Energy and CO2 Implications of Decarbonization Strategies for China beyond Efficiency: Modeling 2050 Maximum Renewable Resources and Accelerated Electrification Impacts

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Energy and CO_2 Implications of Decarbonization Strategies for China beyond Efficiency: Modeling 2050 Maximum Renewable Resources and Accelerated Electrification Impacts

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Highlights:

- China LEAP model used to assess multi-sector decarbonization strategies to 2050
- Energy, CO_2 impacts of accelerated electrification and renewables are assessed
- 2025 CO_2 peak feasible under 4 strategies, peak levels vary from 10.2-10.7 $GtCO_2$
- Faster electrification's CO_2 impact depend on pace of power sector decarbonization
- Demand-side renewable has similar CO_2 reduction impact as power decarbonization

Abstract:

Energy efficiency has played an important role in helping China achieve its domestic and international energy and climate change mitigation targets, but more significant near-term actions to decarbonize are needed to help China and the world meet the Paris Agreement goals. Accelerating electrification and maximizing supply-side and demand-side renewable adoption are two recent strategies being considered in China, but few bottom-up modeling studies have evaluated the potential near-term impacts of these strategies across multiple sectors. To fill this research gap, we use a bottom-up national end-use model that integrates energy supply and demand systems and conduct scenario analysis to evaluate even lower CO_2 emissions strategies and subsequent pathways for China to go beyond cost-effective efficiency and fuel switching. We find that maximizing non-conventional electric and renewable technologies can help China peak its national CO_2 emissions as early as 2025, with significant additional CO_2 emission reductions on the order of 7 Gt CO_2 annually by 2050. Beyond potential CO_2 reductions from power sector decarbonization, significant potential 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 choices in the demand sectors. Managing the pace of electrification in tandem with the pace of decarbonization of the power sector will also be crucial to achieving CO_2 reductions from the power sector in a scenario of increased electrification.

Keywords: China bottom-up model; electrification; renewables; CO_2 emissions

1. Introduction

In support of the Paris Agreement, China has committed to peak its carbon dioxide (CO_2) emissions by 2030 or earlier and to reduce its CO_2 per unit of GDP intensity by 60-65% from 2005 levels by 2030 [1]. China's 13th Five-Year Plan for 2016 to 2020 includes an energy intensity per unit of GDP reduction target of 15% and CO_2 intensity reduction target of 18% by 2020 [2]. These recent targets follow years of

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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 37% from 2005 to 2016, total primary energy consumption increased by 167% over the same time period and coal consumption is still 62% of primary energy consumption in 2016 [3]. Although coal consumption's share of total energy consumption has declined significantly over the last decade, other significant near-terms actions beyond energy efficiency are needed to help China achieve its 2020 and 2030 targets and contribute to global efforts to limit the average global temperature increase to 2˚C or lower.

Two near-term strategies that are currently being pursued in China beyond energy efficiency include promoting the adoption of renewable sources, particularly in the power sector, and electrification. Renewable installed capacity targets for 2020 were laid out in the Strategic Energy Action Plan (2014-2020) and updated under the 13th Five Year Plan for 2016 to 2020 along with target of 15% non-fossil share of primary energy consumption [4,5]. In January 2017, the National Energy Administration announced that China is planning to spend at least 2.5 trillion yuan on renewable energy in the 13th Five Year Plan period [6]. Significant policy focus has also been placed on power sector reform, in order to increase renewable energy utilization by addressing overcapacity and reducing curtailment [7]. China is also pursuing greater electrification through sectoral policies including increasing the use of electric vehicles in the transport sector, electrification of rural households and industrial processes, and promoting the adoption of more efficient, end-use equipment such as heat pump technology in Chinese buildings. The indirect push for electrification coincides with the emergence of the concept of environmentally beneficial electrification in the United States (U.S.) and Europe, or "electrification of energy end uses that have been powered by fossil fuels in order reduce greenhouse gas emissions" [8-10]. In the U.S., the shift towards environmentally beneficial electrification has been enabled by public policy goals for reducing greenhouse gas emissions, declines in power sector's CO_2 intensity due to technological advancements, fuel switching, cost reductions for renewable power, increased efficiency of electric end-use equipment, and growing need for flexible loads to help integrate intermittent renewable energy into the electric grid [9]. For China, environmentally beneficial electrification will likely gain more traction in the near future as China has already adopted policy goals aimed at reducing CO_2 emissions and decarbonizing its power sector.

