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A roadmap for China to peak carbon dioxide emissions and achieve a 20% share of non-fossil fuels in primary energy by 2030

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A B S T R A C T

As part of its *Paris Agreement* commitment, China pledged to peak carbon dioxide (CO_2) emissions around 2030, striving to peak earlier, and to increase the non-fossil share of primary energy to 20% by 2030. Yet by the end of 2017, China emitted 28% of the world's energy-related CO_2 emissions, 76% of which were from coal use. How China can reinvent its energy economy cost-effectively while still achieving its commitments was the focus of a three-year joint research project completed in September 2016. Overall, this analysis found that if China follows a pathway in which it aggressively adopts all cost-effective energy efficiency and CO_2 emission reduction technologies while also aggressively moving away from fossil fuels to renewable and other non-fossil resources, it is possible to not only meet its *Paris Agreement* Nationally Determined Contribution (NDC) commitments, but also to reduce its 2050 CO_2 emissions to a level that is 42% below the country's 2010 CO_2 emissions. While numerous barriers exist that will need to be addressed through effective policies and programs in order to realize these potential energy use and emissions reductions, there are also significant local environmental (e.g., air quality), national and global environmental (e.g., mitigation of climate change), human health, and other unquantified benefits that will be realized if this pathway is pursued in China.

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1. Introduction

In September 2016, China ratified the *Paris Agreement* which commits participating parties to "holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" [1]. According to the Intergovernmental Panel on Climate Change's (IPCC's) *Fifth Assessment Report*, to achieve even a 2 °C goal, world greenhouse gas (GHG) emissions must peak between 2010 and 2020, and 2050 emissions should be 41–72% below 2010 levels [2].

China's specific *Paris Agreement* commitments, as conveyed through their Nationally Determined Contributions (NDCs), include peaking carbon dioxide (CO_2) emissions around 2030 and making best efforts to peak early as well as increasing the share of non-fossil fuels in primary energy consumption to around 20% by 2030 [3].[1] China's *13th Five Year Plan* (2016–2020) establishes three important 2020 goals on the pathway towards the 2030 commitments: (1) energy intensity (E/GDP) reduction goal of 15% below 2015 levels by 2020, (2) carbon intensity (CO_2/GDP) reduction goal of 18% below 2015 levels by 2020, and (3) increasing non-fossil energy to at least 15% of total primary energy by 2020 [4,5]. Further, China's *Energy Supply and Consumption Revolution Strategy (2016–2030)* sets goals of capping China's absolute primary energy consumption at or below 5000 million and 6000 million tons of coal equivalent (Mtce)[2] by 2020 and 2030, respectively [6].

Achieving these domestic and international goals will require a significant departure from China's historic patterns of energy consumption and supply. 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 2016, China's GDP increased by 27 times, growing from 1770 billion RMB (2005 prices) to 48,811 billion RMB (2005 prices) [7]. During the same period, China's primary energy consumption increased by seven times (6% average annual growth) [8] (Fig. 1) [9]. China surpassed the U.S. in primary energy consumption around 2010, making it the largest primary energy consumer in the world [10,11]. In 2016, China's primary energy production reached 3460 Mtce [12], accounting for 17% of global primary energy production [13]. In 2016 primary energy consumption per capita reached 3.15 tce, increasing 172% compared to 2000 [14]. In some areas and cities, per capita energy consumption is close to that of developed countries.

While China consumed 22% of the world's primary energy in 2016, it created just 15% (market exchange rate) or 18% (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 [15]. China is constrained by insufficient domestic energy resources that are consumed by inefficient buildings, industries, and transportation systems. In 2015 the industrial sector consumed 70% of China's primary energy and as much as 56% of total coal use [16]. Compared 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 [17].

Fossil fuels still heavily dominate China's energy mix, especially coal (Fig. 2). Between 1980 and 2015 coal use in China grew by six times, from 440 Mtce to 2752 Mtce, and accounted for 64% of primary energy use [18] far exceeding the coal shares in developed and many developing countries.[3] From 1990 to 2015, China's coal consumption grew by approximately 2000 Mtce [19], accounting for 108% of incremental global coal consumption [20].

China is now the world's largest emitter of energy-related CO_2, having surpassed the U.S. in 2006 [21]. In 2016, China accounted for more than 23% of the world's total energy use and nearly 30% and energy-related CO_2 emissions [22]. Even so, China's per capita CO_2 emissions are relatively low on average compared to those of developed economies; in 2015, Chinese emissions were 6.6 tCO_2 per capita compared to about 10 tCO_2 per capita in Germany and Japan and about 16 tCO_2 per capita in the U.S. [23].

In order to understand China's future energy use and emissions and to provide the academic underpinnings for China's domestic and international targets, many organizations in China have recently developed models to simulate various future development pathways. Starting in the early 2000s, various models have been used to forecast China's energy consumption and CO_2 emissions, including: (1) econometric models, autoregressive integrated moving average (ARIMA) models, and Grey prediction models (GM) [24,25], (2) top-down models such as input-output models and computable general equilibrium (CGE) models [26,27], (3) bottom-up models such as the Integrated MARKAL-EFOM System (TIMES) and the Long-range Energy Alternatives Planning (LEAP) model [28–30], and (4) hybrid modeling tools, such as the Integrated Policy Assessment Model for China (IPAC) [31]. From 2005 to 2013, eighteen modeling tools focused on evaluation of China's future energy use and emissions were developed by ten Chinese organizations [32]. During the past five years, a number of new long-term energy and emissions modeling efforts have been conducted in which Chinese research teams worked either in collaboration with non-Chinese research teams or within larger international modeling efforts. Table 1 summarizes the types of models used and the main findings of these recent studies.

This paper describes the results of the Reinventing Fire: China project, a three-year research effort (June 2013 – August 2016) of the Energy Research Institute of China's National Development and Reform Commission, Lawrence Berkeley National Laboratory, and Rocky Mountain Institute that used the Long-Range Energy Alternatives Planning (LEAP) model platform combined with Electricity and District Heating Optimization (EDO) model to provide 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 supply through 2050. This research effort evaluated the potential share of non-fossil energy in China's total energy in 2030 as well as when China's energy-related CO_2 emissions could peak and provided insights on these and other questions to both Chinese and U.S. policymakers as they prepared for the 2014 U.S.*-China Joint Announcement on Climate Change* [33] and the 2015 *Paris Agreement*.

2. Data and methods

The Reinventing Fire: China analysis is a scenario-based assessment that compares two possible energy and emissions pathways for China to 2050. 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. 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

[1] China's NDCs also include lowering CO_2 emissions per unit of GDP by 60% to 65% from the 2005 level and increasing the forest stock volume by around 4.5 billion cubic meters on the 2005 level.

[2] 1 million tons coal equivalent (Mtce) = 0.0293 exajoules (EJ) = 0.0278 quadrillion British thermal units (Quads)

[3] 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 68% in 2015. For information on these conversion methodologies, see Section 2.1.

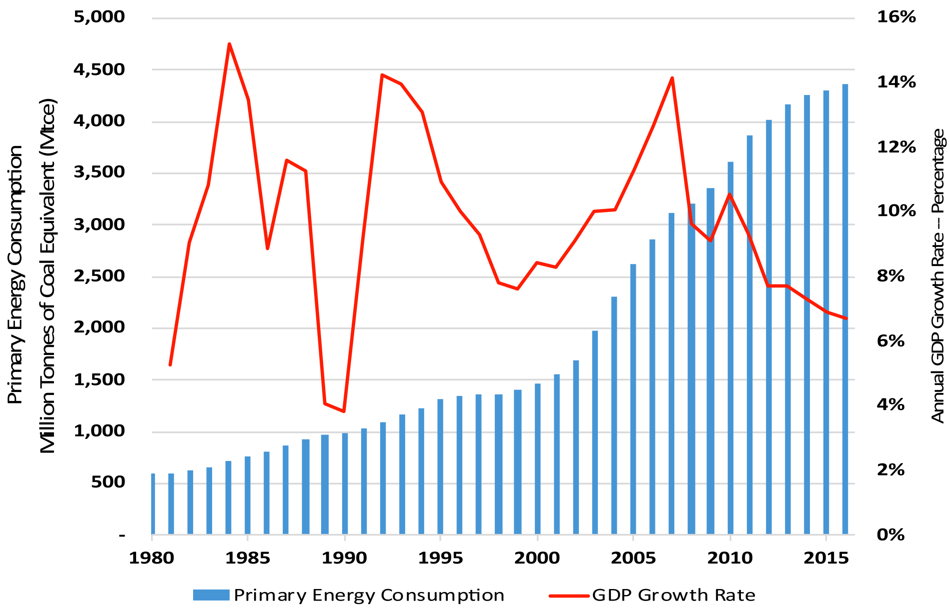


Fig. 1. China's Primary Energy Consumption and Annual GDP Growth Rate, 1980–2016 [8,14].

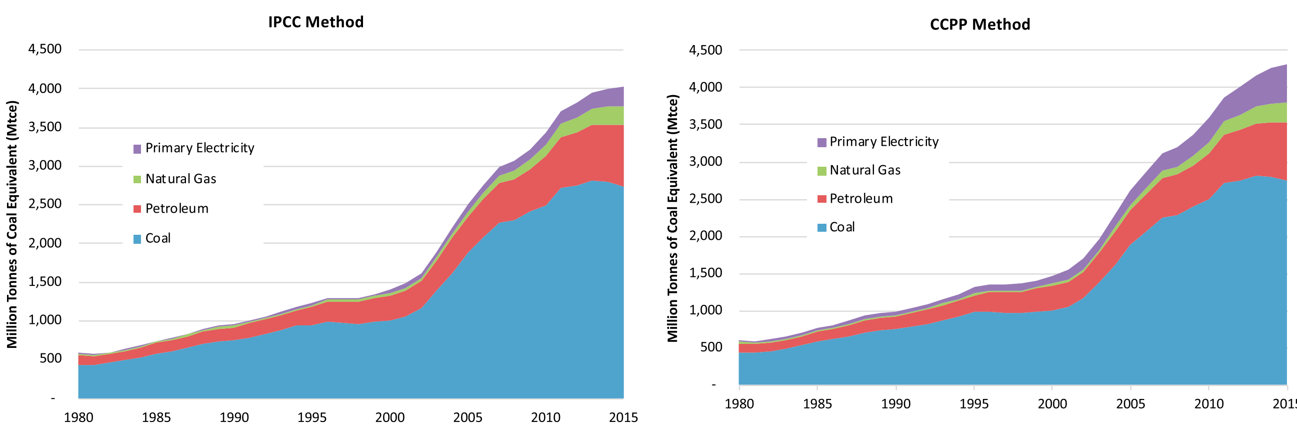


Fig. 2. China's Primary Energy Use by Fuel, 1980–2015 [8]. Note: IPCC method: primary electricity converted using the direct equivalent method (consistent with the IPCC); CCPP method: primary electricity converted using the China Coal Power Plant method.

scenario provides an outlook of the energy demand and structure to reach China's mid-century modernization goals by analyzing future activity levels, structural change, technological advancement, and energy requirements of the industry, buildings, transport, and transformation sectors. 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.[4]

2.1. Data

For both scenarios, the same macroeconomic drivers and assumptions were adopted based on existing Chinese and international projections as shown in Table 2. Each macroeconomic assumption was compared to international projections from the United Nations [42], the U.S. Census Bureau [43], the World Bank [44,45], the U.S. Federal Reserve System [46], the International Energy Agency (IEA) [47], the U.S. Energy Information Administration [48], PricewaterhouseCoopers [49], the Organization for Economic Cooperation and Development (OECD) [50], and the Integrated Assessment Modeling Consortium [51].

