal (including coke): 59% Gas: 3% Electricity: 19% Petroleum: 10% Other (including heat): 9%	Coal (including coke): 34% Gas: 9% Electricity: 33% Petroleum: 12% Other (including heat): 12%	Coal (including coke): 23% Gas: 12% Electricity: 39% Petroleum: 16% Other (including heat): 11%
Carbon capture, utilization, and storage	None	Same as 2010	Same as 2010 – not cost effective or demonstrated for many industries

TABLE A.3: BUILDING ASSUMPTIONS

	2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
Building lifetime	N/A	1980–1999 construction: 30 years; 2000–2019 construction: 40 years; 2020–2050 construction: 50 years	1980–1999 construction: 30 years; 2000–2009 construction: 40 years; 2010–2019 construction: 50 years; 2020–2050 construction: 70 years
Urban residential: proportion of pre-2010 existing building stock that is retrofitted	2% of existing stock of buildings built before 2010	4.9% of existing stock of buildings built before 2010	75% of existing stock of buildings built before 2010
Urban residential: proportion total floorspace that is new, post-2010 constructed	0%	2020: 43% 2030: 64% 2040: 79% 2050: 90%	2020: 43% 2030: 64% 2040: 79% 2050: 90%
Commercial retrofit: proportion of retrofitted pre-2010 existing building stock	0.4% of stock	0.4% of existing stock of buildings built before 2010	75% of existing stock of buildings built before 2010
Commercial: proportion of new, post-2010 constructed buildings of total floorspace	0%	2020: 46% 2030: 63% 2040: 77% 2050: 87%	2020: 46% 2030: 63% 2040: 77% 2050: 87%
RESIDENTIAL BUILDINGS			
Building vintage shares of pre-2010 existing buildings stock	98% no retrofits, 2% current best practice retrofits	95.1% no retrofits, slow increase to 4.9% current best practice retrofits	Nonlinear decline of no retrofits to 65% in 2020, 45% in 2030, 33% in 2040, and 25% in 2050. Increase of best possible retrofits to 10% in 2020, 25% in 2030, 45% in 2040 and 75% in 2050. Current best practice retrofits is the remaining share.
Building vintage shares of post-2010 new buildings stock	100% current best practice new buildings, 0% ultra-low-energy buildings	100% current best practice new buildings, 0% ultra-low-energy buildings	Increase of ultra-low-energy buildings to 60% by 2050

	2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
Building load changes: space heating		Heating loads increase from 2010 to 2050 in northern, transition, and southern (urban only) China due to demand for greater thermal comfort. Specific loads differ by building vintage types.	Same as the Reference Scenario
Building load changes: cooling		Cooling loads increase significantly from 2010 to 2050 in all climate zones (particularly transition and southern) due to demand for greater thermal comfort	Same as the Reference Scenario
Appliance and equipment efficiency improvements	100% adoption of current existing technology in 2010	Linear shift to 60% adoption of current existing technology and 40% adoption of current super-efficient technology by 2050	Linear shift to 100% adoption of current super-efficient technology by 2050
Fuel switching: heating		Urban: shift away from distributed coal boilers to centralized coal and natural gas district heating. Small increase in share of ground-source heat pumps to 5% by 2050. Rural: decreased shares of coal stoves to 40% by 2050, replaced by growing shares of biomass, coal boilers and some electric heaters.	Urban: faster penetration of air-source heat pump to 10% by 2050 with lower gas district heating shares. Rural: a phase out of all coal stoves by 2050, replaced by growing shares of biomass, solar thermal, air source heat pump and some coal boilers.
Fuel switching: cooking		Urban: declining shares of coal stove, coal gas stove, and LPG cooker, replaced by modern and cleaner natural gas cookers and electric cookers. Rural: decline in coal stoves, replaced by LPG and electric cookers and more biomass.	Urban: complete phase out of all coal-based cooking and faster decline of LPG cookers, replaced with greater shares of electric cookers and natural gas cookers. Rural: complete phase-out of coal stoves and declining shares of LPG cookers, replaced by electric cookers and biomass.
Fuel switching: urban water heating		Decline in electric and coal gas water heater shares and phase out of LPG water heaters, with solar water heaters growing to 30% by 2050 and small increases in natural gas water heaters.	Faster decline in electric heaters and replaced by faster growth in solar water heaters to 50% by 2050. Natural gas water heaters decline slightly.
COMMERCIAL BUILDINGS			
Building vintage: shares of pre-2010 existing building stock	99.6% no retrofits, 0.4% current best practice retrofits	99.6% no retrofits, 0.4% current best practice retrofits	Non-linear decline of no retrofits to 65% in 2020, 45% in 2030, 33% in 2040, and 25% in 2050. Increase of best possible retrofits to 10% in 2020, 25% in 2030, 45% in 2040 and 75% 2050. Current best practice retrofits is the remaining shares.

	2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
Building vintage: shares of post-2010 new building stock	100% current best practice new buildings, 0% ultra-low-energy buildings	100% current best practice new buildings, 0% ultra-low-energy buildings	Increase of ultra-low-energy buildings to 60% by 2050
Building load changes: space heating		Heating loads in northern and transition zones increase significantly	Lower (but still rising) heating loads for best possible retrofits and ultra-low-energy buildings due to superior design and thermal insulation
Building load changes: cooling		Cooling loads increase significantly across all climate zones due to greater demand for cooling and improved thermal comfort	Lower (but still rising) cooling loads for best possible retrofits and ultra-low-energy buildings in all climate zones
Equipment efficiency improvements	100% adoption of current existing technology	60% adoption of current existing technology and 40% adoption of current super-efficient technology by 2050	100% adoption of current super-efficient technology by 2050
Fuel switching: heating		North: slight decrease in coal boiler shares. Small increases in shares of ground-source heat pumps to 5% by 2050 and small increases in coal and gas district heating and electric heaters. Transition: lower shares for coal boilers, replaced by growing shares of gas boilers, 25% air-source, and 5% ground-source heat pumps by 2050. South: shift away from electric heaters to 100% air-source heat pumps by 2050.	North: near phase out of coal and gas boilers towards more coal and gas district heating, with 30% ground-source heat pumps and 10% air-source heat pumps by 2050. Transition: additional decline in coal boilers share by 2050, replaced by 20% ground-source heat pump by 2050. South: phase out of electric heaters and replaced by air-source heat pumps with 90% and ground-source heat pump by 10% by 2050.
Fuel switching: cooling		Geothermal heat pump share increases to 5% in 2050, with declining shares of room air conditioning	Geothermal heat pumps phase out by 2050 with declining shares of room air conditioning, replaced by more centralized air conditioning
Fuel switching: water heating		Declining shares of coal and oil boilers and small cogeneration, replaced with increasing shares of gas boiler	Complete phase out of coal and oil boilers and rapid decline of of gas boilers shares, replaced by 30% solar water heaters, 25% air-source heat pumps, and 14% small cogeneration by 2050.

TABLE A.4: TRANSPORTATION ASSUMPTIONS

		2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
ACTIVITY				
Urban Passenger (billion VKT/year)	Passenger motorized travel demand	1,078	6,184	3,967
Intercity Passenger	Billion pkm/year	2,792	15,389	14,323
Freight	Freight activity (billion ton-km)	14,184	70,085	61,375
	Truck avg load factor (tons)	7.7	8.1	8.1
MODE SHARE				
Urban (% of trips)	Autos (private, fleet and taxis)	48%	62%	58%
	Motorcycle	23%	5%	9%
	Public	30%	34%	33%
Intercity (% of PKT)	Air	14%	21%	12%
	Bus	54%	49%	45%
	HSR	3%	6%	15%
	Regular rail	11%	23%	27%
Freight mode share (% ton-km)	Pipeline	2%	2%	2%
	Water	48%	37%	42%
	Air	0%	0%	0%
	Road	31%	45%	31%
	Rail	19%	16%	24%
FUEL MIX				
Urban (% VKT)	Autos gasoline	99.9	63.3	14.7
	Autos electric	0.0	11.1	38.9
	Autos PHEV	0.0	18.9	40.9
	Bus NG	9.8	25.3	26.6
	Bus EV/PHEV	12.0	38.5	63.3
Intercity (% VKT)	Bus NG	0.0	8.0	15.0
	Intercity bus EV/PHEV	0.0	10.8	70.0
	Regular rail electric	43.3	53.9	100.0