This paper focuses on the feasibility for further lowering China's future CO_2 emissions by accelerating electrification in parallel with power sector decarbonization and maximizing demand-side utilization of renewable technologies. We uses a bottom-up national end-use model that integrates energy supply and demand systems and conduct scenario analysis to evaluate even lower CO_2 emissions strategies and subsequent pathways for China to go beyond cost-effective efficiency and fuel switching. We developed individual scenarios of low carbon strategies including energy efficiency, fossil fuel switch, demand and supply-side renewables, and accelerated electrification (with maximized technically feasible electrification rates for selected end-uses) to evaluate the potential energy and CO_2 impacts of these key strategies. By comparing these alternative technology scenarios against a Reference scenario of existing policies, we are able to assess alternative CO_2 pathways if China is able to rapidly decarbonize its power sector while accelerating electrification, 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.

This study contributes to the existing body of energy modeling literature focused on China in several different ways. From a methodological perspective, we use a bottom-up end-use model built using the Long-range Energy Alternatives Planning (LEAP) system software that is able to differentiate nuances at the level of end-uses and individual technologies beyond macroeconomic modeling approaches in existing Chinese modeling studies [11-15]. Our study further contributes to the bottom-up energy modeling field by evaluating newer, multi-sectoral strategies beyond cost-effective efficiency improvements and fuel switching strategies typically considered in the few existing bottom-up China modeling studies [16], and with longer time frame out to 2050 [17-18]. Other China modeling studies have evaluated the potential impacts of accelerated electrification, but most focused on transport without consideration for industry or commercial buildings, two dominant and rapidly growing sectors in China's energy system [12, 19, 20, 21]. Most other studies also do not explicitly model the linkage between electrification and power sector decarbonization [22], or have done so only for other regions [23-26] or only for selected sectors [19, 27, 28]. Other studies have estimated economy-wide electrification rates through historical extrapolation and regression analysis focused on per capita electricity consumption [29-30]. But these often result in relatively high forecasts that overlooks longer term changes such as saturation effects in equipment stock or autonomous efficiency improvements that are considered in bottom-up projections.

While several earlier studies have considered pathways of high renewable penetration for China [31-33], we add to these existing outlooks by evaluating and comparing demand-side utilization of newer renewable technologies to efficiency, fossil fuel switching, and accelerated electrification. We also considered technologies such as low temperature renewable heat and solar thermal heating and cooling technologies that have only been deployed in some European countries as discussed later in section 3.3, but not yet considered in most future renewable scenario outlooks for China [28, 34]. By considering the combined and separate impacts of efficiency, electrification and adoption of non-conventional renewable resources such as renewable heat on China's total energy-related CO_2 emissions through 2050, we fill a key research gap in existing modeling studies of China's climate change mitigation strategies and pathways.

The remainder of this paper is organized as follows: Section 2 reviews the LEAP modeling framework, data validation and projection methodology; Section 3 details the specific storylines and key assumptions for our five different scenarios; Section 4 presents the energy and CO_2 emissions results by sector with overall CO_2 outlook for each scenario; and Section 5 provides an overall discussion of results and policy implications.

2. Methods

2.1 Modeling Framework

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 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 [35]. The China 2050 DREAM model was developed in 2005 and has been used in earlier national outlook studies for China [37-38] and sector-specific policy impact evaluation studies [39-40].

2.2 Data and Historical Calibration

Historical data published in various national statistical yearbooks are used to calibrate the China 2050 DREAM model inputs to the latest available reported statistics, including for both energy demand and supply-side activity variables such as population, floorspace, industrial production, transport vehicle stock, and fossil fuel and electricity production [3, 41]. For reported years, the model calculated energy consumption by fuel and by sector are compared to and validated against national energy balances in terms of fuel consumption by sectors [41]. For calculating energy-related CO_2 emissions, China-specific fuel energy and heat content are entered into the model and multiplied by the IPCC default CO_2 emissions factors for specific fossil fuels [42]. The underlying assumptions of earlier versions of the model were previously compared with other bottom-up energy and emission models for China (43), and have been validated by other modeling studies [44-45].