The analysis relies on publicly-available energy consumption [55] and other statistical data to calculate and project primary energy, primary electricity, energy-related carbon CO_2, sulfur dioxide (SO_2), nitrous oxide (NO_x), and particulate matter (PM) emissions under the two scenarios.

In calculating total primary energy in standardized energy terms, internationally three different methods are used to convert primary electricity into standardized energy units: the Direct Equivalent Method used by the Intergovernmental Panel on Climate Change (IPCC) [56] and the United Nations [57], the Substitution Method used by the U.S. Energy Information Administration [58], and the Physical Energy Content Method used by the International Energy Agency, the Organization for Economic Cooperation and Development, and Eurostat [59]. In addition to these three methods, China has its own unique Power Plant Coal Consumption (PPCC) method 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 [60]. For example, the conversion for 2010 is 1 kWh = 0.3197 kgce (9.4 MJ) for these resources. This analysis

[4] Appendix A provides the key assumptions for each scenario by sector.

Table 1
Recent China long-term energy and emissions modeling efforts.

Study title	Research teams	Model(s) used	Main findings	Sources
China Coal Consumption Cap Plan and Policy Study Project	Natural Resources Defense Council and numerous Chinese and international experts	CGE model to forecast middle-to-long term economic development and associated societal demand coupled with a STOCK model and an end use model	Coal consumption reached its peak in 2014 and could continue to decrease through zero growth or slight reduction in the industry sector, slower growth in the buildings sector, and controlling dispersed coal use	[34–37]
China Energy and Climate Project	Tsinghua University and the Massachusetts Institute of Technology	China-in-Global Energy Model (C-GEM) and the China Regional Energy Model (C-REM), two recursive-dynamic global computable general equilibrium models	If China continued its existing policies on CO_2 emissions and low carbon economy, plus a higher carbon tax and resources tax, China's CO_2 emissions would peak at 10 $GtCO_2$ around 2030, about 15–20% higher than present levels. By 2050, CO_2 emissions would gradually decrease to 8.6 $GtCO_2$, about 16% higher than the 2010 level	[38]
Deep Decarbonization Pathways Project – China Study	Tsinghua University and the National Center for Climate Change Strategy and International Cooperation (NCSC)	Back-casting method to explore a pathway to meet a global CO_2-energy budget for the period 2011–2050 consistent with a 2 °C limit in global temperature increase, considering energy efficiency and conservation, low-carbon electricity and fuel switching	Under the deep decarbonization pathway, China's GDP grows more than 6 times from 2010 to 2050, primary energy consumption peaks at about 6,586 Mtce around the year 2040 and gradually declines to 6,226 Mtce in 2050. China's energy-related CO_2 emissions peak at about 11.5 $GtCO_2$ around 2030 and decrease to 5.2 $GtCO_2$ in 2050, 37% lower than the 2010 level	[39]
New Climate Economy	Tsinghua University's Institute of Energy, Environment, and Economy	Dynamic general equilibrium model	Under an Accelerated Emissions Reduction Scenario, coal use peaks by 2020, energy-related CO_2 emissions peak by 2030 at around 10.6 $GtCO_2$, and primary energy consumption peaks by 2040 due to enhanced structural change, technology improvement, behavior change, and accelerated adoption of low-carbon and pollution control technologies	[40]
China 2050 High Renewable Energy Penetration Scenario and Roadmap Study	China National Renewable Energy Centre (CNREC, part of the Sino-Danish Renewable Energy Development Programme), with the China Energy Storage Alliance, China's State Grid, Tsinghua University, the Energy Research Institute, Energy Foundation China, and others	Regional power deployment optimization model integrating technical and economic evaluation, power system production simulation, macroeconomic impact assessment, and policy evaluation	Analyzed the technical and economic feasibility of increasing renewable energy by overcoming the policy, regulatory, market, and institutional barriers and found that it is both technically and economically feasible for renewable energy to satisfy over 60% of China's primary energy consumption and 85% of electricity consumption by 2050. Under the high renewable energy penetration scenario, the study found that China will be able to peak fossil energy consumption and CO_2 emissions by 2025	[41]

Table 2
Macroeconomic drivers and assumptions for both scenarios.

	2010	2020	2030	2040	2050	Refs
Total Population (billions)	1.34	1.42	1.44	1.42	1.37	[52]
Urbanization Rate (% of Population)	50%	60%	68%	74%	78%	[52]
Decadal Annual Average GDP Growth Rate (%)	**2010–2020**	**2020–2030**	**2030–2040**	**2040–2050**		[52,53,54]
	7.6%	5.9%	4.1%	2.9%		

Table 3
IPCC and China-specific emissions factors for coal, petroleum, and natural gas.

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

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).

Energy-related CO_2 emissions at the national, sector, and sub-sector levels are calculated using the primary energy values for bituminous coal, natural gas, and crude oil and oil products and China-specific CO_2 emissions factors for these fuels. 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. The sum of CO_2 emissions from coal, natural gas, and 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 3) [61,62]. 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.

2.2. Methods and 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 [63] and combines ERI's previously constructed 2050 sector analysis modules with LBNL's China 2050 Demand Resource Energy Analysis Model (DREAM). 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.[5] Results from the EDO analysis are integrated into the LEAP model to create a final integrated Reinventing Fire: China 2050 model. For additional information on these two modeling platforms and how they have been used to create the integrated Reinventing Fire: China model, see Appendix B.

The Reinventing Fire: China analysis focuses on three key end-use energy-consuming sectors of China's economy: industry, buildings, and transportation. For each sector, extensive research and modeling were 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. Technical improvement options were considered for each sector that efficiently and cost-effectively reduce demand and environmental impacts.

The industry sector has 21 subsectors, 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, has residential, commercial, and public buildings and 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 Reinventing Fire: China 2050 model includes the industry, buildings, and transport sectors and also includes power, agriculture, construction, mining, oil refining, coking, coal to oil/gas, and other non-power transformation sectors. 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.

This study establishes systematic 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 transport 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 transport sector, the impact on energy-intensive products by promoting industrial eco-parks, integrative buildings, and electric vehicles, and the impact on industry, transport, buildings, and power sector activities from urbanization.

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. The 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, 78 case studies provided insights to the Reinventing Fire: China analysis.

[5] 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.

Finally, experts from diverse disciplines guided the Reinventing Fire: China research, assisting in the calibration of assumptions and offering critical feedback throughout the three years of research. 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 ten times during the 36-month project and helped establish the initial scope of the work, highlighted critical areas of focus, and assessed interim and final results. The project team conducted a series of in-depth sector and sub-sector reviews in May 2014, mid-way through the project research. The expert feedback checked assumptions and model results, helped identify new case studies, and assessed the practicality of the solutions identified. Finally, individual experts and reviewers both in China and internationally answered questions and reviewed results on a regular basis throughout the project.

3. Results and discussion

3.1. Industry sector

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 [64].[6] 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. 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 2006. In 2015, primary energy consumption of China's industrial sector resulted in 70% of the country's total energy-related emissions [65,66] (6.9 $GtCO_2$), more than the entire energy-related CO_2 emissions of the U.S. or the European Union [67]. Industry 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 [68].

Despite a recent slowdown in China's GDP growth and industrial activity, demand for energy-intensive raw materials and products continues due to urbanization, the associated increase in domestic commodity consumption, and manufacturing exports. 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 [69]. 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 [70,64].

3.1.1. Industry sector pathways

The goal of the Reinventing Fire Scenario for industry is to define a pathway for China's industry to be world-class in terms of energy efficiency and to move away from carbon-intensive fuels. Primary energy savings from China's industry sector in 2050 result from: (1) structural shifts, (2) production demand reduction, and (3) energy-efficiency improvements. Additional energy-related CO_2 emissions reductions are gained by (4) fuel switching to lower-CO_2-emitting fuels coupled with increased electrification, following the decarbonization of the electric grid.

3.1.1.1. Structural shift. Two types of structural shift will occur in China's industrial sector: (1) overall structural shift from the industrial sector to the service sector and (2) structural shift within industry from low-value-added, energy-intensive industry to high-value-added, less-energy-intensive industry. As China begins to transform from the world's factory—producing manufactured goods for both domestic and export markets—to a more service-oriented economy, the share of industrial value added in China's total GDP will fall. Within industry, the role of resource- and capital-intensive industries—such as mining, steel, and cement— will decline due to cost and other market pressures. 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 [71], which is significantly higher than China's current level of 27% [72].

3.1.1.2. Demand reduction. Reduced demand for energy-intensive industrial products can result from: (1) increase in building and commodity life-times through changed practices and the use of higher-quality materials, (2) smarter use of materials through intelligent designs, and (3) increased recycling and remanufacturing of materials. In 2014, 4.2 billion m^2 of buildings and infrastructure was under construction in China [73], more than all construction in all developed countries [74]. The average lifetime of Chinese buildings in urban areas is 25–30 years [75] significantly lower than the average building lifetime of 60 years in the U.S. [76]. Further, 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 [77]. While producing recycled steel from scrap steel requires only one-third the energy required to produce steel from iron ore and other raw materials [78], the proportion of electric arc-furnace (EAF) steel, which predominately uses scrap steel as a raw material, in China has been only about 10%, far below the level of 30–50% in many industrialized countries [79]. There are significant opportunities to increase recycling of aluminum, copper, paper, glass, and other resources in China.

3.1.1.3. Energy efficiency. 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. These options are sector-wide (e.g., efficient electric motors; high efficiency boilers and process heaters; fuel switching), process-specific (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) [80]. Integrative design and system optimization often yield large savings by optimizing whole systems for multiple benefits instead of components for single benefits.[7] Accelerating development of technologies that support information technology, especially for improving production of automobiles, aircraft, ships, machinery, and household electric appliances, increases overall production efficiency. Advanced sensing and controls will speed the development of smart energy systems that includes 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.

3.1.1.4. Fuel-switching and decarbonization. Decarbonizing China's

[6] 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 sub-sectors: 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.

[7] For real world examples of this in practice, see RMI's work in retrofitting the Empire State Building: http://blog.rmi.org/blog_empire_state_retrofit_surpasses_energy_savings_expectations; and RMI's redesign of data centers: http://www.rmi.org/Knowledge-Center/Library/E08-06_SystemsThinkingDataCenters.

industrial sector by 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) is an important means to optimize the industrial sector's energy consumption structure and address environmental pollution.[8] Coal is the dominant fuel that provides power and thermal energy for Chinese industrial production and is an important industrial production material, especially for 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 [64]. There is a large potential for electrification in China's industrial sector. In the steel industry, highly-energy-intensive steel production using blast furnaces and basic oxygen furnaces can be replaced by less-energy-intensive EAFs 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. Reducing CO_2 consistently over time requires the coordinated development of low-carbon electricity supply as industrial processes are electrified.

3.1.2. Industry sector results

In the Reinventing Fire Scenario, the GDP of China's industrial sector increases from 15.3 trillion RMB in 2010 to 75.2 trillion RMB in 2050 while energy consumption decreases, with 2050 energy consumption of China's industrial sector 32% lower than the 2010 value, decoupling energy consumption from economic growth.[9] Under this scenario, industrial sector energy intensity (energy consumption per unit of industrial GDP) in 2050 is 86% lower than the 2010 level, falling more than 4.8% per year on average over 40 years.