		2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
Truck (% VKT)	NG trucks	0.6%	15.4%	25.8%
	Biofuel trucks	0.0%	3.5%	13.7%
	PHEV trucks	0.0%	0.0%	29.0%
Other Freight (% consumption*)	Other NG	1.6%	5.9%	14.4%
	Other biofuels	0.0%	0.5%	8.2%
	Other elec	1.4%	1.6%	11.8%
VEHICLE EFFICIENCY**				
Urban (L gasoline eq./100km)	All autos avg	6.0	4.5	2.8
	Private car EV	1.6	1.4	1.4
	Private car PHEV	4.1	3.3	3.3
	Private car gasoline	8.4	5.3	4.8
	Public bus average	30.6	20.5	19.5
Intercity (L gasoline eq./100PKT)	Air	3.9	2.8	2.7
	Bus	1.0	1.2	0.6
	HSR	0.4	0.3	0.3
	Other rail	0.1	0.1	0.1
Truck (L diesel eq./100km)	HDT	30.7	21.8	17.8
	LDT	13.9	8.4	6.4
	Other	15.1	11.5	9.1
Other Freight (MJ/ton-km)	Rail	0.07	0.05	0.03
	Water	0.15	0.11	0.11
	Air	11.11	8.07	7.38
	Pipeline	0.60	0.56	0.50

**Final Energy*

***Final energy, weighted average consumption. Diesel: 35.5MJ/L. Gasoline: 31.9MJ/L.*

TABLE A.5: ELECTRIC POWER ASSUMPTIONS

	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
Demand	Follows 2010 policy and energy efficiency technology development trend. Total power demand is 16.1 trillion kWh.	Energy efficiency is greatly enhanced. Total power demand is 11.4 trillion kWh. End-use energy consumption's share of electricity rises from 21% to 41%.
Generation side	Continues 2010's development path – coal power plants are the major generator. Coal power plants mainly provide base load while also meeting ancillary service demand. No change in incentive policyes for renewable energy.	Strictly control the construction of new coal-fired power plants. Employ the restraint of air pollutants and CO_2. Coal-fired power plants provide ancillary services, such as peak load shifting. Set the strategy of developing high penetration of renewable energy.
Customer side	Moderate development of distributed PV. Demand response potential is not fully developed. Limited penetration of EVs. EVs are not able to provide charging/discharging response service for the grid.	Rapid development of distributed PV. Demand response potential of residential, commercial, and industrial sectors is fully developed. High penetration of EVs. EVs provide charging/discharging services for the grid.
Grid side	Weak grid interconnection and intercommunication. Conventional centralized grid system. Current transmitted in one direction (from generation to customer).	Stronger inter-region transmission ability. Stronger intercommunication ability. Both centralized and distributed grid system, with dispatch among both generation and customer side. Larger amount of flexible generation, such as pumped hydro and batteries.
Policy	Conservative guidance. Moderate deployment of technically feasible best practices. Lack of restraints for local pollutant and CO_2 emission. Lack of innovation in both policy and business models supporting zero-carbon power.	Technically feasible best practices are broadly promoted. Significant decline in cost of renewable energy, making it competitive for replacing conventional technologies. Stricter restraints on pollutant and CO_2 emissions. More innovation in both policy and business models supporting zero-carbon power.

TABLE A.6: NON-POWER TRANSFORMATION ASSUMPTIONS

HEAT SUPPLY	2010	REFERENCE SCENARIO 2050	REINVENTING FIRE SCENARIO 2050
Fuel mix	15% natural gas 85% coal bituminous	39% natural gas 61% coal bituminous	49% natural gas 51% coal bituminous
Auxiliary fuel use intensity	0.0675 MTCE input energy per MTCE heat output, divided proportionally among natural gas and coal	0.0675 MTCE input energy per MTCE heat output, divided proportionally among natural gas and coal	0.0675 MTCE input energy per MTCE heat output, divided proportionally among natural gas and coal
COGENERATION			
Fuel mix	7% natural gas 85% coal bituminous 1% coal gangue 7% waste residue	16% natural gas 72% coal bituminous 7% coal gangue 5% waste residue	25% natural gas 65% coal bituminous 3% coal gangue 7% waste residue
Auxiliary fuel use intensity	0.0675 Mtce input energy per Mtce heat output, divided proportionally	Same as 2010	Same as 2010
RESOURCE EXTRACTION: FOSSIL FUEL TYPE			
Crude oil auxiliary fuel use intensity	Electricity: 0.02 tce/toe consumed; Crude oil: 0.01 tce/toe; Natural gas: 0.01 tce/toe. Other fuels used include refinery gas, heat, gasoline, diesel, and heavy oil. Total of 0.05 tce/toe.	Electricity: 0.08 tce/toe consumed; Crude oil: 0.02 tce/toe; Natural Gas: 0.03 tce/toe. Other fuels used include refinery gas, heat, gasoline, diesel, heavy oil. Intensities increase over time to reflect more energy-intensive processes required for difficult-to-extract resources. Total intensity of 0.17 tce/toe based on EROEI of 4.1.	Same as Reference Scenario
Natural gas auxiliary fuel use intensity	Electricity: 0.01 tce/tce produced; Crude oil: 0.01 tce/tce; Natural gas: 0.01 tce/tce. Other fuels used include refinery gas, heat, gasoline, diesel, and heavy oil. Total of 0.03 tce/tce.	Electricity: 0.002 tce/tce consumed; Crude oil: 0.001 tce/tce; Natural gas: 0.001 tce/tce. Other fuel used include refinery gas, heat, gasoline, diesel, and heavy oil. Total intensity of 0.125 tce/tce based on EROEI of 8.	Same as Reference Scenario

COKING			
Auxiliary fuel use intensity	Coal: 0.03 GJ/GJ, Heat: 0.01 GJ/GJ. Other fuels include coking products and electricity.	Coal: 0.02 GJ/GJ, Heat: 0.01 GJ/GJ. Other fuels include coking products and electricity. Intensities lowered by 12–18% between 2010 and 2050.	Same as Reference Scenario
COAL-TO-LIQUIDS			
Auxiliary fuel use intensity	Electricity: 335 kWh/tce produced	Electricity: 335 kWh/tce produced.	Electricity: 335 kWh/tce produced.
COAL-TO-GAS			
Auxiliary fuel use intensity	Electricity: 936 kWh/tce produced.	Electricity: 795 kWh/tce produced.	Electricity: 655 kWh/tce produced.
CRUDE OIL REFINING			
Auxiliary fuel use intensity	Electricity: 0.03 tce/toe consumed; Heat: 0.02 tce/toe; Refinery Gas: 0.02 tce/toe; Natural gas: 0.01 tce/toe; Heavy oil: 0.01 tce/toe	Electricity: 0.05 tce/toe consumed; Heat: 0.03 tce/toe; Refinery gas: 0.03 tce/toe; Natural gas: 0.01 tce/toe; Heavy oil: 0.01 tce/toe. All intensities increase over time to reflect more energy-intensive processes of the deep processing units needed for cracking and cleaner fuel production.	Same as Reference Scenario
BIODIESEL			
Process shares		Esterification: 20%; 80% Pyrolysis and Fischer Tropsch.	Same as Reference Scenario
ETHANOL			
Process shares	Starch ethanol production: 100%; cellulosic ethanol production: 0%	Starch ethanol production: 75%; cellulosic ethanol production: 25%	Starch ethanol production: 0%; cellulosic ethanol production: 100%

