China's Trajectories beyond Efficiency:

CO2 Implications of Maximizing Electrification and Renewable Resources through 2050

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Abstract

In support of the Paris Agreement, China committed to peak its CO_2 emissions by 2030 or earlier and to reduce its CO_2 intensity by 60-65% from 2005 levels by 2030. While energy efficiency will continue to play a major role, other significant actions in China beyond efficiency are needed to help limit the average global temperature increase to 1.5˚C. This study uses a bottom-up national end-use model to evaluate even lower CO_2 emissions pathways for China beyond cost-effective efficiency by maximizing end-use electrification and adoption of new renewable resources. Unlike most recent modelling studies that only focus on renewable electricity generation with simplified projections for future electricity demand growth, this study evaluates maximum electrification for specific end-use sectors and non-conventional renewable resources on the demand-side.

We use scenario analysis to evaluate the potential CO_2 reductions if China is able to rapidly decarbonize its power sector while maximizing electrification across all sectors and the additional opportunity from maximizing biomass and low temperature renewable heat use in industry and solar heating, cooling and water heating technologies use in buildings. While already widely used in some European countries, large-scale adoption of these non-conventional technologies have not yet been considered in China. We find that maximizing non-conventional electric and renewable technologies can help China peak its national CO_2 emissions as early as 2023, with significant additional CO_2 emission reductions through 2050. The greatest additional CO_2 reduction potential beyond efficiency lies in fossil fuel displaced by renewable heat in industry. These results suggest accelerating the utilization of non-conventional electric and renewable technologies present additional CO_2 reduction opportunities for China, but new policies and strategies are needed to change technology choice in the demand sectors.

Introduction

In support of the Paris Agreement, China committed to peak its CO_2 emissions by 2030 or earlier and to reduce its CO_2 intensity by 60-65% from 2005 levels by 2030. This was preceded by the joint U.S.-China government announcement in November 2014 when China committed to boost its share of non-fossil fuel energy to 20% by 2030. China’s draft plan for the 13th Five-Year Plan period from 2016 to 2020 also includes energy intensity per unit of GDP reduction target of 15% and carbon intensity reduction target of 18% by 2020. These targets follow years of government-driven efforts to improve energy efficiency across all demand-side sectors while attempting to decarbonize the power sector. While China's energy consumption per unit of GDP declined by 30% from 2005 to 2014, total primary energy consumption increased by 163% over the same time period and coal consumption is still 66% of primary energy consumption in 2014. Other significant actions in China beyond energy efficiency are needed to not only help China achieve its 2020 and 2030 targets, but also contribute to global efforts to limit the average global temperature increase to 1.5˚C. This paper focuses on the feasibility for further lowering China's future CO_2 emissions pathways by maximizing electrification and power sector decarbonization and demand-side utilization of renewable technologies.

Some recent modelling studies including "China 2050 High Renewable Energy Penetration Scenario and Roadmap Study" (ERI 2015) and "Renewable Energy Roadmap 2030 Renewable Energy Prospects: China" (IRENA 2014) reports considered possible trajectories for China with high penetration of renewable deployment. However, we are not aware of any recent studies that considers the combined impacts of efficiency, electrification and adoption of non-conventional renewable resources such as renewable heat on China's CO_2 emissions through 2050. Moreover, demand-side utilization of renewable technologies such as low temperature renewable heat and solar thermal heating and cooling technologies are widely deployed in some European countries, but have not been considered in future CO_2 outlooks for China. In addition, the maximum possible electrification rate are usually estimated for the whole economy through historical extrapolation or based on growth to reach electricity consumption per capita in developed countries, which often result in rather high forecasts that may not be feasible when looked at from the end-use sectoral perspective.

This study uses a bottom-up national end-use model to evaluate even lower CO_2 emissions pathways for China beyond cost-effective efficiency and fuel switching by maximizing end-use electrification and adoption of new renewable resources in the demand sectors. We use scenario analysis to evaluate the potential CO_2 reductions if China is able to rapidly decarbonize its power sector while maximizing electrification across all end-use sectors and the additional opportunity from maximizing the use of biomass and low temperature renewable heat in industry, and solar heating, cooling and water heating technologies in buildings.

The first section of the paper presents an overview of the general bottom-up energy end-use modelling methodology. The second section of the paper reviews the specific assumptions of the four different scenarios used in this study, including evaluation of the potential for maximum electrification and maximum adoption of demand-side renewable technologies in China. Energy and CO_2 emissions results by sector and overall CO_2 outlook for each scenario are then presented, followed by conclusions and policy implications based on key findings.

Modeling Methodology

The China 2050 Demand Resources Energy Analysis Model (DREAM) was used to evaluate China's future energy and CO_2 emissions trajectories and the potential impacts beyond cost-effective efficiency. The foundation for the China 2050 DREAM model is an accounting framework of China's energy and economic structure using the LEAP (Long-Range Energy Alternatives Planning) software platform developed by Stockholm Environmental Institute. LEAP is a medium to long-term integrated modelling platform that can be used to track energy consumption, production and resource extraction in all sectors of an economy as well as conduct long-range scenario analysis. It allows for integrated, scenario-based modeling and characterization of technological development down to the end-use level, and has been used adopted and used in more than 190 countries worldwide (Heaps 2016)[1]. The China 2050 DREAM model was developed using LEAP by the China Energy Group in LBNL in 2005 and it was most recently refined and updated as part of the three-year collaborative "Reinventing Fire: China" project between LBNL and the Rocky Mountain Institute in the U.S. and China's Energy Research Institute (ERI), the leading energy-related government think-tank that advises China's key policymaking body, the National Development and Reform Commission (ERI, LBNL and RMI 2016).