Fig. 3 shows that industrial sector primary energy consumption in the Reinventing Fire Scenario 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. Total primary energy consumption of China's industrial sector peaks around 2020 at 2300 Mtce in the Reinventing Fire Scenario, a decade earlier than the other demand sectors, and is critical for supporting China's goal to peak national CO_2 emissions by 2030. 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).

In terms of structural shift, the share of industrial value added in China's total GDP falls from 40% in 2010 to 33% in the Reference Scenario and 28% in the Reinventing Fire Scenario in 2050 [81]. In the Reinventing Fire Scenario, China's equipment manufacturing industries grow more rapidly than in the Reference Scenario. The added value of these and other high-value-added industries in Reinventing Fire Scenario in 2050 is nearly 12% higher than that of the Reference Scenario.

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. By reducing unnecessary major demolition and construction, material demand can be cut by 20% by 2050 relative to 2010 while providing the same service [82]. 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 [83]. 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.[10]

Every industrial sub-sector in China shows significant autonomous energy-intensity improvements between 2010 and 2050 in the Reference Scenario, 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 industry surpasses 2010 world best practice values by 2050 and exceeds the Reference Scenario by 13–27%, depending on the sub-sector. To achieve this, industrial facilities: (1) fully adopt currently available commercialized technologies—including sophisticated management and control systems, (2) rely more heavily on integrative design 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, and (3) use advanced sensing and control technology to increase efficiency.

In 2050 the share of coal in final energy use in China's industrial sector drops to 25% in the Reinventing Fire Scenario, decreasing by more than half compared with the 2010 level. Compared with the Reference Scenario, coal's share in the Reinventing Fire Scenario in 2050 is 15% lower (Fig. 4). The share of electricity in final energy consumption increases from 19% in 2010 to 38% in 2050 in the Reinventing Fire Scenario, 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. 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.

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 2000 $MtCO_2$ (48%) in 2050 relative to the Reference Scenario. Sulfur dioxide, nitrogen oxides, particulate matter, and other pollution emissions will also decrease 70–80% relative to 2010 levels. In the Reinventing Fire Scenario, 2050 CO_2 savings are realized through structural shift (500 Mt CO_2), production demand reduction (260 Mt CO_2), energy-efficiency improvement (1080 Mt CO_2), and decarbonization (160 Mt CO_2) relative to the Reference Scenario (Fig. 5).

3.1.3. Barriers and policy approaches

To realize the Reinventing Fire Scenario in China's industrial sector, barriers such as the continued demand for manufactured products for urban development and consumption, 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, an artificially low (or zero) cost for waste treatment and disposal, a lack of financial resources to invest in efficient technologies and measures, risk of production disruptions, a

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

[9] 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.

[10] Industrial production activity forecasts were developed in consultation with various Chinese industry experts.

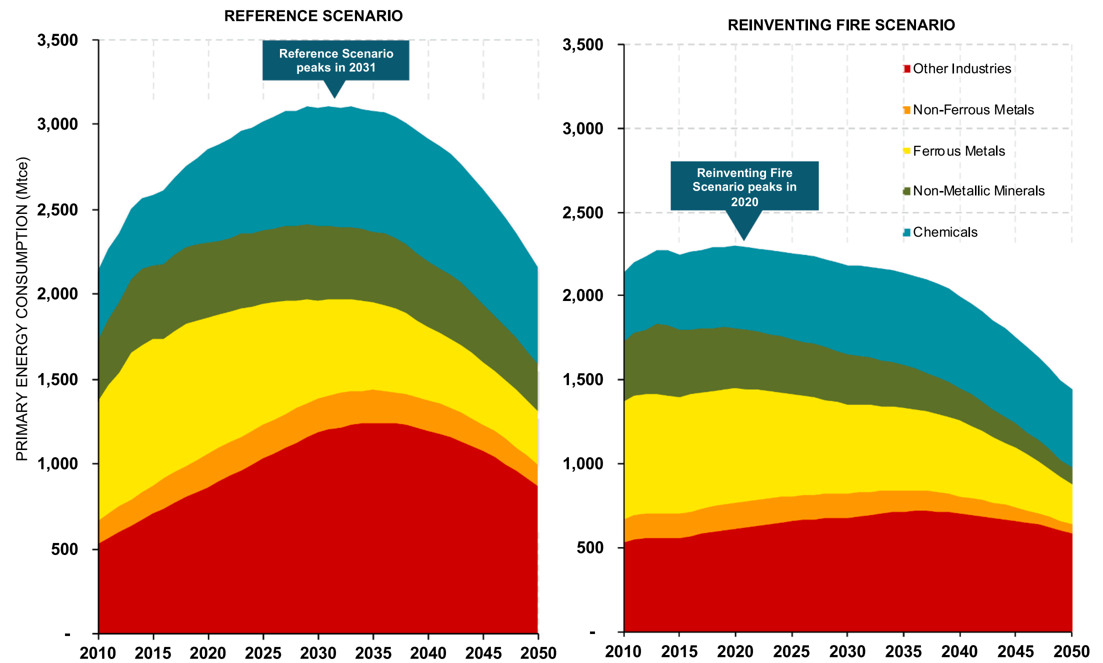
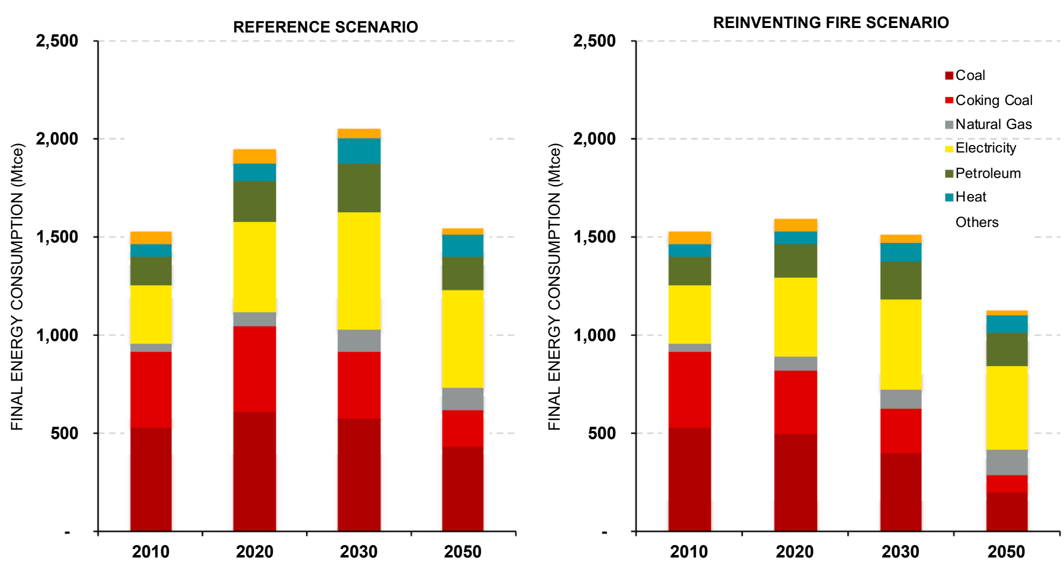


Fig. 3. Primary Energy Consumption of China's Industrial Sector under the Reference and Reinventing Fire Scenarios, 2010–2050.



	2010	2020	2030	2050		2010	2020	2030	2050
Coal/Coke share Percent	60	54	44	40		60	51	41	25
Electricity share Percent	19	24	29	32		19	25	30	38

Fig. 4. Final Energy Consumption of China's Industrial Sector under the Reference and Reinventing Fire Scenarios, 2010–2050.

general lack of information and knowledge of energy-efficiency options, the high cost and lack of domestic low-carbon fuels, the fact that fossil-fuel prices do not reflect their full costs, and the need for significant research and development before carbon capture, use, and storage (CCUS) can be applied in the industrial sector all need to be addressed.

Policy approaches to mitigate these barriers include stimulating structural change by providing incentives such as tax rebates or easier permitting for high-value-added and low-energy-consuming industries, continue the policy of closing small and inefficient manufacturing facilities, promoting long-term urban planning regulations that require high-quality construction practices, developing standards and incentives coupled with strong enforcement to promote higher-quality products and material efficiency, promoting market-based approaches to encourage production demand reduction such as performance rating and labeling schemes that incentivize the use of high quality and recycled materials, transforming existing industrial parks and key enterprises with the concept of eco-design circular economy, establishing municipal waste and waste recycling systems, establishing a nationwide energy-efficiency benchmarking program to identify and reward the most efficient industrial facilities and provide appropriate incentives for

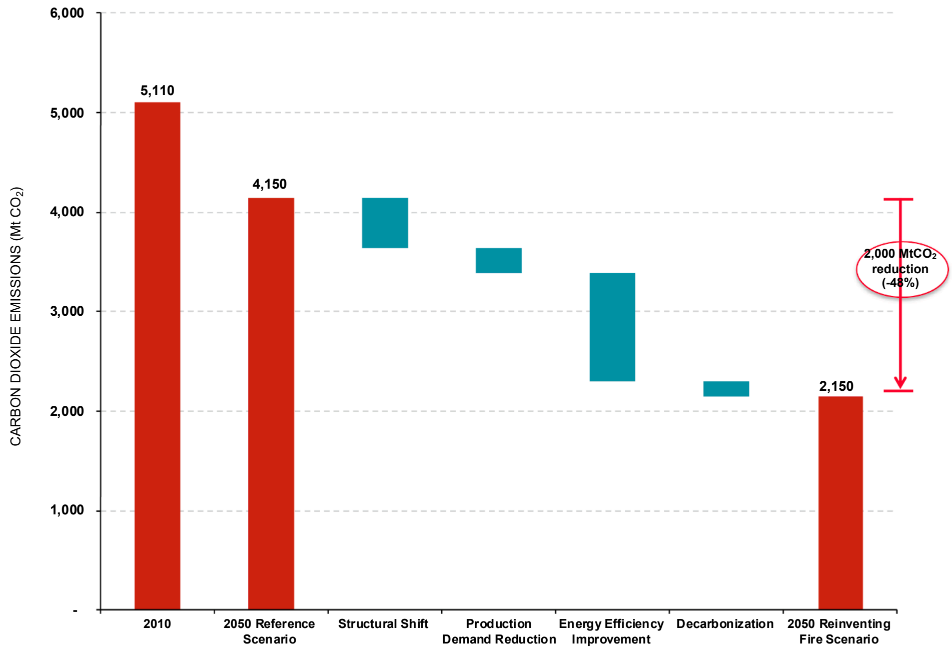


Fig. 5. Reinventing Fire Scenario Energy-Related CO_2 Emission Reductions Pathway for the Industrial Sector, 2010–2050.

less efficient facilities to reduce their energy intensity, improving 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 [84,85], promoting demonstration of best practices in energy efficiency (such as energy management systems that enable continuous improvement) and integrative design, establishing a nationwide CO_2 cap-and-trade program or carbon/fuel tax to stimulate a shift from coal to low-carbon fuels, and developing comprehensive policies to promote combined heat and power as well as distributed generation in the industrial sector in China.

3.2. Buildings sector

Dwarfed by the industrial sector, the share of China's building energy consumption is about 20% of the country's total primary energy [86], significantly lower than the 40% typical of developed countries [87]. In recent years, China's building energy consumption has been increasing rapidly and is projected to increase further since energy use per unit of floor space and energy use per capita are far less than in many developed countries [86]. 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 [88]. 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 [89].