APPENDIX B:
DESCRIPTION OF TECHNICAL MODELING APPROACH

B

APPENDIX B

LONG-RANGE ENERGY ALTERNATIVES PLANNING (LEAP) MODEL

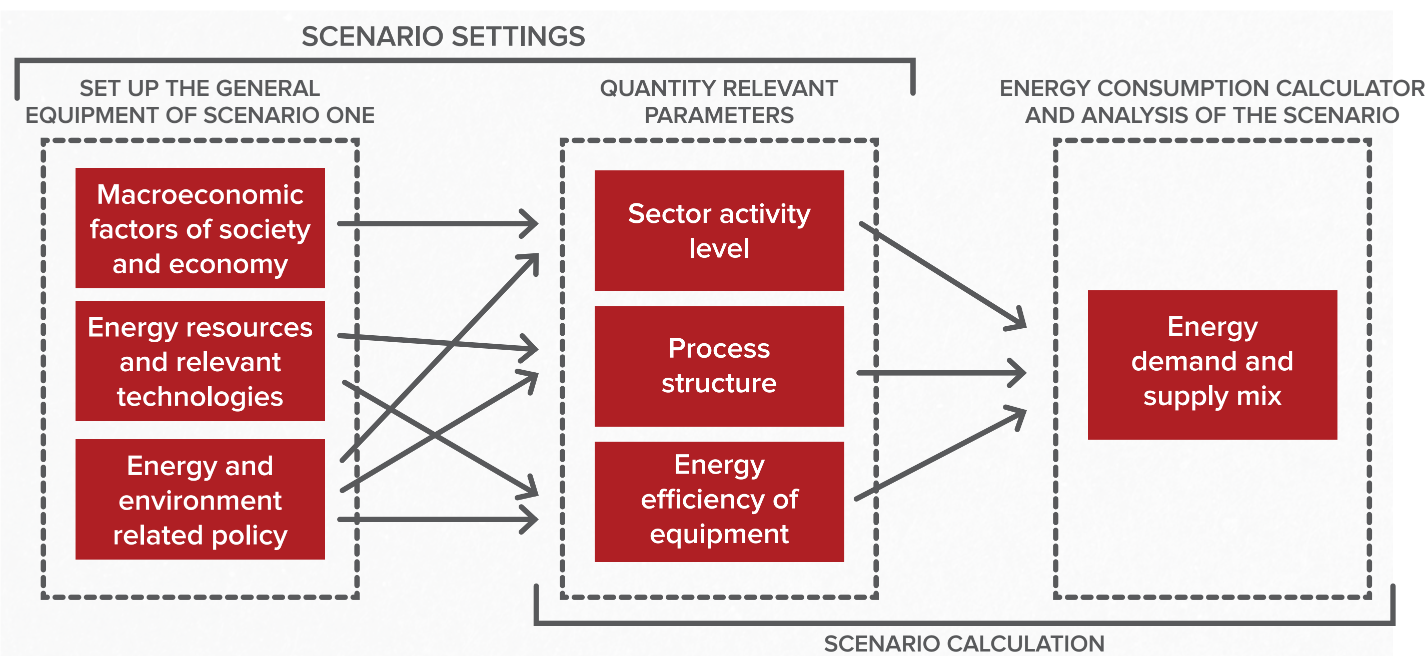
Developed by Stockholm Environment Institute and used in over 190 countries, LEAP is an energy/environmental tool that models national and subnational energy consumption, production, and resource extraction in all sectors of an economy. Driven by macro-economic assumptions, LEAP is a modeling and accounting tool integrating feedback loops within and across the industry, buildings, transportation, and transformation (primary energy supply including electricity) sectors. LEAP is used to calculate energy consumption demand, energy transformation losses, energy supply needs, and related pollutant and greenhouse gas emissions.[i]

ELECTRICITY AND DISTRICT HEATING OPTIMIZATION (EDO) AND POWER LOAD OPTIMIZATION MODEL

The China Renewable Energy Analysis Model – Electricity and District Heating Optimization (CREAM-EDO, or EDO for short) is a power system planning and policy simulation tool co-developed by ERI, China National Renewable Energy Center, Sino-Danish Renewable Energy Development Program, and the U.S. Department of Energy. It is based on the Danish Balmorel modeling engine.[ii] The EDO model is designed to analyze energy systems (especially power systems and combined heat and power systems) and assess technical performance, cost effectiveness, and environmental impacts. It undertakes power source planning and provides comprehensive resource planning, achieving temporal and spatial optimization.

The EDO model is a complex, multi-objective linear optimization tool. Through simple settings of hourly balancing of supply and demand, it simulates China's power generation, transmission expansion, and consumption. Based on production simulation (hourly power balance) and integrating renewable energy into electricity market, this model reflects China's power sector operational environment. The EDO

FIGURE B.1: SCENARIO ANALYSIS AND LEAP MODEL SCHEMATIC



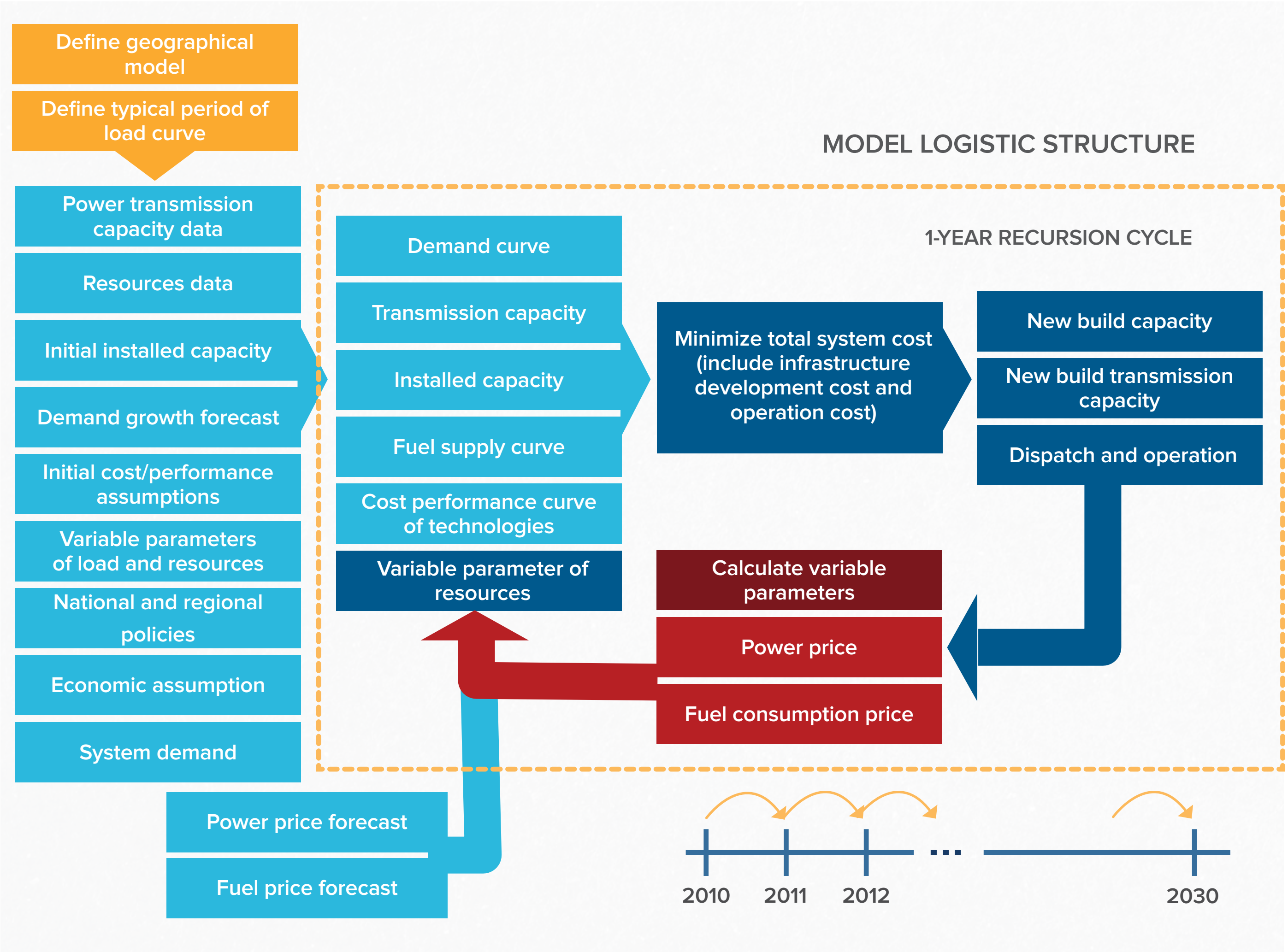
[i] *Community for Energy, Environment and Development (Commend), 2015. An Introduction to LEAP. http://www.energycommunity.org/default.asp?action=47*

[ii] *Balmoral Energy System Model. http://www.eabalmorel.dk/?action=47*

model evaluates types and locations of conventional and renewable energy, transmission infrastructure expansion requirements, and structure and locations of power generation, storage, and demand-side technologies for power supply and demand balance. The model also analyzes the hourly operating conditions of China's power grid when variable solar and wind generation reach high penetration, determines the lowest-cost power generation source (integrating renewable energy), and assesses the added investment and operational costs of adopting the measures that improve renewable energy integration capacity.

The Reinventing Fire: China study constructed a demand response power load optimization tool that links to the EDO model. Using economic and energy parameters, this model evaluates the local energy-saving potential. Based on different local energy-saving potentials, the model can shift the load to reflect the contribution of demand response in reducing power demand, smoothing load curves, reducing the use of peaker plants, and improving economic and environmental benefits.

FIGURE B.2: EDO MODEL ANALYSIS FRAMEWORK



APPENDIX C:
COST-EFFECTIVENESS CALCULATION METHODOLOGY

C

APPENDIX C

C.1 METHODOLOGY OVERVIEW

The cost-effectiveness analysis conducted for this study demonstrates the societal economic effects (excluding health and environmental benefits) of pursuing the Reinventing Fire Scenario compared to the Reference Scenario. The analysis accounts for the increase in infrastructure, capital, and non-fuel operating costs and the decrease in fuel costs between the two scenarios. For each year of the analysis time period (2010–2050), these costs and savings are represented as an annual cash flow. The cash flow is then converted to a net present value (NPV) by summing all annual values and discounting future values at a societal discount rate.