The China 2050 DREAM model includes a demand module consisting of four[2] demand subsectors and a transformation module consisting of energy production, transmission and distribution subsectors. Using LEAP, the China 2050 DREAM model captures the diffusion of end-use technologies and macroeconomic and sector-specific drivers of energy demand as well as the energy required to extract fossil fuels and produce energy and a power sector with distinct generation dispatch algorithms. Using the Impact = Population x Affluence x Technology (IPAT) framework related to the Kaya Identity, this model captures macroeconomic and physical

[1] More information on LEAP and its applications can be found online at: https://www.energycommunity.org/default.asp?action=introduction

[2] Agriculture is also included in the model but is not discussed here as it has marginal and declining share of energy use in China.

drivers of energy-using activity and detailed consideration of technological development at the end-use level to evaluate the total energy and CO_2 emissions impacts for China's development to 2050.

The demand module of the China 2050 DREAM model includes the four main economic sectors of residential buildings, commercial buildings, industry, and transportation. Key macroeconomic parameters that drive energy-using activity such as economic growth, population, and urbanization are aligned with international sources (e.g., the United Nations World Population Prospects) as well as Chinese sources (e.g., China Energy Research Institute reports). For the residential building sector, urbanization and growth in household income drive energy consumption because urban households generally consume more commercial energy than rural households, and rising household incomes correspond to increases in housing unit size (and thus in heating, cooling, and lighting loads) and appliance ownership. Similarly, commercial building energy demand is driven by two key factors: building area (floor space) by building type and end-use intensities such as heating, cooling, and lighting (MJ per m^2). The buildings sectors are also differentiated by three main climate zones, new versus existing buildings and five building efficiency vintages.

For the industrial sector, the model includes 12 energy-intensive industrial subsectors characterized by physical production including key heavy industries such as cement, iron and steel, aluminum, ammonia, and ethylene that are driven by key physical drivers such as the new built environment needed to house growing urban populations, sown area and fertilizer intensity, and per-capita demand for plastics. In addition, there are 18 light industrial subsectors characterized by value-added production such as various manufacturing industries, food, beverage and tobacco, textiles, medicine and metal products with purely economic driven activity projections from ERI's computable general equilibrium model for China. Transportation demand is driven by freight and passenger transport demand, where freight transport is calculated as a function of economic activity, measured by value-added GDP, and passenger transport is based on average vehicle-kilometers traveled, by mode of transportation (e.g., bus, train, private car). Within the energy demand module, the model is able to address sectoral patterns of energy consumption in terms of end-use, technology and fuel shares including trends in saturation and usage of energy-using equipment, technological change including efficiency improvements and complex linkages between economic growth, urban development and energy demand.

Scenario Analysis

For this study, four main scenarios are developed to evaluate the potential CO_2 reductions if China is able to rapidly decarbonize its power sector while maximizing electrification across all sectors and the additional opportunity from maximizing biomass and emerging renewable technologies in industry and building sectors. The Reference and Cost-Effective Efficiency and Renewables Scenarios were developed primarily as part of the "Reinventing Fire: China" project. In addition, two new scenarios were developed to evaluate the additional maximum technical potential beyond cost-effective measures for reducing CO_2 emissions by electrifying all end-use sectors (with decarbonized power sector) and maximizing demand-side renewable technologies. These two additional scenarios are intended to evaluate the maximum technical feasible potential for electrification and demand-side renewable technology adoption, in contrast to the Cost-Effective Efficiency and Renewables Scenario.

All four scenarios have the same macroeconomic drivers such as population, urbanization, and GDP growth. However, the activity level in industrial subsectors differ between the Reference Scenario and the other three "alternative" scenarios as a result of structural shift within industry. Growth in light manufacturing industry is faster and growth in heavy industry is slower under the alternative scenarios when compared to the Reference Scenario as a result of expected structural shift from energy-intensive heavy industries to higher value-added, light industries. The industrial total and subsector activity level (both physical production and value-added production) between the three alternative scenarios are the same. Similarly, the installed capacities of power generation technologies also vary between the Reference Scenario and the other three alternative scenarios, reflecting different paces of power sector decarbonization. Under the Reference Scenario, non-fossil (including nuclear) capacity grows to meet China's announced non-fossil targets with 62% of generation capacity coming from non-fossil sources by 2050. Under the three alternative scenarios, over 2,940 GW of solar and wind capacity are added to the power system by 2050 with non-fossil resources accounting for 83% of total generation capacity.

Reference Scenario

The Reference Scenario serves as the baseline scenario and assumes that all policies in place by 2010 will continue to have impact on all energy demand, supply and transformation sectors. This includes meeting all of the energy and CO_2 intensity reduction targets that China has adopted as of 2010, as well as the announced non-fossil power generation capacity targets for the power sector. As a counterfactual baseline scenario, the Reference Scenario assumes no additional policies will be adopted after 2010, but autonomous technological improvement is expected to occur through 2050.