2.3 Demand Sectors

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 in the extraction of fossil fuels and in non-power transformation sectors 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 drivers of energy-using activity with detailed consideration of technological development at the end-use level. Based on specific scenario assumptions about activity growth and technology choices, the model is able to calculate and evaluate the total primary and final energy consumption and energy-related CO_2 emissions impacts for China's development to 2050 [46].

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 [47] as well as Chinese sources [32, 38]. 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 (e.g., in megajoules per square meter). The buildings sectors are also differentiated by three main climate zones, new versus existing buildings and five building efficiency vintages.

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[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.

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. These subsectors are driven by key physical drivers such as the new built environment needed to house growing urban populations, vehicle production, 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 our collaborator's computable general equilibrium model for China [38]. 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 specific modes 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.

2.4 Supply Sectors

On the supply side, the energy transformation sector includes a power-sector module that can be adapted to reflect changes in generation-dispatch algorithms, efficiency levels, generation mix, and demand-side management. The power generation sector models different power generation technologies including coal, natural gas, biomass, nuclear, wind, hydro, solar, and geothermal power generation. Coal generation is further distinguished into six categories by size and efficiency, ranging from less than 100 MW generation units with average efficiency of 32% to greater than 1000 MW ultra-supercritical generation units with average efficiency of 40%. For each technology type, the model includes parameters on total installed capacity, load factors, and dispatch order. Following specified power sector module parameters, the model uses algorithms to calculate the amount and type of capacity required to be dispatched to meet the final electricity demand from the economic sectors. The model also follows different rules for dispatching electricity to meet demand: a proportional dispatch order which dispatches electricity generation following proportional shares from each fuel source, an environmental or green dispatch order that dispatches generation based on their environmental (i.e. low carbon) merit by prioritizing non-fossil generation before fossil generation, or cost-optimization dispatch.

3. Scenarios and Assumptions

Five main scenarios are developed to evaluate the potential CO_2 reductions if China is able to rapidly decarbonize its power sector while accelerating electrification across all sectors and the additional opportunity from maximizing biomass and emerging renewable technologies in industry and building sectors. The scenarios developed are not driven by climate end-point such as the international goals of keeping global temperature increases to 1.5˚C or 2˚C or intended to reflect certain policy outcomes such as the Nationally Determined Contribution (NDC) commitments and targets, but rather, are based on bottom-up assumptions for activity and technology trends, including differing trends in efficiencies and fuel mixes. However, the results from the different scenarios can be compared to other studies where scenarios are developed based on meeting specific climate end-points, such as the 350ppm and 450ppm scenarios included in the International Energy Agency's World Energy Outlook.

The Reference and Cost-Effective Efficiency and Fossil Fuel Switch Scenarios were developed primarily

as part of the "Reinventing Fire: China" study [38]. In addition, three new scenarios were developed to evaluate the additional maximum technical potential beyond cost-effective measures for reducing CO_2 emissions by more aggressively electrifying all end-use sectors (with decarbonized power sector), maximizing demand-side renewable technologies and maximizing supply-side renewable technologies. The goal of these three additional scenarios is to evaluate the technically feasible potential for accelerating electrification and maximizing demand-side renewable technology adoption, beyond existing strategies of increasing energy efficiency, fuel switching towards cleaner fossil fuels and decarbonizing the power sector. Activity data in all scenarios have been updated and calibrated to the latest available year at the time of analysis, including data through 2014 or 2015.

All five 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 four "alternative" scenarios with expected industrial structural shift as a result of continued policy push and economic development. Faster growth in light manufacturing industry and slower growth in heavy industry are expected under the alternative scenarios when compared to the Reference Scenario due to 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 four alternative scenarios are the same.

Similarly, the installed capacities of power generation technologies also vary between two sets of scenarios with and without more aggressive adoption of renewable power supply beyond current targets, reflecting different paces of power sector decarbonization. Under the Reference Scenario (as well as Cost-Effective Efficiency and Fossil Fuel Switch scenario and Efficiency, Fossil Fuel Switch and Demand-side Renewables 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 Fossil Fuel Switch and All Renewables Scenario and All Strategies Plus Accelerated Electrification scenario, 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. However, green or environmental merit dispatch is used for all five scenarios given Chinese power sector policies with the impact of different dispatch orders having been already evaluated in [40].

Table 1 summarizes the major changes in parameters between each scenario as discussed below in each specific scenario.