The NPV was calculated as the difference between the discounted cash flows for the Reference and Reinventing Fire Scenarios for the three end-use sectors: industry, buildings, and transportation. To avoid double counting, a NPV was not calculated for the electricity sector. Instead, an electricity price was calculated for each scenario and applied in the three end-use sectors, effectively incorporating the economic impact of changes to electricity provision. Table C.1 presents the overarching assumptions made in the cost-effectiveness analysis.[i]

TABLE C.1: KEY OVERALL ASSUMPTIONS

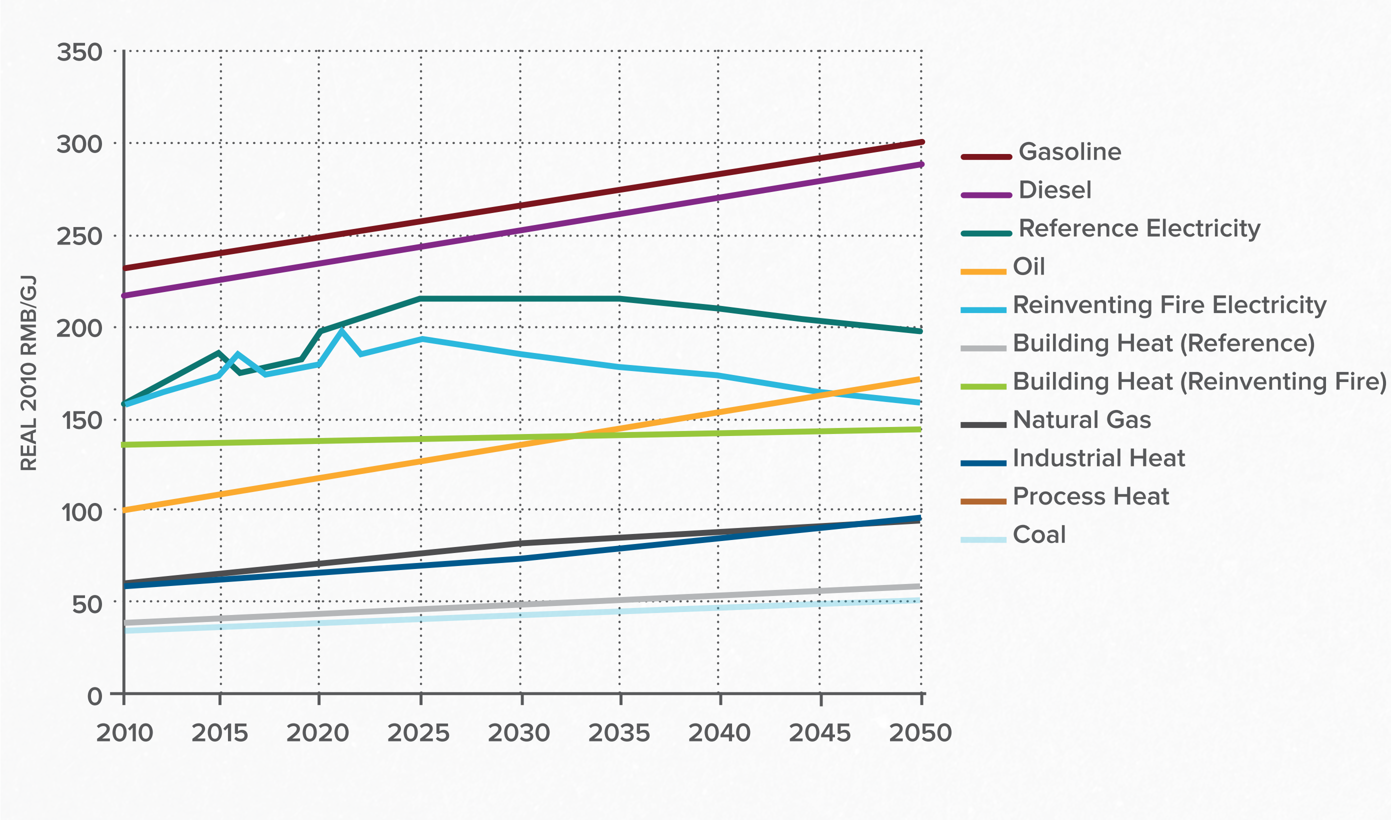
PARAMETER	DATA	SOURCE AND REASONING
Discount rate	5% (net of interest rate)	Based on research by the Asian Development Bank[ii,1]
Exchange rate	6.5 RMB: $1 in 2010	U.S. Federal Reserve[2]
Currency	2010 RMB	2010 is the first year of analysis
Oil and oil based product price projections (including gasoline, diesel)	See Figure C.1	*IEA World Energy Outlook*[3]
Coal price projections	See Figure C.1	ERI internal study
Natural gas price projections	See Figure C.1	ERI internal study
Electricity prices	See Figure C.1	Economic Dispatch Optimization (EDO) model
Building heat, process heat and industrial heat prices	See Figure C.1	U.S. Department of Energy[4]

[i] All fuel prices with the exception of electricity are considered fixed, based on the specified forward projections, and are not adjusted relative to changes in supply and demand. Electricity sector prices were adjusted over time to account for shifts in capital investment for generation, transmission, and distribution. Identical fuel costs were used in both scenarios. Each scenario uses the corresponding electricity price projection. To avoid double counting, a NPV was not calculated for the electricity sector.

[ii] There is little consensus on what level of societal discount rate is appropriate for developing countries. China's 10-year government bonds—a reasonable proxy for the risk-free social discount rate—have ranged between a record low of 2.51% in December 2008 and 4.85% in November 2013. To be conservative, a discount rate of 5% (at the upper end of this range) was used for all NPV calculations.

FIGURE C.1: FUEL PRICE PROJECTIONS

2010–2050



C.1.1 BOUNDARIES

The cost-effectiveness analysis focuses on quantifying the economic impact of fuel savings and the required investment to achieve those savings. As a result, several areas of potential economic impact are omitted from the analysis, including capital costs savings, non-fuel operating costs savings, and any economic impacts on upstream and downstream industries. The analysis excludes all transaction costs (e.g., financing, program costs) as well as environmental or public health benefits (e.g., pollution reduction).

Due to the limitations of the cost-effectiveness analysis, conservative assumptions were made to avoid overstating the economic savings of the Reinventing Fire Scenario. Three key conservative assumptions were made throughout the analysis. First, a societal discount rate was used; this reduces the present day economic value of cash flows in the future. Second, only current, commercially available technologies are included in the analysis. Finally, the cost of efficiency technologies was assumed to stay constant from 2010 to 2050 with three exceptions: efficient appliances in the buildings sector, electric vehicle technologies in the transportation sector, and renewable energy generation and energy storage technologies in the electricity sector. In all of these cases, peer-reviewed papers with established cost curves were used as a justification of the cost reductions. This assumption is conservative because it ignores cost reductions in areas outside of these exceptions.

C.1.2 SENSITIVITIES

The cost-effectiveness analysis is most sensitive to changes in three key areas: 1) discount rate, 2) fuel prices, and 3) capital cost inputs.

To illustrate sensitivities in the first area (discount rate), imagine a cash flow of 100 million RMB (real 2010) that occurs 20 years in the future. With a 5% discount rate, that 100 million RMB has a present value of 35 million. If the discount rate were lowered to 4%, that same cash flow would have a present value of 44 million RMB (real 2010). At a 6% discount rate, the value would drop to 29 million RMB (real 2010).

To capture the sensitivity of the present-value analysis in the other two key areas (fuel prices and capital cost inputs), a sensitivity range is included (reflected as a bar in all economic figures), reflecting high and low estimates for both categories. For capital costs, sensitivities are derived within each end-use sector to account for high and low projections of initial capital costs and differences in learning curve projections.

CASE STUDY C.1: CALCULATING NET PRESENT VALUE: A CASE STUDY ON LIGHTING

In 2015, an investor purchases an light emitting diode (LED) bulb for 30 RMB instead of a compact fluorescent light-bulb (CFL) bulb for 10 RMB. The LED bulb has a lifetime of 23 years. Since a CFL bulb has an eight-year lifetime, the investor gets credit for avoided CFL re-purchases every eight years. This schedule of purchases, repurchases, and avoided purchases gives the incremental capital expenditure cash flow (Figure C.2). Next, assumptions about bulb usage and operating power provide an estimate of annual lighting electricity consumption—12 kWh/year for an LED bulb and 16 kWh/year for a CFL bulb. Multiplying energy consumption estimates by the projected electricity rate for each year gives the difference in annual energy costs. The annual sum of energy cost savings and incremental capital costs is the net cash flow. Summing the annual cash flows of each year between 2015 and 2050 and discounting future cash flows at a societal discount rate of 5% approximates the net present value of the decision to switch from a CFL to an LED in 2015 (Figure C.3).