Cost-effective Efficiency and Renewables Scenario

This scenario assumes that China adopts the maximum feasible share of today's commercially available and cost-effective energy efficiency technologies and renewable energy supply by 2050. For example, in the buildings sector, the most efficient appliances and equipment that are still cost-effective[3] today are assumed to reach 100% market saturation by 2050. Accelerated adoption of high efficiency and cleaner (e.g., non-fossil) technologies is assumed to occur across all end-use, power generation and heat generation sectors over time. In addition, increased end-use electrification is also incorporated into this scenario to the degree that it is cost-effective based on detailed review of technology-specific capital and operating costs and energy use, international experiences, input from sectoral stakeholders and expert opinion.

Due to space constraints, more details on the sector-specific assumptions about technology uptake and fuel switching in the Reference and Cost-Effective Efficiency and Renewables Scenarios are discussed in the Reinventing Fire: China Executive Summary (ERI, LBNL and RMI, 2016) and is the focus of another ECEEE Summer Study 2017 paper number 1-242-17 (Price et al. 2017).

Maximum Electrification Scenario

In order to evaluate the additional CO_2 reduction from maximizing electrification in demand sectors beyond cost-effective efficiency and renewable technologies, the Maximum Electrification scenario was developed based off of the Cost-effective Efficiency and Renewables Scenario but with additional electrification for all end-use sectors. The assumptions about maximized electrification of selected building end-uses, transport modes, and industrial processes were developed based on evaluation and analysis of international adoption rates and policy trends.

Transport

For passenger transport, the maximum electrification of taxi and fleet cars assumes that policies will be adopted requiring 100% electric vehicles (EV) by 2050. Nearly 40 Chinese cities have already set 30% electric vehicle share targets for municipal fleets for 2015 and additional growth is expected with continued subsidies through 2020 (MIIT 2013). Supporting policies and infrastructure are also needed to rapidly increase private EV adoption from now through 2050. Currently, 21 cities of the 40 cities have adopted both monetary and non-monetary incentive policies for electric vehicles including matching local subsidies to national subsidies and exemptions from local license plate restrictions (Shi et al. 2015). For freight transport, the expected driving range of light-duty and medium-duty trucks were considered in setting the maximum technically feasible penetration rate of plug-in hybrid diesels in the truck fleet by 2050.

Industry

The electrification of glass, food and beverage, and pulp and paper industrial processes are based on the industrial decarbonization and energy efficiency roadmaps of the Government of United Kingdom in the absence of China or Asia specific information. Three specific applications are considered, including:

- Replacing fossil fuel melting with electricity in the Glass sector
- Replacing coal firing with electricity in the Food and Beverage sector
- Replacing heat dryers with electricity in the Pulp and Paper sector

Currently, none of those applications are commercially available. According to Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 – Glass Report of the Government of UK, commercial (i.e. large-scale) implementation of electric melting in glass sector will likely occur after 2030 (UK 2015a). Based on this information, it is assumed that electric melting in the Chinese glass sector will be available starting from 2030 with a 30% share by 2050. It is also assumed that electricity firing in Chinese food and beverage sector and electricity dryers in Chinese pulp and paper sector will be commercially available starting from 2035 (UK 2015b, UK 2015c) and reach 10% and 5% share, respectively, by 2050. Some of the electric equipment, such as infrared (IR) heaters for paper drying, have already been developed but much of its market has been replaced by

[3] Cost-effectiveness is defined as technologies or processes where the cost of conserved energy is less than today's energy prices. In other words, the financial savings from energy saved exceed the incremental cost for higher efficiency.

gas IR dryers due to lower gas prices. In addition, the IR units do not replace the heat dryers but are used to supplement steam drying.[4]

Replacement of old equipment with electric technologies would require more advanced technologies with high upfront costs. In addition, electrification options in China would be very sensitive to electricity prices given the uncertainty around power sector reform and future electricity prices. Higher prices may complete change the cost-competitiveness of these options. Our assumptions about future market share penetration rates are relatively conservative, given that most of these technologies are all currently still in the research stage, and there is no knowledge on incremental costs.

Electric arc furnace (EAF) process is responsible for 15% share of current Chinese steel production. The Maximum Electrification Scenario assumes that this share will reach 40% by 2050, compared to 30% in the Reference scenario. Currently, China depends heavily on import for steel scrap, which is the main raw material of EAF production process. Even though it is expected that China will have enough domestic scrap by 2030, basic arc furnace (BOF) production is still considered as the dominant production process due to large coking coal reserves (main raw material of BOF production) of the country and newly added BOF production capacities. Therefore, it is assumed that there would be only 10% increase in EAF production in the Maximum Electrification Scenario. On the other hand, current share of DRI and smelting process is only 1%. Based on the same reasoning, we assume this share will increase very slowly and reach 10% and 15% by 2050 in the Reference and Maximum Electrification scenarios, respectively.

Buildings

For commercial buildings, geographic limitations and different climate zone conditions are considered with the maximum technically feasible adoption of air source and ground source heat pumps for heating and cooling, respectively, since current technologies of air source heat pump do not work effectively in colder temperatures. In particular, heat pump characteristics and adoption in North, Transition, and South China climate zone regions are based on Norway and Sweden, France, and Italian benchmarks, respectively (see Table 1).

Table 1 summarizes the key assumptions by sector of the Maximum Electrification scenario.