Due to rapid economic growth over the last several decades, China is the world's largest market for new building construction, adding 1.8–2.0 billion m^2 of floor space annually [90]. 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 1706 Mt respectively, representing about 12% of the year's national energy use [91]. China's urbanization rate will increase from 50% of total population in 2010 to 68% in 2030, adding 280 million people to cities [92], driving growth in household incomes and leading to larger household sizes, increased use of energy-consuming appliances, and growth in residential energy. Urban households consume more energy than rural households, particularly of non-biofuels [93]. In China's commercial buildings, 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 [94].

Across its vast land mass, China's climatic zones encompass cold northern winters, hot and humid southern summers, and mixed seasons in transition areas. Envelope thermal integrity and infiltration are key problems in Chinese buildings. Many buildings are not metered or properly controlled and few buildings are commissioned—resulting in higher energy consumption than designed. Low-quality construction, short building lifetimes, and extensive development are significant issues for China's buildings sector. Appliance and equipment efficiency lag behind international levels. 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.

3.2.1. Building sector pathways

The goal of the Reinventing Fire Scenario for the buildings sector is to define a pathway for China's buildings and communities to be self-sustained and resilient with increased comfort levels. In this scenario, China's buildings 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. Primary energy savings and reductions of energy-related CO_2 emissions from China's building sector in 2050 result from full adoption of: (1) advanced construction practices, (2) integrative design, passive strategies, and retrofits, (3) super-efficient equipment and appliances, (4) smart systems, and (5) clean energy sources.

3.2.1.1. Advanced construction practices. Advanced construction practices include controlling floor space growth through policies that

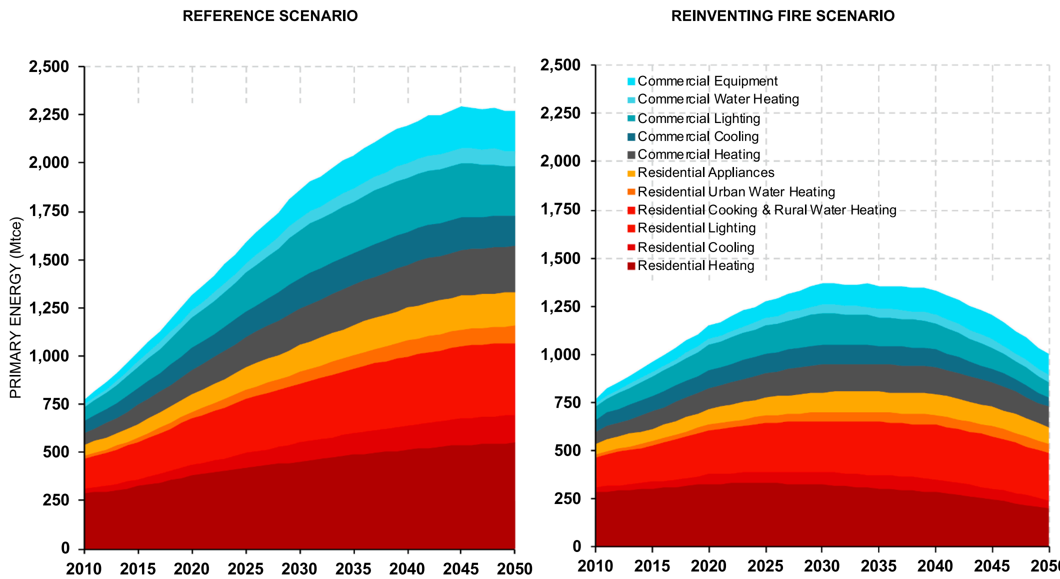


Fig. 6. Primary Energy Consumption of China's Residential and Commercial Buildings under the Reference and Reinventing Fire Scenarios, 2010–2050.

discourage rapid new urban construction and demolition of older buildings (China demolished 345–460 million m^2 buildings each year during the 11th Five Year Plan that had not reached their end-of-life) [95] and promoting compact layouts that improve building space utilization and decrease overall building envelope area and its associated energy losses. New buildings can be constructed for durability and adaptability through prefabrication which dramatically reduces material waste and on-site construction time and improves quality and durability, increases building lifespan, and ensures greater building thermal integrity and better energy performance. Prefabricated buildings in China and elsewhere have increased lifetimes by 10–15 years [96], reduced construction material loss by 60%, and decreased overall building waste by 80% [97].

3.2.1.2. Integrative design, passive strategies, and retrofits. Integrative design is an approach to optimize technologies and components at the whole-building level, enabling cost trade-offs among multiple energy-related building systems (e.g., envelope, appliances, lighting, ventilation, cooling, and heating) to reach a high level of energy performance at zero or little added cost [98]. Passive design is a "bioclimatic" (sensitive to the local climate and occupants) design and construction approach with as little reliance on mechanical systems as possible, using strategies such as daylighting, shading, thermal mass, and natural ventilation to reduce energy consumption. Energy retrofits can improve building operation, decrease operating costs, 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.

3.2.1.3. Super-efficient equipment and appliances. Super-efficient equipment and appliances can reduce the primary energy demand of buildings, focusing on the largest end-uses in 2050 under the Reinventing Fire Scenario of residential heating (20% of building sector energy), residential cooking and water heating (19%), and residential end uses include appliances (9%), cooling (4%), and lighting (5%) along with commercial lighting (8%), heating (11%), equipment (11%), cooling (5%), and water heating (4%). Buildings not connected to a distributed heating system can use air-source heat pumps and new ultra-low energy buildings with low heating loads can rely on air source heat pumps, electric heating, and other decentralized systems.

3.2.1.4. Smart systems. Smart system technologies for buildings include sensors, controls, data access, and analytics for performing fault detection and diagnosis, and optimizing operations across systems for improved efficiency, reliability, and maintainability. For commercial buildings, this approach 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 and tenants to understand a building's relative energy performance. Smart systems also enable retrofit service providers and others interested in reducing energy use to target the buildings with greatest opportunity for efficiency improvement and enable the tracking of national building energy use intensity.

3.2.1.5. Clean energy sources. Energy-related CO_2 emissions reductions can be realized by using cleaner energy sources in buildings through switching on-site equipment to cleaner energy sources, installing rooftop solar photovoltaic systems, purchasing electric power generated from low-polluting fuels, and utilizing waste heat as an energy source (where possible). Switching to clean site energy sources can nearly eliminate coal boilers and coal stoves in northern climates and significantly reduce their use in transition climates. This includes the use of cleaner district heating in the north and increased use of electric heating, particularly air-source and ground-source heat pumps, in both the north and transition zones.

3.2.2. Building sector results

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. 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 [99].

Building lifetimes for both scenarios are the same for existing pre-2000 buildings (30 years) and 2000–2009 buildings (40 years). Due to better materials and construction methods in the Reinventing Fire Scenario, 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.

Under the Reference Scenario, China's 2050 primary energy in the buildings sector increases 195% to 2270 Mtce (Fig. 6). Space heating and cooling represent the largest energy uses in residential and commercial buildings. Growth in floor area and increased thermal comfort in residential buildings increase heating and cooling primary energy use two- and six-fold, respectively, from 2010 to 2050. In commercial buildings, growth in the amount of floor area cooled result in a 150% increase in primary energy use for cooling.

In the Reinventing Fire Scenario, the annual primary energy use of China's buildings in 2050 increases significantly less − 30% - to 1000 Mtce compared to the actual 2010 value of 770 Mtce. The total primary energy savings for the buildings sector is 1270 Mtce compared to the Reference Scenario. The Reinventing Fire Scenario achieves increased comfort with slightly lower primary energy use for cooling due to the more rapid penetration of efficient air conditioners and the prevalence of load-reducing strategies, resulting in savings of 110 Mtce in 2050 compared to the Reference Scenario. Load reducing strategies also result in decreased annual residential heating energy consumption and only a two-fold increase in annual residential cooling energy consumption.

Under the Reinventing Fire Scenario, 2050 primary energy consumption for residential and commercial buildings total 1000 Mtce, a savings of 56% compared to the Reference Scenario 2050 total. Primary energy use peaks in 2031 at 1370 Mtce and decreases thereafter. The largest savings in 2050 in the Reinventing Fire Scenario, 410 Mtce or 44% of total annual primary energy, are from the increased adoption of integrative design, passive strategies, and retrofits for commercial and residential buildings. The second largest savings potential (370 Mtce), 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

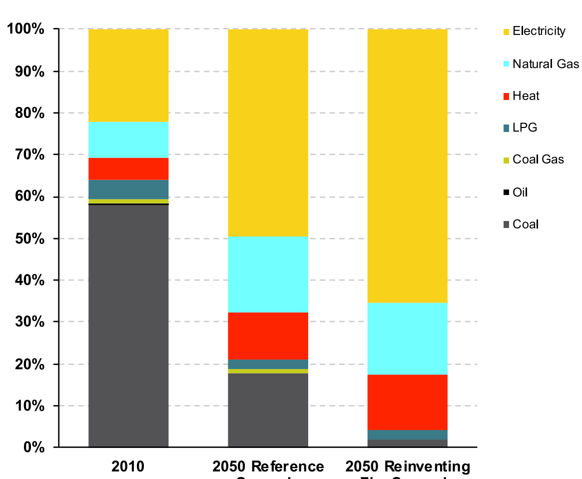


Fig. 7. Final Energy Consumption of China's Buildings Sector under the Reference and Reinventing Fire Scenarios, 2010–2050.

incorporates aggressive adoption of today's global best-in-class technologies, achieving 100% market penetration by 2050. 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. Energy efficiency retrofits of buildings, adoption of smart systems, and building prefabrication (including savings from less material waste), contribute primary energy savings of 150 Mtce, 130 Mtce, and 120 Mtce, respectively. Incorporating smart systems into building operation accounts for 10% of the total 2050 primary energy savings under the Reinventing Fire Scenario.

In 2050, China's buildings have transitioned to cleaner fuels are significantly electrified (50% in the Reference Scenario and 66% in the Reinventing Fire Scenario) (Fig. 7). By 2050, coal use has been reduced to 18% in the Reference Scenario and nearly eliminated in the Reinventing Fire Scenario.

Fig. 8 shows that in the Reinventing Fire Scenario, annual energy-related CO_2 emissions in buildings are 1010 $MtCO_2$ by 2050, or 46% lower than the 2010 CO_2 emissions of 1880 $MtCO_2$. The projected emissions for the Reinventing Fire Scenario are 2890 $MtCO_2$ lower (74%) than the Reference Scenario. The largest CO_2 emissions reductions in the buildings sectors come from key energy efficiency related strategies of integrative/passive design (690 $MtCO_2$) and super-efficient equipment/appliances (670 $MtCO_2$), building retrofits (270 $MtCO_2$), and smart systems (245 $MtCO_2$). 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. Prefabrication accounts for 100 $MtCO_2$ reduction in the buildings sector with additional 130 Mt CO_2 reduction in the industrial sector when less construction material waste is included. Clean energy sources for on-site end-use equipment (600 $MtCO_2$) and clean energy sources for power generation (315 $MtCO_2$) together account for nearly one-third of the total emissions reductions. Fuel switching also has a relatively large impact on CO_2 emissions reductions in the buildings sector because of the combined effects of increased electrification with significant decarbonization of the power sector.