This analysis can be scaled nationwide by using equipment stock projections from the LEAP model. To calculate residential lighting capital costs across China, multiply the cost (RMB/bulb) by the projected number of newly installed bulbs of each type in each year under the Reference Scenario and Reinventing Fire Scenario (Figure C.4). The overall resulting difference in annual capital costs between the two scenarios is the Reinventing Fire Scenario incremental capital cost for the residential lighting end-use category (Table C.2). For commercial lighting, the calculation is similar, but rather than the number of installed bulbs, the economic model tracks the square meters of floor area served by generic inefficient and efficient lighting systems. Commercial lighting unit capital costs are accordingly defined in terms of costs per square meter.

LEAP model output data is used to calculate the energy savings from switching to more-efficient lighting equipment; this is done by comparing the electricity used by the mix of lighting types in both scenarios (Figure C.4). To calculate electricity price savings, the Reference Scenario price for each year is multiplied by the Reference electricity usage in that year. The same is done for the Reinventing Fire Scenario. Finally, the difference between the two results is calculated (Figure C.5).

Summing annual cash flows—again with future values discounted at the societal discount rate—converts the cash flow into a single NPV for the building lighting end-use category (Figure C.6).

FIGURE C.2: CASH FLOW OF SWITCHING A CFL BULB TO AN LED

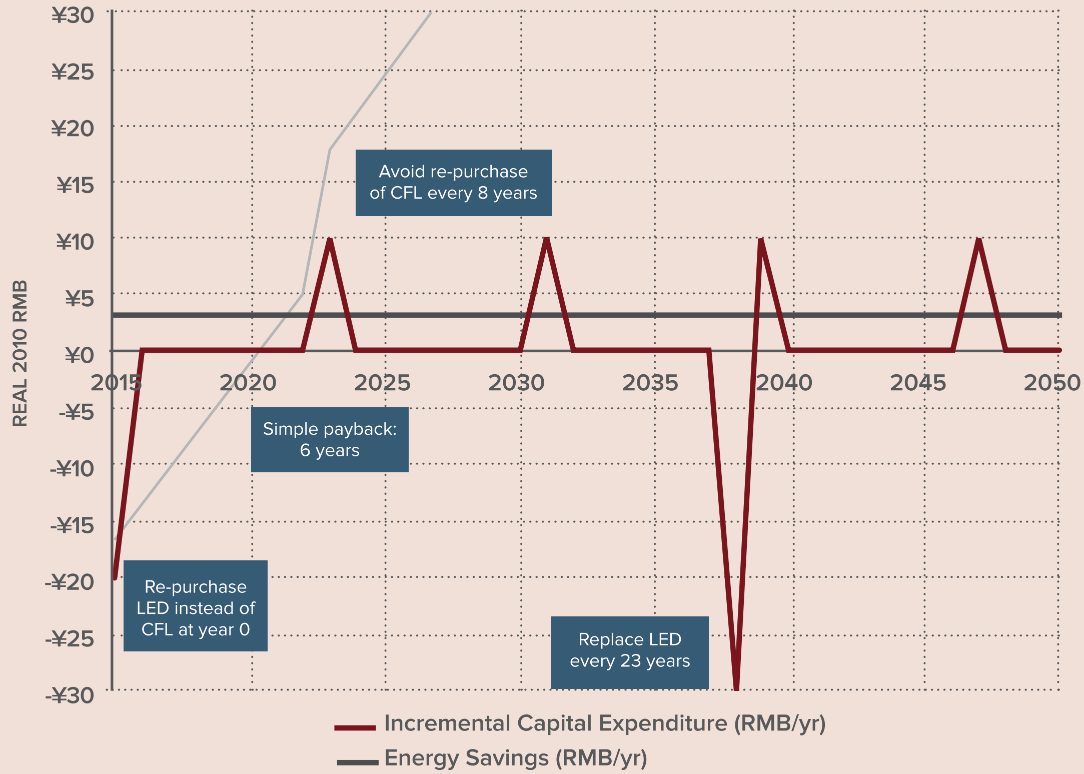


FIGURE C.3: COST, FUEL SAVINGS, AND NET PRESENT VALUE OF SWITCHING TO AN LED

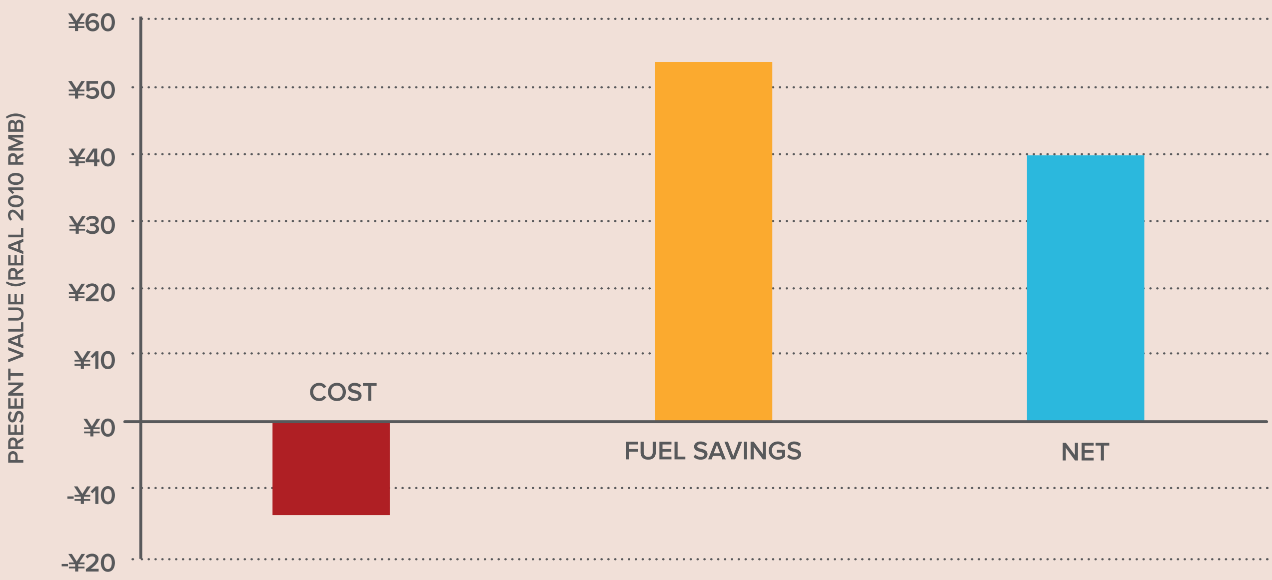


FIGURE C.4: RESIDENTIAL LIGHTING STOCK

2010–2050, REFERENCE AND REINVENTING FIRE SCENARIOS

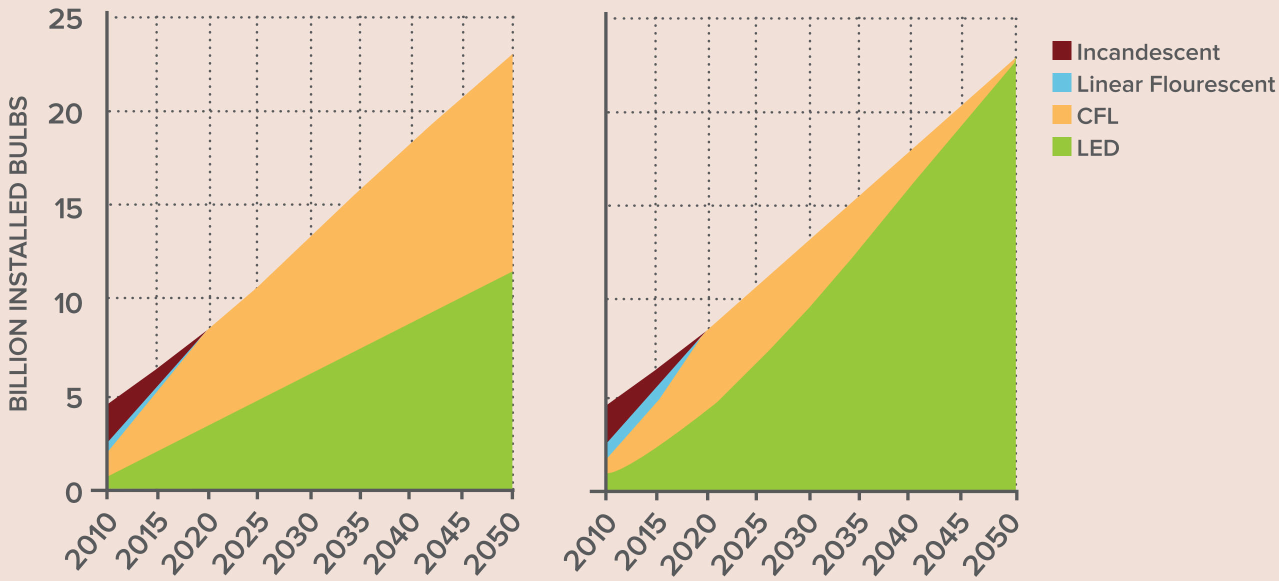


TABLE C.2: LIGHTING ANNUALIZED COSTS USED IN THE BUILDINGS SECTOR ECONOMIC MODEL

	UPFRONT CAPITAL COST[iii]	LIFETIME
RESIDENTIAL	(RMB/BULB)	(YEARS)
CFL	14.56	8
LED	32.11	23
INCANDESCENT	7.16	1
LINEAR FLUORESCENT	11.37	6
COMMERCIAL	(RMB/m_2)	(YEARS)
INEFFICIENT LIGHTING	98	5
EFFICIENT LIGHTING	125	5