Table 1. Overview of Scenario Analysis and Key Parameter Differences

Scenarios	**Macroeconomic Assumptions**	**Sectoral Activity Levels**	**Cost-effective Efficiency Improvements**	**Cleaner Fossil Fuel Switch**	**Demand-side Renewables**	**Supply-side Renewables**	**Accelerated Electrification**
Reference	Reference levels	Reference levels	Not included	Not included	Not included	Not included	Not included
Efficiency and Fossil Fuel Switch	Same as Reference	Structural shifts included	Included	Included	Not included	Not included	Not included

Efficiency, Fossil Fuel Switch and Demand RE	Same as Reference	Same as Efficiency and Fossil Fuel Switch	Included	Included	Included	Not included	Not included
Efficiency, Fossil Fuel Switch and All RE	Same as Reference	Same as Efficiency and Fossil Fuel Switch	Included	Included	Included	Included	Not included
All Strategies Plus Accelerated Electrification	Same as Reference	Same as Efficiency and Fossil Fuel Switch	Included	Included	Included	Included	Included

3.1 Reference Scenario

The Reference Scenario serves as the baseline scenario and assumes that all policies currently in place 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 under the 12th Five-Year plan, as well as the announced non-fossil power generation capacity targets for the power sector. This scenario is intended to reflect all policies that have been adopted to date, including those adopted in support of China's NDC commitments for 2030, but is not intended to reflect the outcome of the NDC commitments or targets. As a counterfactual baseline scenario, the Reference Scenario assumes no additional policies will be adopted in the future, but autonomous technological improvement is expected to occur through 2050.

3.2 Cost-Effective Efficiency and Fossil Fuel Switch Scenario

This scenario assumes that China adopts the maximum feasible share of today's commercially available and cost-effective energy efficiency technologies by 2050 while also maximizing the adoption of cleaner fossil fuel (e.g. natural gas) by shifting away from dirtier fossil fuels such as coal and coke. Because this scenario is intended to quantify the impact of only efficiency and fossil fuel switching, it assumes no additional electrification or adoption of renewables beyond the Reference scenario. 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 fossil fuel technologies is assumed to occur across all end-uses.

More details on the sector-specific assumptions about cost-effective technology uptake and fuel switching is discussed in the Reinventing Fire: China Executive Summary [38].

3.3 Efficiency, Fossil Fuel Switch and Demand-side Renewables Scenario

Beyond cost-effective efficiency and cleaner fossil fuel switching, this scenario considers the impact of adoption of additional renewable resources across applicable end-uses as well as maximized renewable adoption across selected end-uses in the buildings and industry sectors. More specifically, for selected

[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.

industries and commercial buildings, this scenario considers additional adoption of non-conventional renewable heat and biomass in industry and solar thermal technologies in commercial buildings based off of the Cost-effective Efficiency and Renewables 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.

3.3.1 Renewable heat applications in industry

In industry, low grade heat defined as below the 100 °C temperature range can be found in process steam, process cooling and HVAC system, with process steam dominating low grade heat demand [48]. Process heat is required for industrial processes such as hot water or steam demand processes, drying and dehydration processes, preheating, pasteurization and sterilization, washing and cleaning, and chemical reaction [49].

In Europe, about 30% of the total industrial heat demand is required at temperatures below 100°C and 57% at temperatures below 400°C [50]. The key sectors identified for application of low grade heat include food, pulp and paper, textile, chemical, machinery, transport equipment, and mining and quarrying. Given the similar processes utilized for specific industrial subsectors, we assume that the share of low grade heat demand found in European industries is representative of corresponding sub-sectors around the world and therefore applies to Chinese industrial sectors (Figure 1).