3.2.3. *Barriers and policy approaches*

The key barriers to realizing the Reinventing Fire Scenario in China's buildings sector can be summarized as follows: the practice by cities of demolishing existing buildings before the end of their useful lives for economic stimulus, and rapidly constructing buildings with low-quality materials; a lack of stringent codes and standards that raise the threshold for new building design and quality; a lack training for designers, builders, and operators to implement energy-efficient and integrated design approaches to ensure construction quality, and operate the building as intended [100,101]; the lack of using actual energy consumption as building energy codes and standards requirements; inadequate specialized knowledge and a weak infrastructure for compliance monitoring among building code implementation officials [102]; lack of public awareness of building energy use and data transparency to publicly disclose building energy information; outdated appliance efficiency standards laws and regulations coupled with very limited financial and human resources for both standards development and enforcement; lack of information for consumers and building owners on the most efficient appliances or products; high upfront costs and split incentives that inhibit purchases of more efficient products as well as smart building systems; high upfront costs of new equipment for clean energy sources; and the lack of availability or accessibility to cleaner energy sources such as solar.

Policy approaches to mitigate these barriers include: establishing a comprehensive national government-led system for urban planning to avoid urban sprawl that incorporates sustainable urban form principles into urban planning regulations; adopting property taxes to reduce the

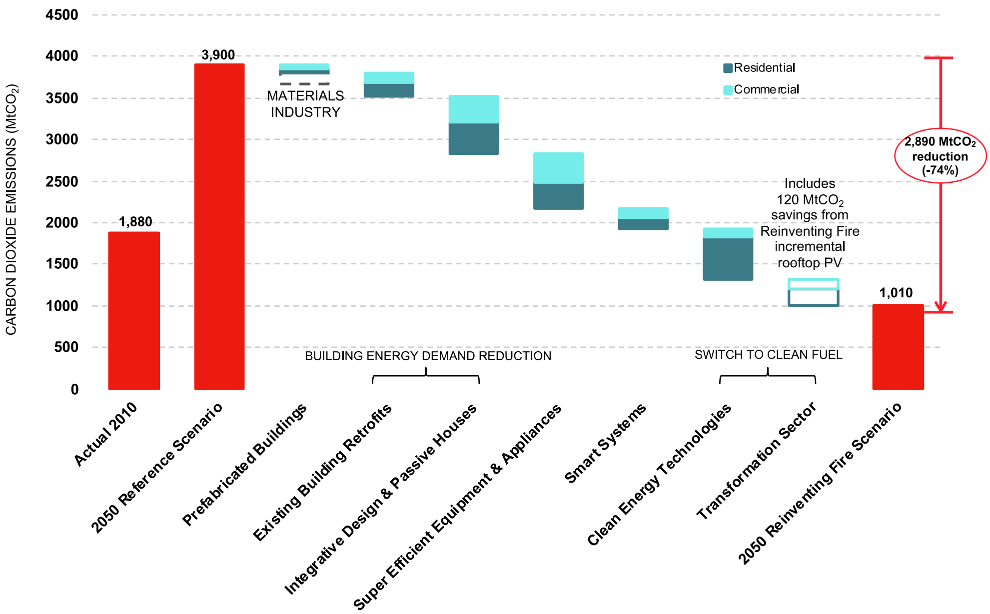


Fig. 8. Reinventing Fire Scenario Energy-Related CO_2 Emission Reductions Pathway for the Buildings Sector, 2010–2050. Note: (1) Black dashed box indicates savings from less wasteful construction accounted for as part of the Industry Sector, (2) blue outlined boxes indicate savings from cleaner power used by buildings generated by the Transformation Sector. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unoccupied building rate and discourage excessive demand for housing purchase; promoting the development of smaller size urban residences and more efficient affordable housing units; improving the quality of building materials; improving the standardization of prefabricated building design, construction, and components production; establishing building energy consumption indexes and benchmarks; disclosing building energy information especially for state and municipal buildings; implementing outcome-based energy consumption standards for different types of buildings especially the standard for ultra-low energy buildings; establishing codes, standards, and construction regulations for passive houses, focusing codes on whole-building energy use; setting more ambitious targets and roadmaps for longer-term buildings and appliances codes and standards (2030 and 2050) and updating periodically with timelines to achieve best available levels internationally; establishing information/statistical systems for building energy consumption data; introducing innovative financing models for building efficiency projects; offering government incentives (financing or tax policies) to offset the cost of energy-saving retrofits and attract more energy service companies to the market; establishing designated budgets for standards enforcement and market surveillance at national and local levels; conducting consistent national enforcement check-testing, possibly with targeted sampling; conducting more trainings and capacity building on energy efficient and low carbon design, practices and equipment; and supporting the reform of the electricity sector and pricing formation.

3.3. Transportation sector

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%. China's transportation sector consumed 383 Mtce of primary energy in 2015, of which 302 Mtce or about 80%, came from petroleum products. In 2015, transportation accounted for 61% of total oil demand in China. In 2010, internal-combustion powered vehicles accounted for over 70% of the sector's total oil consumption, with 44% of the sector total used by freight trucks alone. Rapidly increasing car ownership is the largest contributor growth in oil demand; 47% of the total new demand between 2000 and 2009 came from automobiles [73].

The key driving force in passenger transportation demand in China has been urbanization and associated increasing incomes. In the last 15 years, private vehicle ownership accelerated as urban transportation demand grew [103] and intercity passenger transport moved away from rail travel and towards road and air travel [73]. 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 [104].

Similarly, in freight transportation growing demand for goods movement and an increasing reliance on trucks have been the main drivers in energy demand growth. Freight demand remains positively correlated to GDP growth, albeit with a declining elasticity as per capita incomes increase, and, in the Reference Scenario, mode share continues to deteriorate as economic growth increasingly comes from consumption, which tends to favor the flexibility and reliability provided by trucks.

3.3.1. Transportation sector pathways

The goal of the Reinventing Fire Scenario for the transportation sector is for China's transportation systems to provide increased mobility with fewer emissions and lower costs. By 2050, it is envisioned that China will have the world's most efficient, multimodal transportation system featuring efficient vehicles running on low-carbon fuels. Primary energy savings from China's transport sector in 2050 result from: (1) reducing unnecessary transport demand, (2) optimizing transportation mode shares, and (3) improving vehicle energy efficiency. Additional energy-related CO_2 emissions reductions are gained by (4) shifting to clean fuels coupled with increased electrification, following the decarbonization of the electric grid.

3.3.1.1. Reducing demand. Transportation demand in China can be reduced through changes in the size and layout of cities around the country and the layout of infrastructure within cities. Smart growth rationally utilizes existing urban land, balancing residential areas and commercial areas in city design (i.e., mixed use development), establishing public transportation networks that enable and shape development, developing non-motorized transit infrastructure, and reducing sprawl. Additionally, information and communication technology (ICT) can be used to replace passenger trips with e-commerce and telecommuting while also streamlining freight logistics.

Structural economic shifts towards service industries and high-value-added manufacturing are important means of reducing freight demand [105]. Encouraging goods sourcing from strategically positioned industrial sites and cities can reduce the distance that freight travels and reduce overall energy demand from freight transportation [106]. Efficient logistics decrease lengths of haul, reduce empty running and improve load factors. These logistics improvements will increase in importance as China shifts towards higher value goods that require fast, flexible, and reliable delivery [107].

3.3.1.2. Optimizing trans portation mode s hares For urban passenger transport, mode shift entails reducing the use of private cars while increasing the use of public transit or non-motorized modes such as walking or bicycling. Cities can manage private automobile use through congestion pricing and parking policy reform. 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. Simultaneously, providing high-throughput convenient public transport and non-motorized transport infrastructure can ensure that reduction in car use does not create a reduction in mobility. On intercity passenger transit, mode shift is primarily accomplished through the substitution of air travel with high speed rail (HSR) which consumes one-tenth the energy of air travel per passenger kilometer (pkm) [108]. HSR has both cost and time advantages over civil aviation for trips of 1000 km or less.[11] In the past decade, opening new HSR lines caused five air travel routes between 500 and 1000 km to close due to lack of demand. Currently, 65% of Chinese air transport is under 1200 km and 3 5% is under 800 km [109]. Future growth in HSR use will come from improved network connectivity and convenience [110–112]. Increases in network size, from 16,000 km in 2014 to 25,000 km in 2020 [113], will increase the number of destinations served. At the same time, locating HSR stations close to major cities and improving connections to urban public transit will reduce time costs of switching between national hub and spoke networks and an urban feeder network.

With regards to freight, trucks gain market share annually at the expense of more efficient modes like rail and coastal shipping and inland water transport. The main reasons for those declines are a lack of freight rail and domestic shipping capacity. Investment to resolve network bottlenecks and improve throughput are critical for improving freight modal shares. Another barrier to increased adoption of rail and water transport is the difficulty of switching to intermodal shipments. Enhancing the value proposition both through reduced cost, created by a better network of logistics parks and infrastructure improvements such as double stack clearing, as well as improved service levels, are also key pathways to improving mode share.

3.3.1.3. Improving vehicle energy efficiency. Increasing the efficiency of Chinese passenger cars becomes crucially important as private vehicle ownership rapidly expands. The Chinese government is carrying out the fourth stage of passenger car fuel-consumption limits, which established a 2015 target of 6.9 L/100 km and a 2020 target of 5 L/100 km [114]. A similar situation exists in trucks, where current fuel efficiency is well below OECD averages [115]. To improve efficiency the Chinese government has issued a set of heavy truck fuel efficiency standards [116] that are expected to force industry to adopt known pathways to cost effective fuel efficiency. Those known technologies to improve efficiency in trucking include improved aerodynamics and tires, tire pressure monitoring, and electrified pumps and fans. In light-duty urban delivery vehicles hybrid electric, plug-in hybrid electric vehicles (PHEVs), and battery electric drivetrains are also projected to become widely adopted.

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

3.3.1.4. Shifting to clean fuels. China is the largest EV market in the world with 777,000 EVs sold in 2017 [117]. 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 [118]. Emissions reductions will increase in the future as more of China's power grid is based on renewable energy sources. 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 can be prioritized. 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.

Light-duty trucks used for urban freight delivery can also be replaced by hybrid, PHEV, and pure electric vehicles. 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 [119]. Heavy-duty trucks (HDTs) are difficult to electrify but will increasingly rely on natural gas and biofuels, 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 [120].

3.3.2. Transportation sector results

Between 2010 and 2050, the Reinventing Fire Scenario's transportation primary energy use grows only 2.1%, despite growth rates of 5.8% for GDP, 4.5% for passenger travel, and 3.9% for freight 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, and 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. 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 increasing truck payloads and thereby reducing empty running.

By 2050, rail accounts for 24% of freight transport 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. The proportion of railway passenger transport using HSR increases to 40% by 2050 in the Reinventing Fire Scenario.

Fig. 9 shows that China's primary energy demand from transportation peaks around 2035 and then drops to 840 Mtce in 2050 in the Reinventing Fire Scenario, approximately half of that in the Reference Scenario (Fig. 9). 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. 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 trucks (LDT) efficiency improves by 50%.

In the Reinventing Fire Scenario, electricity, natural gas, and biofuels develop quickly and account for 50% of 2050 transportation final energy demand (Fig. 10). The share of EVs (including PHEVs) reaches 80% by 2050 and over 60% of urban buses are also electrified by 2050.