[iii] *Estimated based on current retail prices.*

FIGURE C.5: LIGHTING CASH FLOW

2010–2050

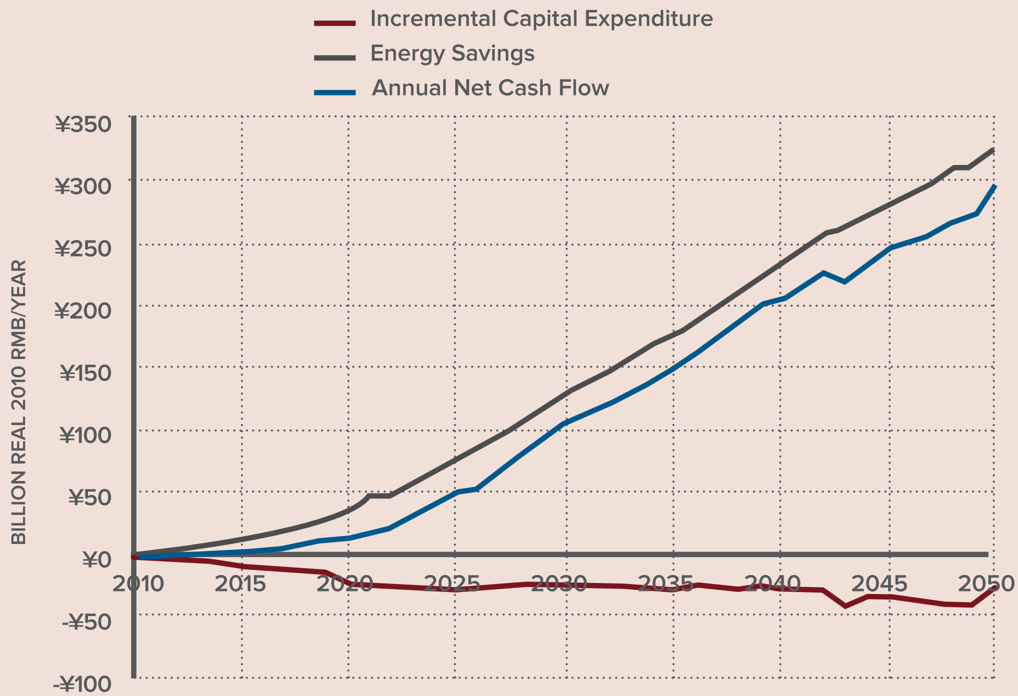
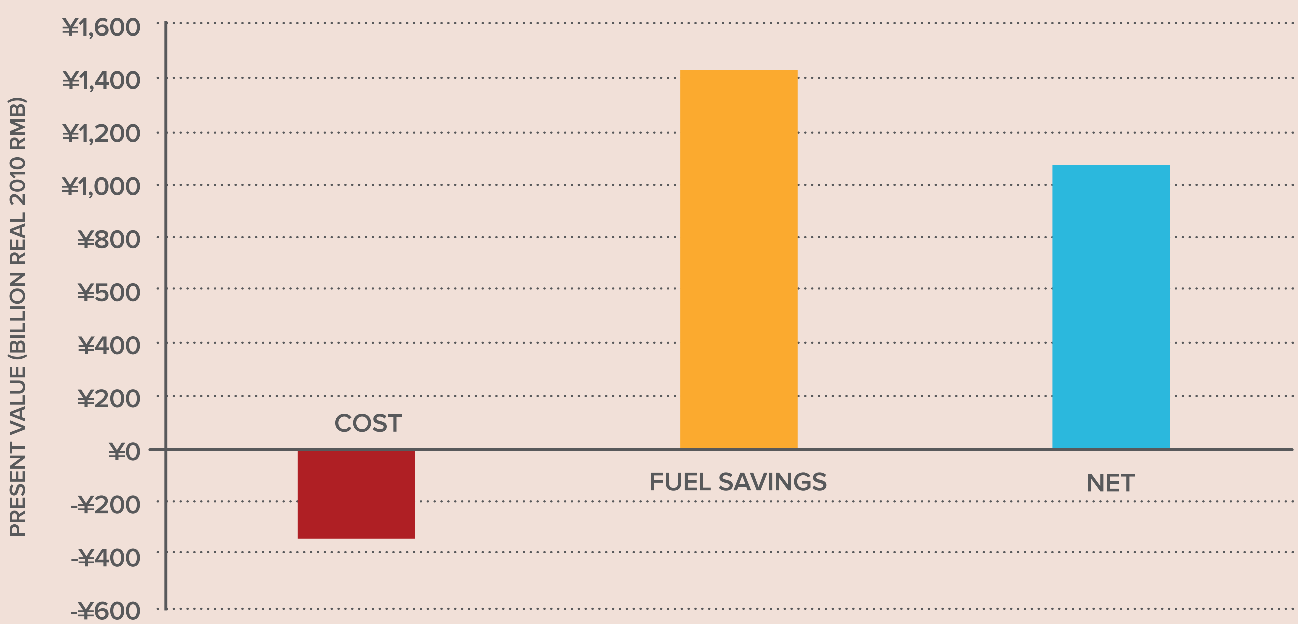


FIGURE C.6: REINVENTING FIRE SCENARIO LIGHTING NPV

2050



C.2 INDUSTRIAL SECTOR METHODOLOGY

There are five key steps in this analysis in calculating the cost effectiveness of the Reinventing Fire Scenario for industry.

1. **Use industry-level conservation supply curves (CSCs) to calculate the average unit cost of energy efficiency for selected industries.**
   CSCs plot the energy savings potential—be it a kWh of electricity or joule of fuel—of energy efficiency measures as a function of the cost of conserved energy (CCE). The cost of conserved energy is calculated by dividing an option's capital costs and non-fuel operations and maintenance costs (O&M) by the option's energy savings.[5] Separate CSCs have been developed for fuel savings (e.g., coal burned on-site) and electricity savings (typically produced off-site); thus, separate average unit costs for fuel efficiency improvements and electricity efficiency improvements were also developed. CSCs distinguish two sets of measures: 1) cost-effective measures (those measures with costs lower than the discounted weighted average price of fuel or electricity) and 2) measures that are not cost effective.

2. **Use system-level CSCs to calculate the average unit cost of energy efficiency for all other industries.**
   45% of industrial energy use—such as chemical materials and products, textiles, food, and machinery—have no CSCs for China. As an alternative, systems-level analyses for motor systems and steam systems were used to evaluate the costs of energy efficiency improvement in these industries.

3. **Calculate yearly (2010–2050) capital costs and subsequent replacement costs using energy savings from the Long-Range Energy Alternatives Planning (LEAP) model.**
   The energy savings difference between the two scenarios from energy efficiency alone, by fuel type, by year, was extracted from the LEAP model. To isolate the energy savings achieved in a given year, only incremental savings were used from one year to the next. Lifetime savings were calculated and multiplied by the average unit cost of energy to estimate total capital costs for that year.[iv]

4. **Calculate yearly (2010 to 2050) energy savings using avoided energy savings from the LEAP model.**
   Fuel savings were calculated by multiplying the fuel savings in a given year by the fuel price forecast for that year. This calculation segregated fuel type as determined by the LEAP model.

5. **Calculate the net present value (NPV) of energy efficiency improvements from 2010 to 2050.**
   The final step is to calculate the net savings by subtracting incremental cost from fuel savings. That is, the total annual cost of conserved energy is subtracted from the total annual value of fuel savings associated with implementation of energy efficiency measures. Having established net costs or savings for each year between 2010 and 2050, a 5% discount rate is used to calculate the NPV of installing energy efficiency measures in the industry sector.

[iv] In the industry analysis, only the cost and savings associated with efficiency technologies are considered. Neither the costs, nor the associated fuel savings of economic structural shift and production demand reduction (due to efficiency in other sectors) were included in the analysis because of the large amount of associated uncertainty.

C.3 BUILDINGS SECTOR METHODOLOGY

The buildings cost-effectiveness analysis compares the incremental investment required to go from the Reference Scenario to the Reinventing Fire Scenario, producing the resulting energy savings.