Table 1. Key Sectoral Technology Adoption Assumptions in Scenario Analysis

	2010	2050 Reference	2050 Maximum Electrification
Transport			
Passenger Vehicles	0% EV shares	10% EV share in private cars, 30% EV share in taxis and fleet car markets	75% EV share in private cars, 100% EV share in taxi and fleet car markets
Trucks	0% plug-in hybrid diesels	0% plug-in hybrid diesels	18% plug-in hybrid diesel share in medium-duty trucks, 50% plug-in hybrid diesel share in light-duty trucks
Industry			
Glass Industry	0% electric melting	0% electric melting	30% electric melting to replace fossil fuel melting
Food and Beverage Industry	0% electrification of firing	0% electrification of firing	10% electrification of firing to replace coal-firing
Pulp and Paper Industry	0% electric dryers	0% electric dryers	5% electric dryers to replace heat dryers
Commercial Buildings			
Heating	1.5% air source heat pump	10-25% share for air source heat pump depending on climate zone	40-90% share for air source heat pump depending on climate zone
Cooling	0.5% ground source heat pump share	0% ground source heat pump share	20-25% share for ground source heat pump depending on climate zone
Water Heating	0% heat pump water heater share	0% heat pump water heater	48% heat pump water heaters
Residential Buildings			
Heating	1.5% air source heat pump	10%-80% share for air source heat pump depending on climate zone	40-100% share for air source heat pump depending on climate zone

[4] http://gaspaperdryer.org/learn-about-paper-drying/paper-manufacturing-overview/

Maximum Demand-side Renewables Scenario

In addition to maximum technically feasible electrification in transport, selected industries, and commercial buildings, the Maximum Demand-side Renewables Scenario considers additional adoption of non-conventional renewable heat and biomass in industry and solar thermal technologies in commercial buildings based off of the Maximum Electrification Scenario. The assumed additional uptake of non-conventional renewable energy in demand sectors for China by 2050 are based on existing international applications of these technologies. Additional adoption of renewable energy on the supply-side (including in the power sector) are not considered, and the power generation fuel mix for this scenario is the same as the Cost-effective Efficiency and Renewables scenario.

Renewable Heat Use in Industry

In this study, we focus on low grade heat below 100 °C temperature range. Renewable heat sources considered include solar thermal, conventional geothermal energy, and biomass. In industry, low grade heat demand can be found in process stream, process cooling and HVAC system, in which process steam dominants the low grade heat demand (USEPA 2016). Process heat is required for industrial process such as, hot water or steam demand process, drying and dehydration processes, preheating, pasteurization and sterilization, washing and cleaning, and chemical reaction (Mekhilef, Saidur, & Safari 2011). Globally, renewable energy is estimated to account for 10% of total industrial heat use, of which 99% is bioenergy-based (Eisentraut & Brown 2014). The availability of biomass process residues in certain sub-sectors, such as pulp and paper and the food industry, has been the main driver for using biomass to produce process heat (Eisentraut & Brown 2014). In contrast to the wide use of natural gas in OECD countries, the heat sources in Chinese industry are dominated by coal with 85% share in 2011 (Eisentraut & Brown 2014).

A European study showed that about 30% of the total industrial heat demand in Europe is required at temperatures below 100°C and 57% at temperatures below 400°C (Caludia, Battisti, & Drigo 2008) .The key sectors identified are for example, food, pulp and paper, textile, chemical, machinery, transport equipment, mining and quarrying etc. Many of these industries are less energy intensive but have high demand on low grade temperature heat below 100 °C as seen in Figure 1. Although this data was derived from Europe, the share is representative of corresponding sub-sectors around the world and is assumed to apply to China's industrial sectors. This study assumes that, by 2050, the low temperature heat demand portion is fully supplied by various renewable energy sources based on an assumed mix of biomass, solar thermal and geothermal heat. Based on the AmbD 2030 scenario in IRENA study (IRENA 2015) and in the absence of detailed projections, the shares of different renewable energy sources are assumed to remain constant from the base year through 2050 with 63% biomass, 30% solar thermal and 7% geothermal heat through 2050. This fuel mix result is drawn from the IRENA study (IRENA 2015) in which the low temperature process heat for all industrial sector is supplied 16.5 EJ/year from biomass, 7.8 EJ/year from solar thermal and 1.9 EJ/year from geothermal energy respectively.

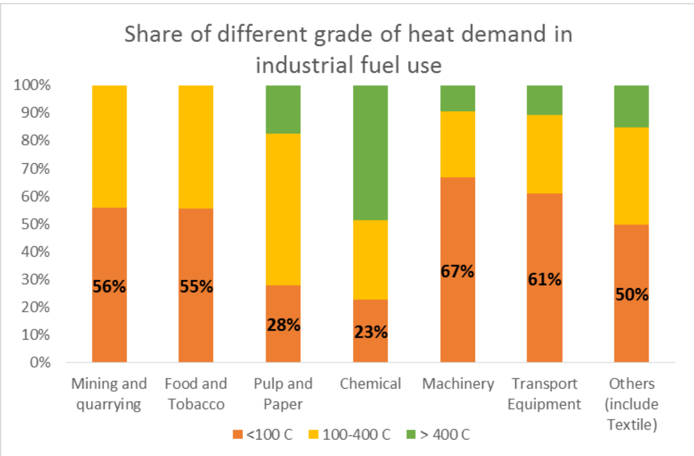

Figure 1. Low Temperature Grade Heat Demand Shares of Industrial Fuel Use in Key Industrial Subsectors Data taken from Caludia, Battisti, and Drigo, 2008.