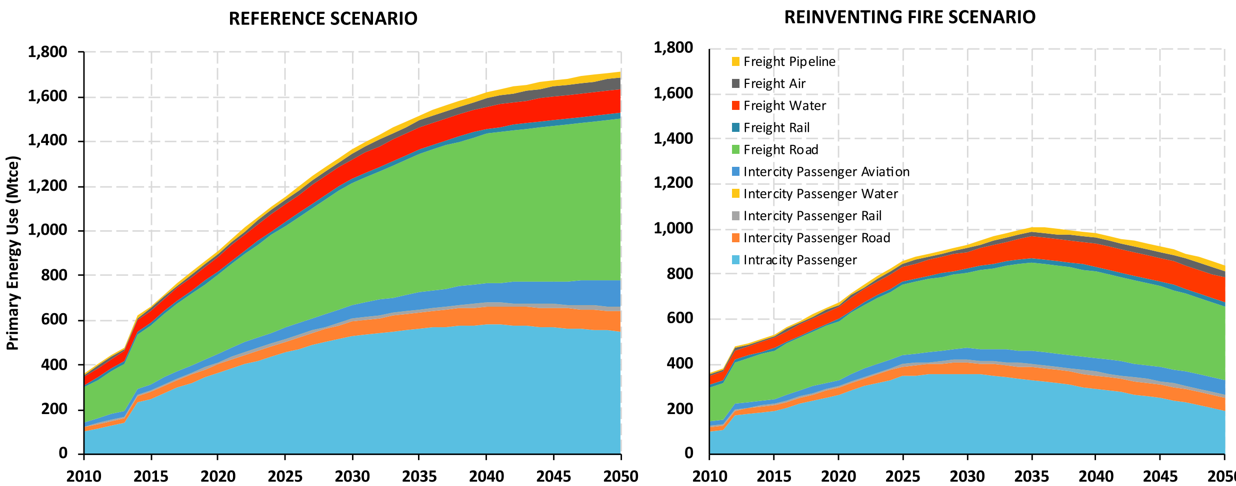


Fig. 9. Primary Energy Consumption of China's Transportation Sector under the Reference and Reinventing Fire Scenarios, 2010–2050.

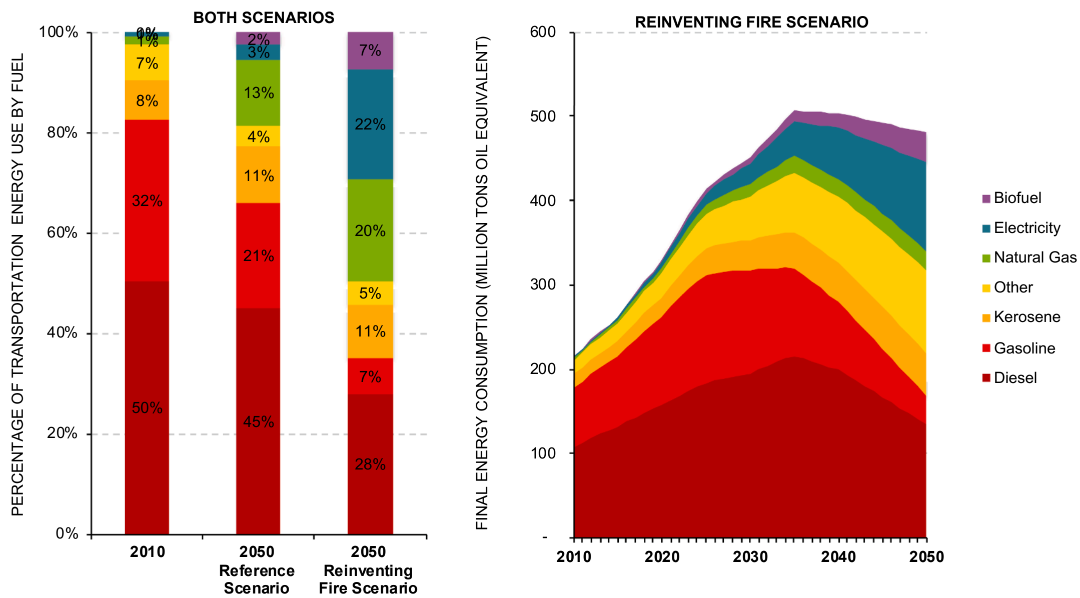


Fig. 10. Final Energy Consumption of China's Transportation Sector under the Reference and Reinventing Fire Scenarios, 2010–2050.

The share of natural gas vehicles reaches 8% of total vehicle ownership in 2050, primarily in HDTs and urban public transportation fleets, and natural gas-fueled trucks account for over 25% of total truck travel.

China's transportation oil demand grows 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, is 22% greater than 2010 and oil demand peaks around 2033 at 677 Mtce. China's diesel demand grows by 24% from 2010 to 2050, to 192 Mtce. Gasoline demand falls 51% lower than 2010 levels, to 49 Mtce. Biofuels account for approximately 7.5% of transportation final energy demand by 2050, equivalent to 35 Mtce of energy consumption.

Applying the four strategies of activity reduction, mode shifting, vehicle efficiency improvement, and fuel switching reduce 2050 transportation CO_2 emissions by nearly 2040 $MtCO_2$, contributing to a 61% reduction in overall CO_2 emissions under the Reinventing Fire Scenario compared to the Reference Scenario (Fig. 11). CO_2 emissions from transportation peak around 2035 at 1925 $MtCO_2$ and emissions progressively fall to 1289 Mt CO_2 by 2050.

Activity reduction results in the largest share of transport CO_2 emissions reductions under the Reinventing Fire Scenario with annual reduction of 700 $MtCO_2$ (34%). Decarbonization of the power sector contributes 450 $MtCO_2$ (22%) in 2050 because of the high degree of electrification in the road and rail transport sectors, while fuel switching to natural gas and biofuels contributes an additional 240 $MtCO_2$ (12%). Mode shifting and vehicle efficiency improvements also contribute 350 $MtCO_2$ (17%) and 300 $MtCO_2$ (15%), respectively, in 2050.

3.3.3. *Barriers and policy approaches*

To realize the Reinventing Fire Scenario in China's transport sector, barriers must be overcome in both passenger and freight transportation markets. In freight transportation, trucking market conditions that discourage logistics improvement, a lack of logistics technical expertise

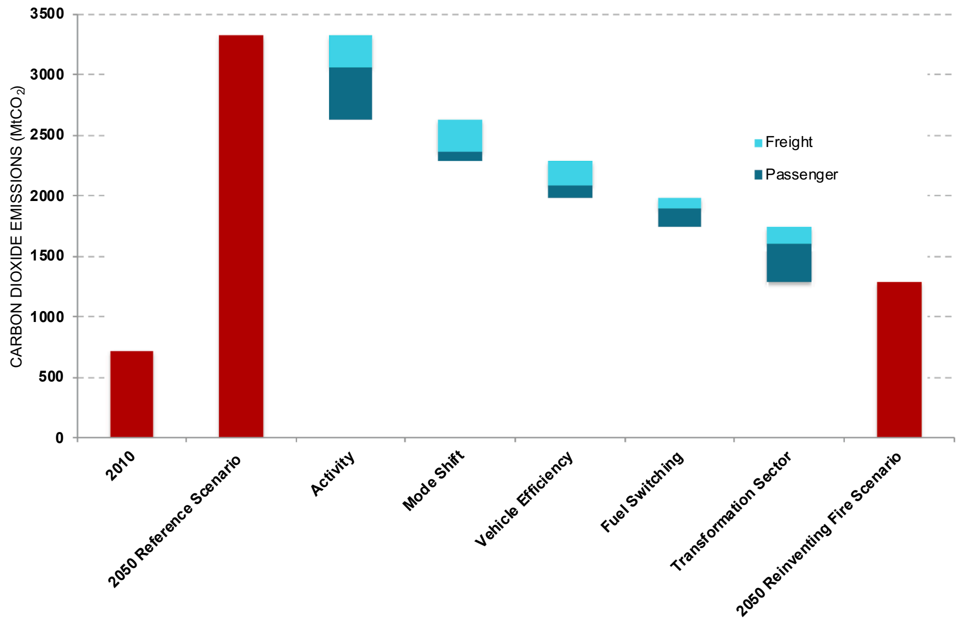


Fig. 11. Reinventing Fire Scenario Energy-Related CO_2 Emission Reductions Pathway for the Transportation Sector, 2010–2050.

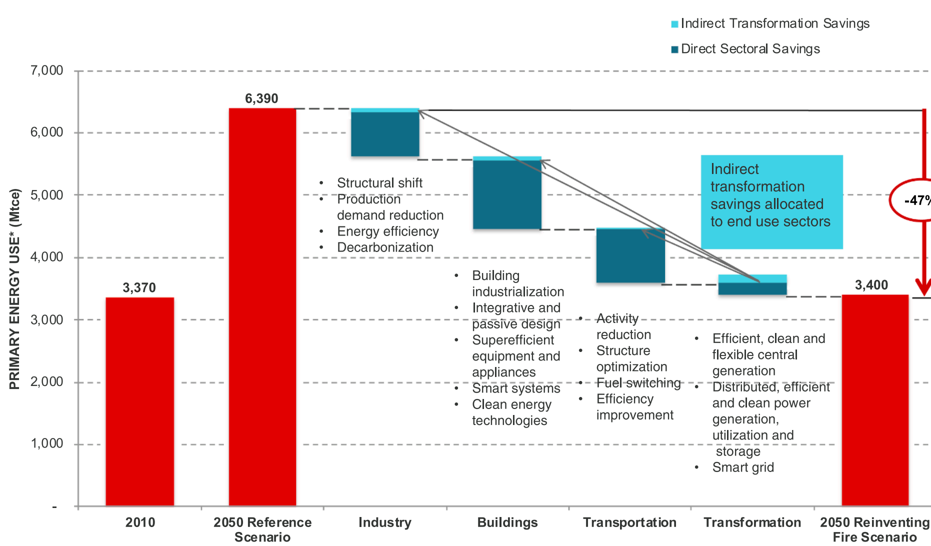


Fig. 12. Primary Energy Use Reduction Potential in 2050 under the Reference and Reinventing Fire Scenarios, 2010–2050. Note: primary electricity converted using the direct equivalent method (consistent with the IPCC).

and poor access to capital that limit operational efficiency, a large existing stock of inefficient trucks and limited demand for more expensive fuel-efficient trucks and finally, a lack of connectivity, capacity shortages and unacceptable service levels on efficient modes all pose barriers to efficient goods transport. In passenger transportation, a focus on private car infrastructure over public transportation, poor final mile connectivity to public transport, low focus on ICT to improve public transportation performance, HSR stations which are not integrated into urban public transportation networks all pose barriers to enhanced efficiency. Finally, barriers common to both passenger and freight transport such as high upfront costs to fuel switching and electrification of vehicles, concentrating populations in megacities, and poor coordination between transport planning and city development also pose barriers to efficient transportation.