The analysis detailed in the case study on light bulbs is used for all equipment types—lighting, space heating, space cooling, water heating, cooking, commercial equipment, and residential appliances. Since residential lighting and appliances are tabulated by LEAP in terms of number of units, the economic model capital cost inputs are in terms of cost per unit. All other equipment stock is projected by LEAP in terms of floor area served by the equipment types, so capital cost inputs are in terms of cost per floor area. For each equipment type, separate costs were determined for standard efficiency units and for best-in-class efficiency units. These costs were determined from a variety of sources, such as construction cost estimation publications[6] and web searches for equipment types commonly available from retail vendors. U.S. market equipment costs were converted to Chinese market costs using a multiplier determined by international construction cost surveys.[7]

A similar approach is used for efficiency measures related to building stock, integrative design, and smart systems. Retrofitted floor area is assigned a capital cost distinct from new construction (minus equipment, which is accounted for separately). Capital cost premiums are applied to building stock with prefabricated construction, integrative and passive design, smart systems, and best possible retrofits. Cost for these items were determined from case study research of the building sector in both China and the U.S.

Incremental capital costs for efficient equipment and building design are modeled to reduce over time as the building design and construction industry follows a learning curve and energy efficiency becomes standard practice. The incremental cost of prefabricated construction over standard construction is modeled to drop by 75% by 2035; incremental costs of smart controls reduce by 25% by 2035; incremental costs of integrative and passive design decrease by 50% by 2040; and the incremental cost of efficient equipment over standard equipment drops by 50% by 2035.

The simple cash flow analysis described above does not capture the energy savings benefit of that equipment beyond 2050. To avoid accounting problems that arise from including incremental costs for efficient equipment purchased that continues service beyond 2050 (the end of our analysis period), the economic model calculates an equivalent investment value of the post-2050 years of the equipment stock lifetime and subtracts that amount from the overall cash flow. This aligns the appropriate portion of the incremental investment and the related 2010 to 2050 energy savings.

C.4 TRANSPORT SECTOR METHODOLOGY

Calculating the difference in incremental cost and incremental savings between the Reference and Reinventing Fire Scenario provides the economic impacts for the transportation sector. To determine the incremental costs, the sector was split into two subsectors: freight and passenger transport. The savings were calculated by using the incremental fuel use and fuel price assumptions.

C.4.1 PASSENGER TRANSPORTATION COSTS

The incremental costs for passenger transportation under the Reinventing Fire Scenario were calculated by transport mode. For each mode, capital, operating costs (not including fuel), and infrastructure costs were considered. The incremental cost calculations for each mode of travel followed the formula (where RF stands for Reinventing Fire Scenario and Ref. stands for Reference Scenario):

Incremental cost of RF Scenario for mode 1 of travel =

{"[RF passenger kms traveled]"}_1 x ([RF capital cost per passenger km traveled]1 + [RF operating cost per passenger km traveled] 1 + [RF infrastructure cos per passenger km]1) –

[Ref. passenger kms traveled] 1 x ([Ref. capital cost per passenger kms traveled] 1 + [Ref. operating cost per passenger kms traveled] 1 + [Ref. infrastructure Cost per passenger km traveled] 1)

Importantly, because only fuel savings are considered, if the Reinventing Fire Scenario created net savings in capital, operating, or infrastructure costs within a mode, those savings were not included in the analysis.

C.4.2 FREIGHT TRANSPORTATION COSTS

The incremental costs for freight transportation under the Reinventing Fire Scenario were also determined by mode operating costs (not including fuel, which was considered separately), capital costs, and infrastructure costs.

C.4.2 FUEL SAVINGS

Fuel savings were calculated by multiplying the project's fuel price assumptions by the incremental fuel savings determined by the LEAP model. The results were split into categories; this allows a comparison between the incremental cost and the incremental fuel savings between the two scenarios.

C.5 ELECTRICITY SECTOR METHODOLOGY AND RESULTS

In the electricity sector, instead of calculating a net present value, a cost per kWh of electricity was calculated. Any savings or costs incurred by moving from the Reference Scenario to the Reinventing Fire Scenario in the electricity sector are passed directly through to electricity rates that are then used in the end-use sectors. This methodology allocates the associated costs/savings to the sector responsible for consuming the electricity (i.e., industry, buildings, or transportation), giving a clearer picture of savings by sector.

Electricity is split into generation, transmission, and distribution. Electricity costs were determined using an economic dispatch optimization model: the China Renewable Energy Analysis Model – Electricity and District Heating Optimization (CREAM-EDO, or EDO for short). Using the EDO model, a cost-optimization analysis was performed for each of five-year periods between 2010 and 2050. Average delivery costs were calculated on an annual basis by assessing the cost of capacity (amortized over its lifetime) and the variable costs associated with each asset (based on the full operating hours assigned to that generator in each year). Cost outputs from EDO reflect the true cost to produce, transmit, and distribute electricity to end users (not including overhead, tax or profit margins). These EDO average costs do not reflect the rates paid by consumers—wholesale and retail electricity prices are set by the central government. The EDO average costs break down into six primary components:

- **Capital costs** for new build generators are assigned to each generator type on a RMB/MW basis. Capital costs are updated every 10 years in the EDO model. Capital costs are amortized over the lifetime of the asset. A 5% rate requirement is applied to all capital investments in order to cover financing costs.
- **Transmission and distribution costs** are broken into two costs: capital and operations. Capital costs are based on current costs for transmission assets on a mileage per MW basis and are amortized over the asset lifetime. Operations costs include a minimal amount of operations and maintenance. Line losses are not included here and are instead ascribed to generators.
- **Fuel costs** are aligned with global projections and use regional adjustment factors provided by internal ERI analysis, where available. Fuel prices are consistent between scenarios. Fuel expenditure is assessed based on a generator's operating hours and fuel efficiency.
- **Fixed operations and maintenance (O&M) costs** are assigned by generator type and are based on ERI estimates and global market outlooks. In the Reinventing Fire Scenario, fixed O&M costs for renewable generators decrease more substantially due to improved system integration and technology.
- **Variable operations and maintenance costs** are assigned by generator type and are based on ERI estimates and global market outlooks. Due to the difficulty in assessing changes in variable O&M, it is conservatively assumed they decrease to best in class rates in 2015 and stay consistent until 2050. Due to increased pollution controls and flexible operation for coal plants, fixed O&M for these facilities increase in the Reinventing Fire Scenario.
- **Start-up costs** are flat costs associated with startup support for large plants that go offline for maintenance or grid emergency. The total amount of start-up costs increases in the Reference Scenario because there are more fuel-based generators these charges would apply to. Existing assets use real 2010 operation data

for variable and fixed O&M costs, fuel efficiency, remaining lifetime, and capital costs. Capital costs are amortized based on overall lifetime of the asset, but pay only the annuities for the asset's remaining lifetime.

[v] *Estimated sensitivities in calculation based on methodology could lead to up to a ¥10 trillion RMB variance in net result (¥5 trillion RMB in transportation, ¥3 trillion RMB in buildings, and ¥2 trillion RMB in industry, suggesting the total net benefit over the 40 year timeframe is between ¥5-25 trillion RMB.*

C.6 INTEGRATED RESULTS

The overall NPV of the Reinventing Fire Scenario is demonstrated by summing the NPV of the industry, buildings, and transportation sectors. Associated sensitivities are also summed and indicated using sensitivity bars (Figure ES 10).[v]

[1] *Zhuang et al. May 2007. Asian Development Bank. "Theory and Practice in the Choice of Societal Discount Rate For Cost Benefit Analysis" < http://adb.org/sites/default/files/pub/2007/WP094.pdf>*

[2] *Board of Governors of the Federal Reserve System (U.S.), China / U.S. Foreign Exchange Rate [DEXCHUS], retrieved from FRED, Federal Reserve Bank of St. Louis https://research.stlouisfed.org/fred2/series/DEXCHUS/, July 29, 2015.*

[3] *International Energy Agency. "World Energy Outlook 2014." International Energy Agency, 2014.*

[4] *U.S. Department of Energy. September 2003. "How to Calculate the True Cost of Steam."*

[5] *Hasanbeigi et al. 2012.*

[6] *Ibid.*

[7] *Two corroborating sources:*

EC Harris Research. 2012. International Construction Costs: A Changing World Economy. Page 10. Accessed July 30, 2015. http://www.echarris.com/pdf/Intl%20Construction%20Cost%20Report2012FINAL.pdf

Turner & Townsend. 2012. International Construction Cost Survey 2012. Pages 12 & 36. Accessed July 30, 2015. http://www.turnerandtownsend.com/construction-cost-2012/TT_ICC_Report_Single_Pages_j98ul.pdf.file

APPENDIX D:

CASE STUDIES

D

APPENDIX D

TABLE D.1: INDUSTRY SECTOR CASE STUDIES FOR REINVENTING FIRE: CHINA[i]