Biomass Use for High Temperature Heat

Currently, biomass offers the only renewable energy option to provide high-temperature heat in industry sector. The Maximum Demand-side Renewables Scenario considers biomass usage in steel and cement production processes which require heat of more than 400°C.

The introduction of biomass in blast furnace in integrated steelmaking route includes two technology upgrades:

1. Blending biomass during coke making to produce bio-coke

Blending biomass during coke making is discussed widely in literature (MacPhee et al. 2009; Wei et al. 2013; Suopajärvi and Fabritius 2013) and a maximum 5% biomass addition is allowed to maintain coke properties without reducing the mechanical strength. It is assumed that share of biomass in coal blend in coke making in China would not exceed 5%. In addition, a coke/biomass replacement rate of 1/0.67 is considered (Wei et al. 2013).

2. Biomass fully or partially replacing pulverized coal through injection

Biomass can fully replace pulverized coal in blast furnace (Wei et al. 2013). Feeding charcoal instead of pulverized coal in blast furnaces is a common practice in the Brazilian steel industry. In the Maximum Demand-side Renewables Scenario, it is assumed that biomass/pulverized coal replacement rate is 1/1 with 75% maximum deployment by 2050.

Biomass is also used as alternative fuel in kilns in cement production route in Netherlands and Finland (EUBionet 3 2009a&b). The maximum deployment rate in Chinese kiln combustion is set to 50%, based on pilot plants in Netherlands and Finland.

Solar Thermal Technologies for Commercial Heating, Cooling and Water Heating

An adoption rate of 8% by 2050 is assumed for solar heating technologies across China commercial buildings based on the UK experience with decarbonizing heat in their buildings sector (UK 2015d). As mentioned earlier, our renewable scenario is based off of the Maximum Electrification Scenario, which considers a large use of air source and ground source heat pumps for commercial heating and water heating in China (see Table 1). This renewable scenario assumes solar thermal can replace almost all of the shares that remain from heat pumps in Transition and South regions with 8% share, but stays more conservative in the Northern region with 15% share to coal and gas district heating due to less solar availability.

Solar cooling in Chinese commercial buildings are assumed to vary by climate with 15% and 20% penetration in North and Transition regions of China, respectively, based on the Swedish example (Gustavsson et al. 2011) and 30% penetration in Southern China by 2050 (IEA 2012). We assume moderate levels of solar thermal AC adoption in Chinese commercial buildings. Larger magnitudes of change to Chinese cooling market is unlikely to occur without significant long-term policy changes to direct the transformation to solar cooling, which is not considered in this study.

In addition, it is assumed that 30% of water heating in commercial buildings will be from solar water heaters, which are already prevalent in the residential sector, by 2050 based on Faninger (2010). As in the commercial heating case, the Maximum Electrification Scenario considers a large use of heat pump for commercial water heating in China with 48% share. Together with heat pumps, solar water heating provides almost 80% of the water heating need in the Maximum Demand-side Renewables Scenario.

Results

Maximum Electrification Results

Figure 2 shows the electrification rate, which is defined as electricity's share of total final energy demand, of the four demand sectors in the base year of 2010 and in 2050 under the three scenarios. While residential and commercial building sectors were already electrified in 2010 with electrification rates of 22% and 44%, respectively, the industry and transport sectors were electrified to a lesser extent with electrification rates of only 19% and 1% in 2010. For all four sectors, there is significant potential for increasing electrification over the next forty years. Most of the increased electrification will occur as a result of autonomous technological change, such as the increasing adoption of electrical appliances in residential buildings as a result of urbanization and growing household incomes. However, in light of the decarbonized power sector, *additional* cost-effective electrification can occur in all four sectors to varying degrees with the push towards fuel-switching to cleaner fuels for specific end-use technologies as highlighted in Table 1. At the same time, the concurrent accelerated adoption of cost-effective efficiency measures and technologies help lower China's total final energy demand. As a result, the 2050 electrification rates of each sector is higher under the Cost-effective Efficiency and Renewable Scenario, with the largest increase in the residential and commercial buildings, followed by transport and industrial sectors.

Under the Max Electrification Scenario, there is limited potential for additional electrification in the industrial sector because of the limited applicability to only the pulp and paper, food and beverage and glass industries.

Similarly, additional electrification is also limited in residential buildings because of the continued wide application of centralized district heating for meeting heating demand in Northern China, 100% reliance on electric air conditioners for cooling, and the continued use of other fuels in rural households. For commercial buildings and transport sectors, however, there is significant potential for increasing electricity's share of total final energy demand as seen in Figure 2.