Policy approaches to mitigate barriers to improved efficiency in freight transport may include market reforms in rail in trucking markets, invest in the planning and construction of high-performance rail and domestic water freight networks, support of the development of technical and operational expertise in logistics operators, development of the physical assets and technical capabilities to enable competitive rail-intermodal services and improved access to capital for small and medium logistics enterprises. Policy approaches to overcome barriers to efficient passenger transportation can include "smart-growth" city planning and mobility-oriented development, deploying congestion

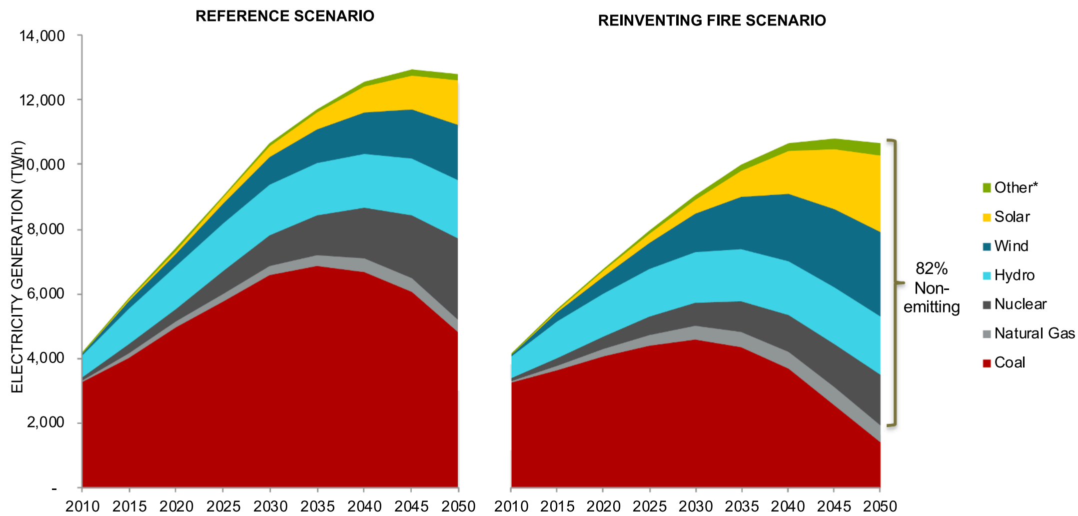
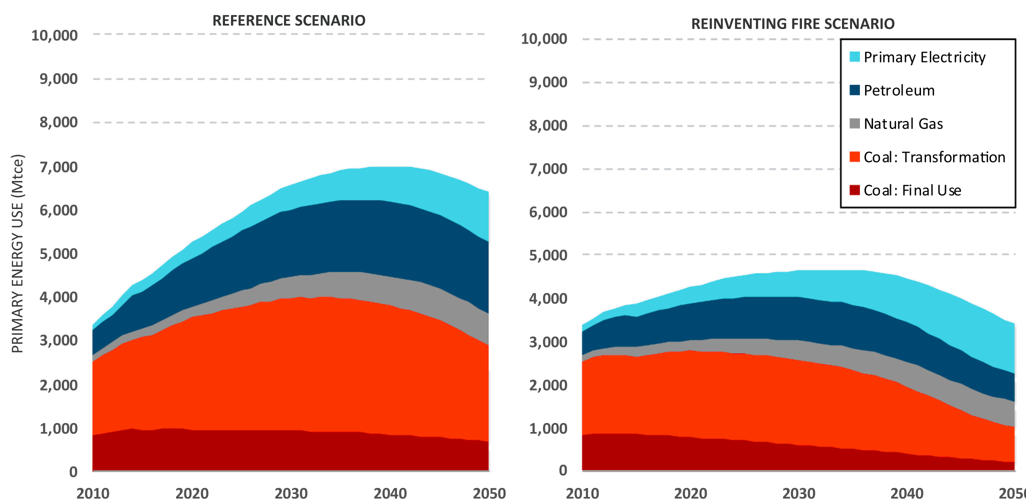


Fig. 13. China's Electricity Generation by Source in the Reference and Reinventing Fire Scenarios, 2010–2050. *Other includes waste to electricity, biogas, straw, wood, geothermal, ocean energy, and biomass.



Reference non-fossil share of primary energy

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

Reinventing Fire non-fossil share of primary energy

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

Fig. 14. China's Primary Energy Fuel Mix under the Reference and Reinventing Fire Scenarios, 2010–2050. Note: primary electricity converted using the direct equivalent method (consistent with the IPCC).

pricing and parking fees to limit private vehicle use, improving HSR integration with urban public transport networks, implementing flexible pricing structures to enhance the use of HSR and develop infrastructure for non-motorized transit modes. Finally for barriers effecting both passenger and freight policy solutions may include a coordinated urbanization model that supports efficient industry placement, developing China's West to create employment opportunities away from the East coast, enhanced and coordinated transport planning at urban and provincial levels, reforms to tax and land use codes, building electric charging infrastructure in cities and along major intercity corridors for EVs, the continuation of strong and varied incentives for EV adoption, and continued tightening of vehicle efficiency standards.

4. Conclusions

Myriad barriers and challenges exist in all sectors of China's economy that will need to be addressed through varied policy and programmatic efforts if the Reinventing Fire Scenario pathway is to be achieved. Many of these barriers and potential approaches to address them have been outlined above.

Overall, one of the most significant challenges is the continuously increasing demand for energy and material goods associated with urbanization. Between 2010 and 2050, China's urban dwellers are slated to grow from roughly 50% to 78% of the total population, increasing by about 400 million inhabitants. These urbanites consume about 50%

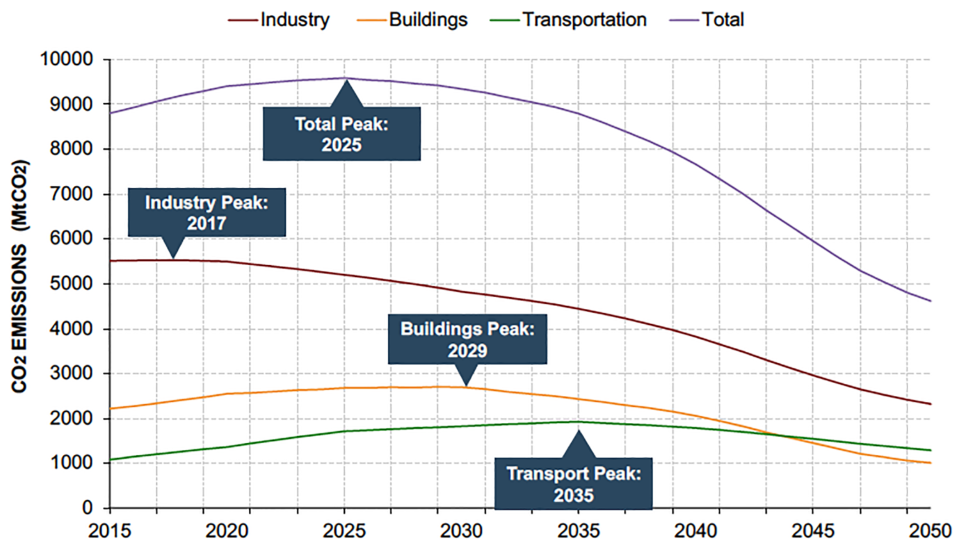


Fig. 15. China's Energy-Related CO_2 Emissions in the Reinventing Fire Scenario, 2015–2050.

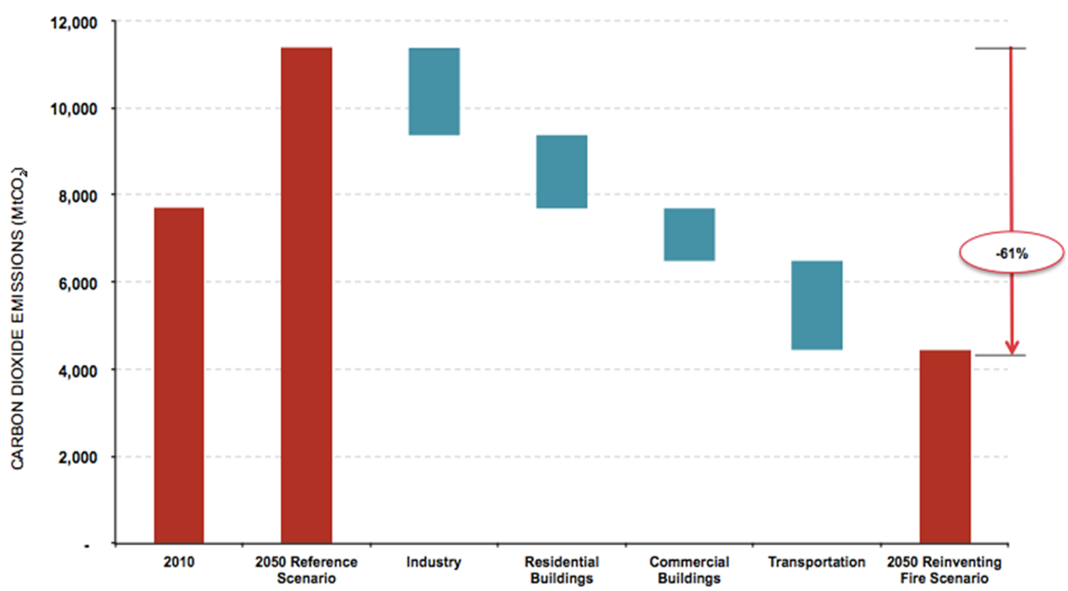


Fig. 16. Sectoral Contributions to 2050 Energy-Related CO_2 Emissions Savings in the Reinventing Fire Scenario.

more energy per capita than rural residents because of their higher personal incomes and demand for more amenities. Further, these growing cities must construct and provide the energy for housing, commercial buildings, and government and civil society facilities. These cities will also have growing transport systems that include passenger vehicles as well as mass transit systems. All of this urban infrastructure growth and associated consumption of goods by urban residents will require continued outputs – and energy consumption - from China's manufacturing sector, much of which is currently also located within city boundaries [121].

Another significant challenge is moving China's energy system toward the use of more non-fossil resources. For the electricity sector, this involves limiting the construction of new coal-fired power plants, accelerating the retirement of coal-fired units, eliminating inefficient distributed coal-fired boilers and furnaces, strengthening the constraints on pollutants, CO_2, and other emissions from coal-fired power plants, and significantly improve energy efficiency of coal-fired units. Further, accelerated development of clean low-carbon energy sources, including wind power resources, distributed solar photovoltaic, solar power generation, solar thermal utilization, hydropower resources, nuclear power, and waste, straw, and biomass generation based on local conditions coupled with natural gas-fired power generation to enhance grid flexibility, supporting peak adjustment and the integration of distributed energy is needed. It will be important for China to enhance power forecast planning, create a market that rewards the reduction of electricity consumption during peak periods by decoupling electricity sales from generation and profit of utilities and power companies, using environmental dispatch to prioritize energy efficiency as the first fuel, implementing real time electricity pricing that reflects the environmental costs of fuels, and raising the demand charge in tariff rate structure to encourage the reduction of peak loads, to lower capacity, and to create a market for demand response that encompasses smart meters, distributed energy, and smart controls. China will further need to continue with incentives to promote adoption of renewable energy resources, such as the subsidies for qualified PV demonstration projects, and provide low-cost project financing, implement the existing distributed generation policy, and implement new policies to encourage grid integration of on-site generation such as a feed-in tariff and net-metering.

If China is able to successfully adopt policies and approaches to address the many barriers associated with reducing energy use and related emissions by deploying the maximum feasible share of cost-effective energy efficiency and renewable supply through 2050, it will be able to follow the Reinventing Fire Scenario pathway and meets its energy needs and improve its energy security and environmental quality. This analysis finds that China's primary energy demand in 2050 will be roughly the same as the country's primary energy demand in 2010 with a seven-fold increase in GDP if the Reinventing Fire Scenario is realized. When compared to the Reference Scenario, where only policies in place in 2010 continue to have effect and autonomous technological improvement occurs with no technological breakthroughs or major policy changes, there are significant reductions in primary energy in each of China's end-use sectors. Through 2044, industry comprises the largest opportunity for energy savings. By 2050, however, the largest savings potentials shift to the higher-growth buildings and transportation sectors. China's primary energy requirements are 47% lower under the Reinventing Fire Scenario than under the Reference Scenario in 2050 (Fig. 12).