A. PRODUCTION/ ENERGY DEMAND REDUCTION	B. ENERGY EFFICIENCY IMPROVEMENT	C. FUEL SWITCHING/CCS	D. STRUCTURAL SHIFT
A1. Higher-quality products and alternative materials a. High-quality concrete – U.S. b. Optimized reinforcing steel – Australia and UK	**B1. Integrative design/system optimization** a. Semiconductor facility – U.S. b. Vehicle assembly plant – U.S.	**C1. Lower-carbon fuels** a. Solar energy in the textile industry – Egypt b. Sewage sludge in the cement industry – China	**D1. Less-energy-intensive processes within industries** a. Non-blast furnace iron-making – South Korea b. Foam technology in fabric finishing – U.S.
A2. Material recycling, material efficiency a. Material recycling through solid bonding – UK and Germany b. Additive manufacturing and 3D printing – U.S.	**B2. Energy-efficient commercial and emerging technologies** a. High-activation grinding for cement making – U.S. b. Near-net-shape casting/ strip casting in steelmaking – North America, Australia, and Japan c. Open-loop sensors/controls – England d. Closed-loop sensors/ controls – New Zealand e. Closed-loop sensors/ controls – U.S. f. Closed-loop sensors/ controls – Canada g. Networks to improve data center energy efficiency – U.S.	**C2. Electrification and on-site electricity generation** a. Electrification using radio frequency heating – U.S. b. Plasma technology in textile wet process c. Heat recovery and electricity generation – Belgium d. Electrification through sensors and controls – Belgium	**D2. Increase high-value-added, lower-intensity industries** a. National strategies to promote green growth – South Korea b. Structural change in industry – U.S.
A3. By-product synergy/ industrial parks a. By-product synergy – China b. Eco-industrial park – Denmark c. Eco-industrial park – South Korea	**B3. Energy management** a. Standard certification and verification – North America b. Energy management systems – Denmark	**C3. CCS** a. Carbon capture and storage in coal liquefaction – China b. Carbon capture, separation, and recovery in steel making – Japan c. Carbon capture, sequestration and use in cement manufacturing – U.S.	**D3. Move from industry to service sector** Tech city clusters – UK

[i] Industrial case studies focused on commercialized technologies and also included examples of emerging technologies. Note that the industrial case studies do not include energy-efficient design for buildings or transport. Design case studies are included in end-use sectors, depending on the end-uses of the products. transportation, ¥3 trillion RMB in buildings, and ¥2 trillion RMB in industry, suggesting the total net benefit over the 40 year timeframe is between ¥5-25 trillion RMB.

TABLE D.2: BUILDINGS SECTOR CASE STUDIES FOR REINVENTING FIRE: CHINA[ii]

A. INTEGRATIVE DESIGN	B. PASSIVE BUILDINGS	C. RENEWABLE AND CLEAN ENERGY	D. SUPER-EFFICIENT APPLIANCES	E. MICROGRIDS AND DEMAND RESPONSE	F. PREFABRICATED BUILDINGS
A1. Maximum whole-building system energy efficiency in a cost-effective way Integrative design of Shenzhen IBR building – China	**B1. Passive House for northern residential buildings** “Passive building” in Qinhuangdao, Hebei Province – China	**C1. On-site generation** Renewable energy at the Tianjin Qibuqu community center – China	**D1. Higher penetration of super-efficient appliances** HP Wynyard Data Center – UK	**E1. Microgrid with distributed generation** St. Francis Hospital and Medical Center – U.S.	**F1. Longer building lifetime** Vanke Shanghai Project – China
A2. Bundled and optimized measures for retrofit Empire State Building – U.S.	**B2. Natural ventilation and shading for southern buildings** NRDC Head Quarter – U.S.	**C2. PV, solar thermal, geothermal** Renewable energy at the DOE National Renewable Energy Lab – U.S.	**D2. Super-efficient appliance** Retrofit on Adobe’s San Jose headquarters – U.S.	**E2. Storage such as battery, EV, fuel cells** Nissan Advanced Technology Center – Japan	**F2. Durable, recyclable material** Private multi-story residential building in Hong Kong – China
	B3. Day lighting NRDC Head Quarter – U.S.	**C3. From coal to natural gas and electricity** Zero-emission city district in Heidelberg Bahnstadt – Germany		**E3. Demand response** 77 West Wacker Drive – U.S.	**F3. Less material intensity** T30 Hotel, Xiangyin – China
				E4. Smart control UNIQA Towers in Vienna – Austria	**F4. Speedy and high quality construction** Wilmslow Park – UK

[ii] *Building case studies focused on emerging technologies both in commercial and residential buildings.*

TABLE D.3: TRANSPORTATION SECTOR CASE STUDIES FOR REINVENTING FIRE: CHINA

A. URBAN TRANSPORT SYSTEMS	B. AUTO EFFICIENCY AND ELECTRIFICATION	C. HIGH-SPEED RAIL OUTCOMPETING AIR TRAVEL	D. FREIGHT MODE SHIFTING	E. FREIGHT LOGISTICS	F. FREIGHT VEHICLE EFFICIENCY	G. OTHER EFFICIENCY
A1. Smart Growth Study in Jinan on superblocks vs. traditional, enclave, or grid development patterns – China	**B1. New PHEV in China** BYD Qin PHEV– China	**C1. HSR vs. Air Travel** In 2009 the opening of the Guangzhou to Wuhan HSR line drastically reduced the amount of air traffic on this route – China	**D1. U.S. Class 1 Railway capacity and bulk handling** Positive NPV of capacity improvement, benchmark for bulk rail mode share – U.S.	**E1. Sinotrans IT and supply chain management** Load factors improved from ~50% to greater than 80%, saving fuel and very cost effective – China	**F1. U.S. Dept. of Energy Supertruck collaboration with Cummins/ Peterbilt and Navistar** Cummins/ Peterbilt and Navistar prototype doubles efficiency with cost effective technologies – U.S.	**G1. Upgraded efficiency in River Shipping** Chongqing Changjiang Shipping Company – China
A2. Car Sharing Car sharing program and a joint venture with automaker Geely – China	**B2. Tesla in China** Tesla's luxury, long-range electric vehicles		**D2. U.S. long distance intermodal corridors** Cost effective and fast LA to Chicago route focused on long-haul exports w/ port integration – U.S.	**E2. Henan logistics for fragmented trucking industry** Henan Freight Exchange: logistics workaround for fragmented industry – China		
A3. Bike Sharing World's largest bike sharing program with over 60,000 bikes – Hangzhou, China			**D3. Competitive shorter intermodal routes** U.S.-FL East Coast Line focused on streamlined shorter-haul domestic movement – U.S.	Walmart or UPS for benchmarking global best practice, further savings potential.– U.S.		

TABLE D.4: ELECTRIC POWER SECTOR CASE STUDIES FOR REINVENTING FIRE: CHINA

A. CENTRALIZED GENERATION	B. DEMAND SIDE	C. GRID SIDE	D. SYSTEMIC OPTIMIZATION
A.1. Integrated Resource Planning a. Brattle Connecticut Case – U.S.	**B.1.Energy Efficiency** a. Seattle City Light (SCL) Home Electricity Report Program – U.S. b. Efficiency Power Plant (EPP) pilots in Jiangsu and Guangdong – China c. On-bill Financing – U.S., UK, Canada d. Transmission and Distribution Rate Reform Pilot in Shenzhen – China	**C.1. Information Communication Technology** a. "E-energy" eTelligence Pilot Project – Germany b. Smart Grid Investment Grant Program in U.S. – U.S. c. Cell Controller Pilot Project in Denmark – Denmark	**D.1. Optimize Dispatch Rules** a. PJM Capacity Market (Reliability Pricing Model) – U.S.
A.2.Flexibility Resources a. Lignite-Fired Power Station at Neurath – Germany b. The value of storage technology to the electricity system – EU	**B.2. Demand Response** a. Demand Response Programs in Eskom South Africa Power Utility – South Africa b. Pacific Gas & Electric Company (PG&E) SmartRateTM – U.S. c. PJM Interconnection Marketization of demand response – U.S.	**C.2. Interconnectivity** a. Interconnection (European Case) – Netherlands, Norway b. Wind variability decreases due to greater geographic diversity – U.S.	**D.2. Reform Electricity Price Signals** a. Dynamic Pricing Program Design – U.S.
A.3. Renewable Energy Procurement and Integration a. Solar Energy Support in Germany – Germany b. Wind Energy Curtailment Practices and Compensation – U.S., Germany, Ireland	**B.3. Distributed Storage and Generation** a. Los Angeles Air Force Base Vehicle-to-Grid program – U.S. b. Solar Business Model (SolarCity) – U.S.	**C.3. Improved Predictive System** a. Advanced Weather Predictive System of Xcel Energy – U.S.	

REINVENTING FIRE: CHINA

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