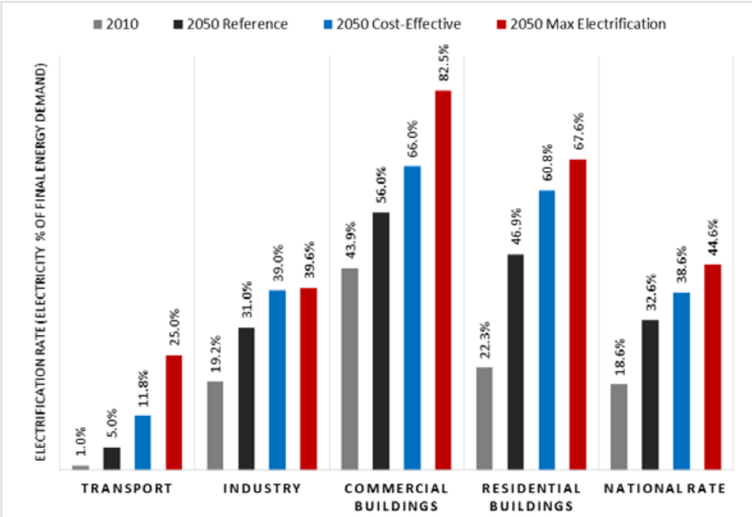

Figure 2. 2010 and 2050 Sectoral Electrification Rates by Scenario

Note: Electrification rate is electricity's share of total final energy demand.

While China's 2050 national electrification rate increases from 33% in the Reference Scenario to 39% in the Cost-effective Efficiency and Renewables Scenario, Figure 3 shows that China's total electricity demand is significantly lower under the Cost-effective Efficiency and Renewables Scenario with a 21% (2,380 TWh) reduction relative to the Reference Scenario demand in 2050. This is even more pronounced when comparing China's 2050 electrification rates under the Reference and Maximum Electrification Scenarios, with the higher national electrification rate of 45% under Maximum Electrification associated with a 13% reduction in electricity demand, when compared to a lower electrification rate of 32% under the Reference Scenario but higher total electricity demand of 11,320 TWh.

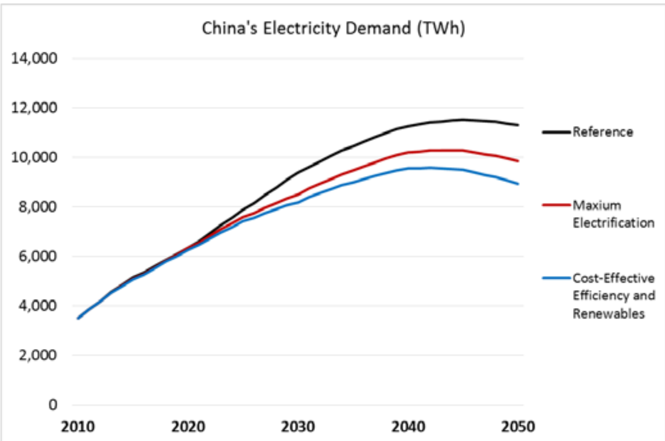

Figure 3. China's Electricity Demand by Scenario, 2010 to 2050

The key difference is that there is lower total final energy demand under the Cost-effective Efficiency and Renewables and Maximum Electrification Scenarios as a result of more aggressive efficiency improvements, and with substantially lower coal and coke as well as oil products demand due to fuel switching across all sectors as seen in Figure 4. China's total final energy demand is the lowest under the Maximum Electrification Scenario with 2718 Million tonnes of coal equivalent (Mtce[5]) of total energy demand in 2050, compared to demand of 4266 Mtce under the Reference Scenario and 2850 Mtce under the Cost-effective Efficiency and Renewables Scenario, due to additional adoption of higher efficiency electrical equipment. These results suggest that the CO_2 impact associated with maximum electrification and subsequent increased utilization of renewables in the power

[5] Mtce is the standard Chinese unit for energy. 1 Mtce = 29.27 million gigajoules.

sector can only be realized if total energy demand can first be lowered through energy efficiency improvement and then through additional fuel switching. In other words, fully deploying supply-side renewables without concurrently pursing efficiency improvements will limit the potential for electrification and utilization of clean electricity.

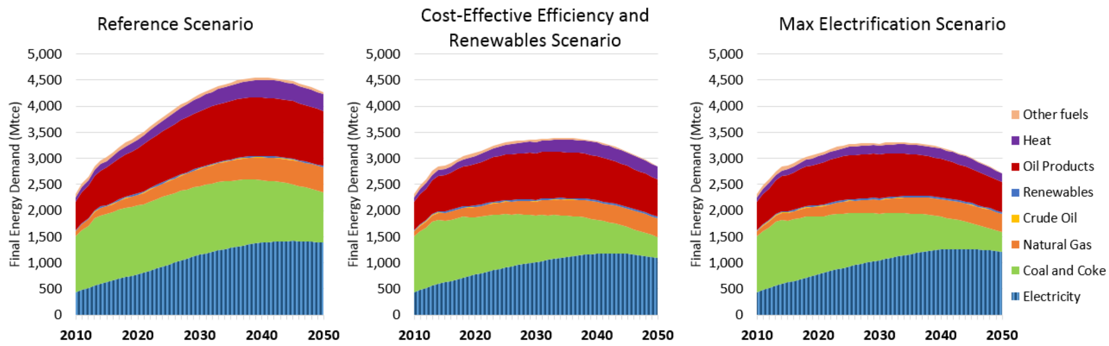

Figure 4. Final Energy Demand by Fuel by Scenario, 2010 to 2050

Maximum Demand-side Renewable Results

Beyond the Cost-effective Efficiency and Renewables Scenario, maximizing the deployment of demand-side renewable technologies in China's commercial and industrial sectors can result in additional utilization of 216 Mtce of renewable energy by 2050. Figure 5 shows the breakdown of the additional renewable resources that China could utilize from 2010 to 2050 to further lower its CO_2 emissions under the Maximum Demand-side Renewable Scenario. Renewable heat use in industry becomes the largest source of additional renewable resource utilized by Chinese demand sectors in 2025, when it overtakes the steadily growing utilization of solar energy in the commercial building sector. The large growth in renewable heat utilization can be traced back to the industrial sector's dominating, albeit decreasing share, of China's final energy consumption with 47% share in 2050, as well as growth in the light industries that are able to utilize renewable heat.