China's primary energy demand peaks in 2034 at 4670 Mtce under the Reinventing Fire Scenario, significantly lower than the Reference Scenario, which peaks in 2039 at 6990 Mtce. 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.

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 (Fig. 13). 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 flexibility 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 7900 kWh by 2050 in the Reinventing Fire Scenario, roughly on par with Austria and Singapore today.

In the Reinventing Fire Scenario, China's coal use will peak around 2020 at 2880 Mtce. By 2050, China's coal demand further declines to 1020 Mtce, about 60% lower than 2010 levels. Fig. 14 shows that the share of fossil energy drops 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 use is 60% lower in 2050 than it was in 2010 in the Reinventing Fire Scenario.

Looking at China's *Paris Agreement* NDC goal to increase the share of non-fossil fuels in primary energy consumption to around 20% by 2030, this analysis finds that under the Reinventing Fire Scenario, using China's power plant coal consumption (PPCC) method for primary energy conversion, the share of non-fossil in primary energy in 2030 is 28%, growing to 55% in 2050.[12] Given the assumptions of the Reinventing Fire Scenario, this finding shows that China's non-fossil NDC goal is achievable and could be surpassed.

Looking at China's *Paris Agreement* NDC goal to peak CO_2 emissions around 2030 and make best efforts to peak earlier, this analysis finds that in the Reinventing Fire Scenario, China's CO_2 emissions begin to level off in 2022, peaking in 2025 at a level of 9590 $MtCO_2$ (Fig. 15). Industry sector emissions peak first – around 2017 – followed by the buildings sector in 2029 and the transportation sector in 2035. This finding shows that in order for China to meet this NDC, it is essential that industrial sector energy use and related emissions be addressed immediately; delays in reducing that sector's CO_2 emissions will lead to delays in the achievement of overall peaking of China's CO_2 emissions. If successfully addressed – and if energy use and related CO_2 emissions in the buildings and transportation sectors can also be slowed and then reduced in line with the assumptions of the Reinventing Fire Scenario - this analysis finds that China can peak its national CO_2 emissions earlier that 2030.

Finally, this analysis finds that under the Reinventing Fire Scenario, China's total CO_2 emissions decline to 4620 $MtCO_2$ in 2050, about 41% lower than the 2010 levels. Fig. 16 shows that these reductions are spread across the industry, buildings, and transportation sectors.

Overall, this three-year analysis effort finds that if China follows the Reinventing Fire Scenario pathway and aggressively adopts all cost-effective energy efficiency and CO_2 emission reduction technologies while also aggressively moving away from fossil fuels to renewable and other non-fossil resources, it is possible for China to not only meet its *Paris Agreement* NDC commitments, but also to reduce its 2050 CO_2 emissions to a level that is 42% below the country's 2010 CO_2 emissions. While numerous barriers exist that will need to be addressed through effective policies and programs in order to realize these potential energy use and emissions reductions, there are also significant local environmental (e.g. air quality), national and global environmental (e.g. mitigation of climate change), human health, and other unquantified benefits that will be realized if a Reinventing Fire Scenario type pathway is pursued in China.

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[12] For further information about the difference between the direct equivalent and China's power plant coal consumption (PPCC) methods of conversion, 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.

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Appendix A. Scenario and sector assumptions

See Tables A1–A6.

Table A1
Model assumptions.

	Reference scenario	Reinventing fire scenario
GDP	Achieve national "three step" strategic goals GDP annual growth: 2010–2020: 7.6% 2020–2030: 5.9% 2030–2040: 4.1% 2040–2050: 2.9%	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 portion of exported primary products begins to fall. Energy-intensive products are used to meet domestic demand. Imports of energy intensive products increase; exports of high value-added products increase.
Domestic Environmental Problems	While the environment is more of a focus, pollution remains a serious problem (Kuznetz curve)	With better governance, China will follow the rule of "pollution first, governance later." Kuznetz curve peaks lower, going from "∩"to "⁀"
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.
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 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 A2
Industry assumptions.

	2010	Reference scenario 2050	Reinventing fire scenario 2050
Structural Shift			
Total industry value added	11 RMB trillion (2005)	80 RMB trillion (2005)	66 RMB trillion (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	1980–1999 construction: 30 years; 2000–2019 construction: 40 years; 2020–2050 construction: 50 years	1980–1999 construction: 30 years; 2000–2019 construction: 50 years; 2020–2050 construction: 70 years
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 sub-sectors 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 sub-sectors 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 A3
Building assumptions.

	2010	Reference Scenario 2050	Reinventing Fire: China 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	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% 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
Building load changes: space heating		Heating loads increase from 2010 to 2050 in North, Transition and South (urban only) China due to demand for greater thermal comfort. Specific loads differ by building vintage types.	Same as the Reference Scenario.

(*continued on next page*)

Table A3 (*continued*)

	2010	Reference Scenario 2050	Reinventing Fire: China Scenario 2050
Building load changes: cooling		Cooling loads increase significantly from 2010 to 2050 in all climate zones (particularly Transition and South) 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 superefficient technology by 2050	Linear shift to 100% adoption of current superefficient 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.
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 North 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 superefficient technology by 2050	100% adoption of current superefficient 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 gas boilers shares, replaced by 30% solar water heaters, 25% air source heat pumps, and 14% small cogeneration by 2050.

Table A4
Transportation assumptions.

		2010	Reference scenario 2050	Reinventing fire scenario 2050
Activity				
Urban Passenger (billion VKT/year)	Passenger motorized travel demand	1070	6090	3900
Intercity Passenger	Billion passenger km/year	3140	18,630	17,080
Mode Share				
Urban (% of VKT)	Public	37%	56%	45%
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%
Vehicle Efficiency[a]				
Urban (L eq./100 km)	All autos - average	6	4.5	2.8
Intercity (MJ/PKT)	Air	0.041	0.030	0.028
Other Freight (MJ/ton-km)	Water	7		
	Air	23	21%	32%
	Other		26%	32%

[a] Weighted average consumption.

Table A5
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 – 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 policies 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 A6
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.
		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 modeling approach

B.1. Long-Range energy Alternatives planning (LEAP) model

Developed by Stockholm Environment Institute and used in over 190 countries,[1] LEAP is an energy/environmental tool that models national and subnational energy consumption, production, and resource extraction in all sectors of an economy.[1] Driven by macro-economic assumptions, LEAP is a modeling and accounting tool integrating feedback loops within and across the buildings, industry, 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[13] (see Fig. B1).

B.2. 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 US Department of Energy. It is based on the Danish Balmorel modeling engine.[14] The EDO model is designed to analyze energy

[13] Community for Energy, Environment and Development (Commend), 2015. *An Introduction to LEAP*. http://www.energycommunity.org/default.asp?action=47.
[14] Balmoral Energy System Model. http://www.eabalmorel.dk/.

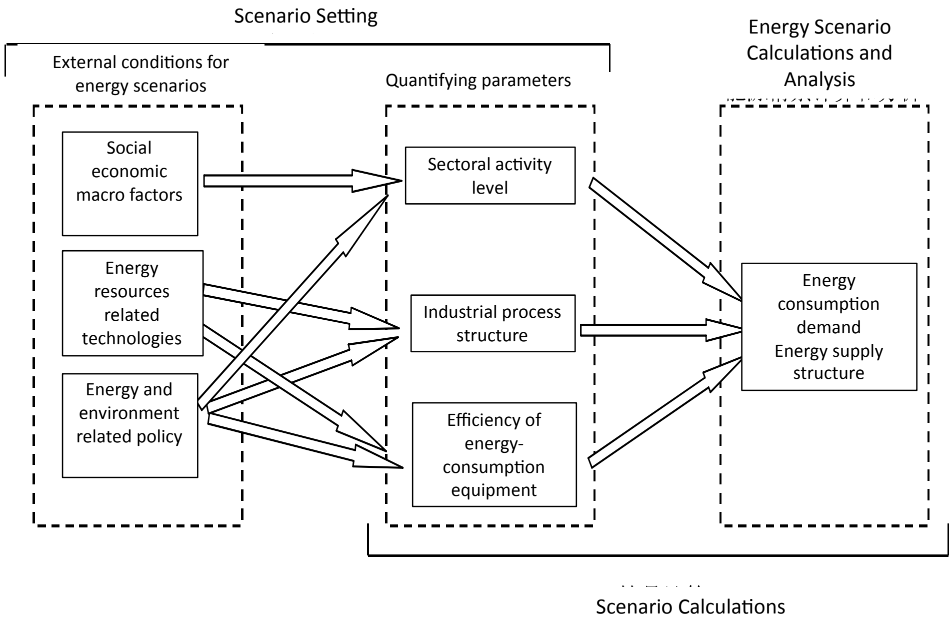

Fig. B1. Scenario Analysis and LEAP Model Schematic.

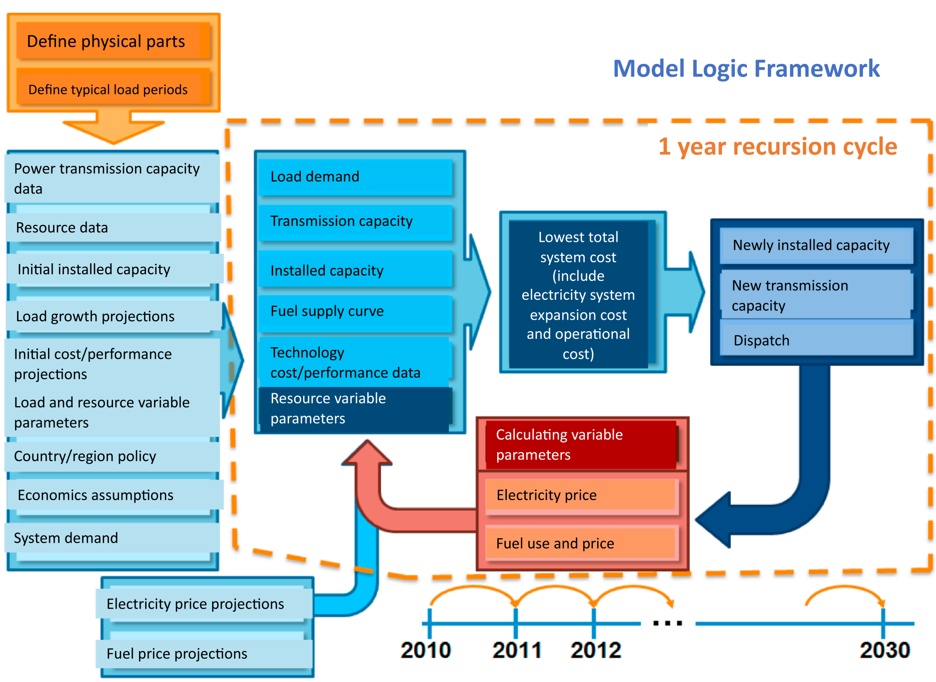

Fig. B2. EDO Model Analysis Framework.

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 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 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 (see Fig. B2).

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.

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