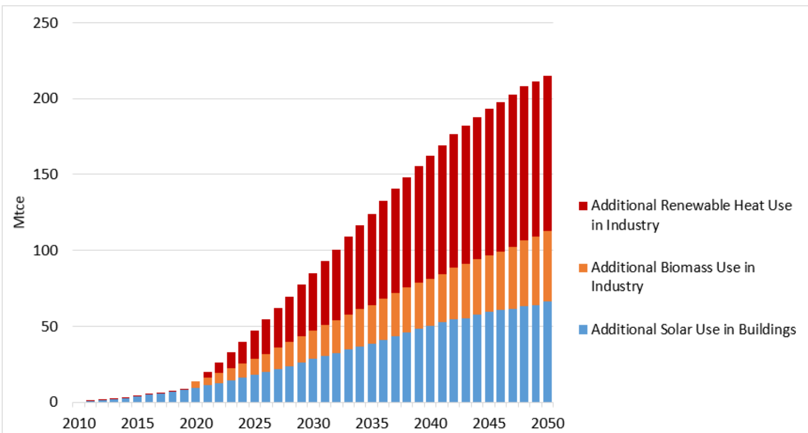

Figure 5. Additional Renewable Energy Utilization under Maximum Demand-side Renewable Scenario, 2010 to 2050

Figure 5 also indirectly shows the sectoral potential for additional renewable penetration on the demand-side between China's building and industrial sectors. Prior to 2022, the commercial building sector holds greater potential for utilizing new solar thermal technologies that are already commercialized. After 2022, however, the growing adoption of renewable heat and biomass technologies in the industrial sector overtake the steady deployment of solar thermal technologies in commercial buildings. By 2050, the industrial sector holds 69% of the additional renewable utilization potential, compared to 31% in commercial buildings.

Table 2 shows the CO_2-emitting fuels that can be displaced if China utilizes additional renewable energy under the Maximum Demand-side Renewable Scenario. Most of the additional renewable energy utilized is used to replace coal and coke, heat, and natural gas, with smaller amounts for electricity and heat. The mix of fuels being replaced by demand-side renewable energy utilization is important as it directly affects the CO_2 reduction potential of the additional renewable energy used. By 2050, 87 Mtce of coal, 54 Mtce of natural gas, 45 Mtce of heat, 26 Mtce of electricity and 4 Mtce of oil products can be replaced by the 216 Mtce of solar thermal, biomass and renewable heat energy. This translates into 634 Mt of CO_2 reduction per year in 2050, or 13% reduction when compared to the Cost-Effective Efficiency and Renewables Scenario.

Table 2. CO_2-emitting Fuels Displaced by Additional Demand-side Renewable Utilization

Unit: Mtce	**2020**	**2030**	**2040**	**2050**
Coal and Coke	4.12	43.78	65.36	86.98
Natural Gas	2.65	15.93	36.94	54.06
Oil Products	-	2.63	4.62	4.25
Heat	1.01	12.59	30.37	44.99
Electricity	2.99	8.62	20.49	26.17
Total Displaced	10.76	83.55	157.78	216.45

CO_2 Implications

Figure 6 shows the projected total energy-related CO_2 emissions for China under each of the four scenarios. Under the Reference Scenario, China's CO_2 emissions will grow from 8.35 gigatonnes (Gt) CO_2 in 2010 to 11.57 Gt CO_2 in 2050, with CO_2 emissions peaking at 14.64 Gt CO_2 in 2036. The Cost-effective Efficiency and Renewables Scenario and Maximum Electrification Scenario have very similar CO_2 trajectories, with both scenarios peaking in 2023 at 10.43 Gt CO_2 and 10.39 Gt CO_2, respectively. By 2050, there is a sharp decline in China's CO_2 emissions under both of these alternative scenarios, with the total emissions reaching 4.79 Gt CO_2 under the Cost-effective Efficiency and Renewables Scenario, compared to a total of 4.72 Gt CO_2 under the Maximum Electrification Scenario. Under both of these scenarios, China's 2050 CO_2 emissions will be about 60% lower than the total emissions under the Reference Scenario. Although the two scenarios' CO_2 emissions trajectories look similar, China's can reduce its 2010 to 2050 cumulative CO_2 emissions by 3.98 Gt CO_2 under the Max Electrification Scenario when compared to the Cost-effective Efficiency and Renewables Scenario. This reduction is possible even without further decarbonization of the power sector, which suggests that maximizing electrification with an even more decarbonized power sector (beyond what is cost-effective) could help China achieve additional CO_2 emissions reductions.

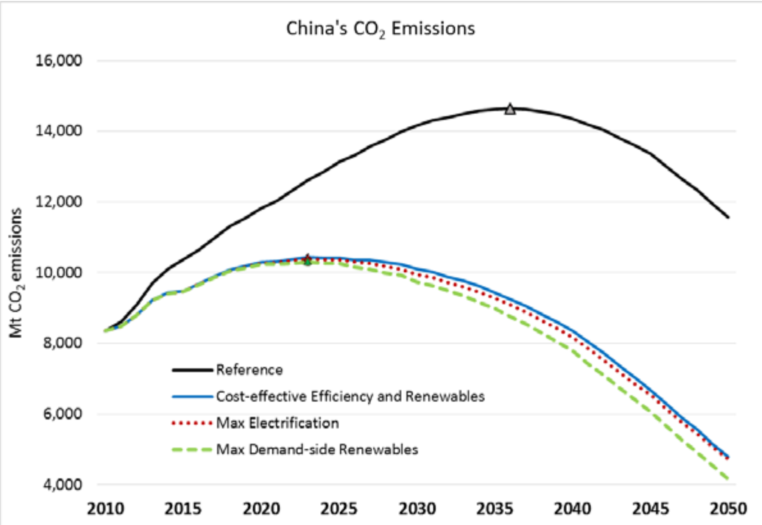

Figure 6. China's Projected CO_2 Emissions from 2010 to 2050 under Different Scenarios

Note: Y-axis not set to zero.

While China also reaches a CO_2 emissions peak in 2023 under the Maximum Demand-side Renewables Scenario with 10.30 Gt CO_2, its CO_2 emissions trajectory after 2025 with maximized demand-side renewables is notably lower than the other three scenarios. By 2050, China's total emissions will reach only 4.16 Gt CO_2, or 13% lower than the total emissions under the Cost-effective Efficiency and Renewables Scenario and 64% lower than the total under the Reference Scenario. In other words, maximizing demand-side renewables can help China further reduce its annual CO_2 emissions by 634 Mt CO_2 in 2050 beyond what it can already cost-effectively achieve with efficiency improvements and renewable adoption. Cumulatively from 2010 to 2050, this translates into 13.3 Gt CO_2 of additional CO_2 reduction potential for China.

Conclusions and Policy Implications

The results of this study show that there are several pathways for China to achieve its target of peaking its CO_2 emissions by 2030 or earlier, and to significantly reduce its future CO_2 emissions by as much as 60% annually by 2050 when compared to a Reference Scenario of no new policies. While China's CO_2 emissions can peak as early as 2023 by only pursuing cost-effective efficiency measures and fuel switching strategies, further maximizing demand-side electrification and utilization of non-conventional demand-side renewables can result in sizable additional CO_2 emissions reductions. However, achieving the CO_2 emissions reductions associated with each of the alternative scenarios requires overcoming significant barriers. Even for the Cost-effective Efficiency and Renewables Scenario, a multitude of barriers exist including lack of resources and knowledge for pursuing efficiency improvements, lack of coordination and enforcement of standards for strengthening efficiency, distorted tariff and energy prices, and concerns with regional unemployment issues and limited alternatives in some sectors for fuel switching. Comparing the national electrification rates between the different scenarios also highlight the important role that efficiency improvements play in reducing China's total national energy demand, which makes it more feasible to increase electrification. Without reducing total final energy demand across all sectors, it would be difficult for electricity to contribute to a higher share of final energy demand because there are limited end-uses in sectors such as transport and industry that can be replaced by electric technologies. Limited national electrification in turn limit the utilization of cleaner electricity and displacement of fossil fuels.

There is significant potential for cost-effectively increasing the electrification of all four demand sectors as well as additional potential for adopting maximum technically feasible electrification to achieve additional CO_2 reductions, but both scenarios also face key challenges. While some sectoral policies have been introduced to promote electrification in the transport sector, greater policy focus is needed to increase the adoption of electric heating, cooling and water heating technologies in the buildings sector and electrified industrial processes. In addition, one of the largest barriers is the interdependence between electrification and the successful decarbonization of the power sector, which requires resolving existing challenges with integrations of renewable power generation and continued growth in coal-fired generation. Maximizing demand-side renewables requires a shift in policy focus on not only expanding supply-side renewables, but also in promoting adoption and utilization of distributed demand-side renewables such as solar thermal heating, cooling and water heating technologies for the commercial buildings sector. Supporting policies, programs and measures such as subsidies and pilot demonstration projects will be needed to promote both new electric technologies such as heat pumps and electric vehicles and demand-side renewables. In addition, greater awareness and capacity building on possible applications for low temperature renewable heat in the industrial subsectors are also key to achieving the large potential for additional CO_2 emissions reductions from the industrial sector. Nevertheless, full realization of the potential for low temperature renewable heat will likely take time to achieve given the large scale and relatively decentralized nature of Chinese industries so it is important to start as soon as possible. Globally, the development of low temperature renewable heat used in industry remains slow, but lessons in the building sector of European countries such as Iceland, Sweden and Austria could be valuable for renewable heat deployment in the industrial sector.

The four scenarios included in this study represent four possible pathways for China's future energy and CO_2 emissions development, but they do not explicitly quantify and compare the individual impacts of efficiency improvement, adoption of demand-side versus supply-side renewables and end-use electrification. Thus, new research and additional scenario analysis are needed to disentangle the impact of cost-effective efficiency improvements versus fuel switching on CO_2 emissions reductions that are currently embedded in the Cost-effective Efficiency and Renewables Scenario. Additional modeling and analysis are also needed to separately analyze the individual CO_2 emissions reduction impact of power sector decarbonization on maximizing electrification, as well as compare the CO_2 emissions reduction impact of increasing adoption of demand-side versus supply-side renewables to help inform policymakers of policy prioritization needs.

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