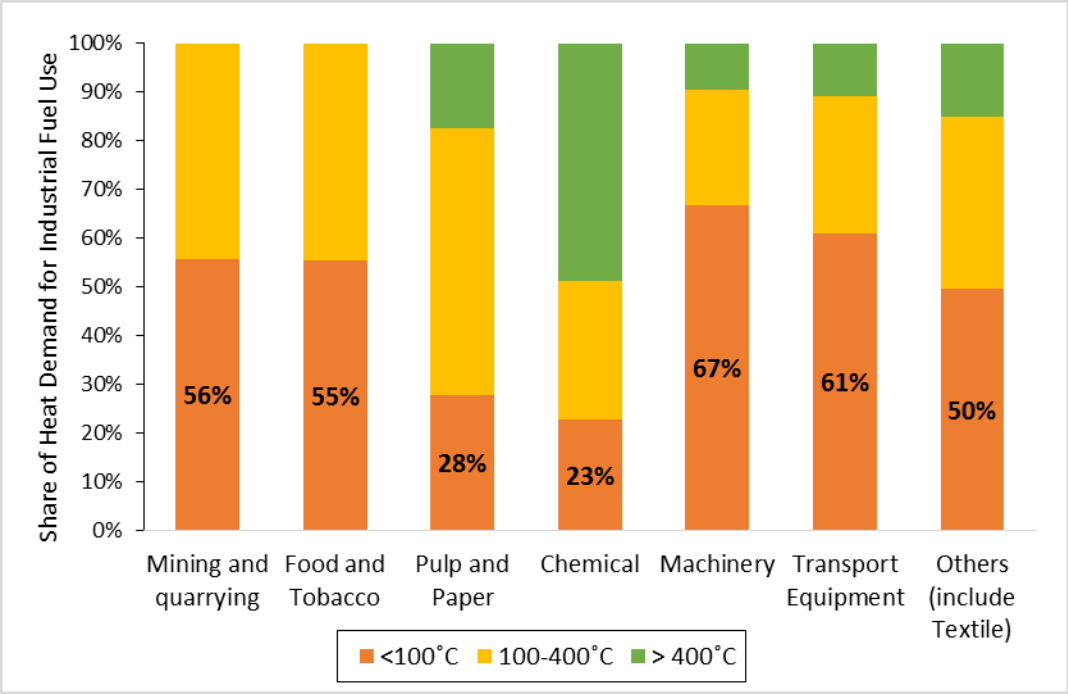

Figure 1. Low Temperature Grade Heat Demand Shares of Industrial Fuel Use in Key Industrial Subsectors

Note: Recreated based on data from [50].

Globally, renewable energy is estimated to account for 10% of total industrial heat use, of which 99% is

bioenergy-based [51]. 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 [51]. This study assumes that, by 2050, the low temperature heat demand portion of energy demand from the industrial sectors shown in Figure 1 is fully supplied by an assumed fuel mix of renewables based on the fuel mix result for low temperature process heat in IRENA's AmbD 2030 scenario [52]. Specifically, the assumed mix of renewable sources for low grade heat includes 63% biomass, 30% solar thermal and 7% geothermal, and is expected to remain constant from the base year through 2050 in the absence of detailed projections.

3.3.2 Biomass Use for High Temperature Industrial Heat

Currently, biomass is the only available renewable energy option for providing high-temperature (i.e., >400°C) heat in the industrial sector with limited applications in steelmaking and cement production processes. For steelmaking, biomass can be introduced in integrated steelmaking through two technological upgrades:

1. Blending biomass during coke making to produce bio-coke, with a maximum of 5% biomass blend to maintain coke properties without compromising mechanical strength [53-55]. We assume 5% biomass addition to the coal blend for coke making with a coke/biomass replacement ratio of 1/0.67 based on [54].
2. Biomass replacement of pulverized coal in blast furnaces has been utilized in the Brazilian steel industry [54]. Based on the Brazilian experience, we assume a biomass/pulverized coal replacement rate of 1/1 with 75% maximum deployment by 2050.

For cement production, biomass is used as an alternative fuel in Netherlands and Finland [56-57]. Based on the Dutch and Finnish pilot plants, we assume 50% deployment rate in Chinese kiln combustion by 2050.

In considering the increased biomass usage for industrial applications, we assume biomass will only be sourced domestically and consider a conservative total biomass resource of 800 million metric tons of coal equivalent (Mtce[4]) limit for residential, industrial and power sector use. The assumed deployment rates are also based only on technical potential and do not consider technological costs or deployment barriers.

3.3.3 Solar Thermal Applications for Commercial Buildings

We considered increased adoption of solar thermal technologies for heating and cooling only for commercial buildings because of the limited rooftop space availability in multi-story Chinese residential buildings due to widespread utilization of solar water heaters. Based on the United Kingdom's experience with decarbonizing buildings sector, we assume solar thermal can replace coal boilers in Northern China, and gas boilers in Transition and South climate regions with 8% share by 2050 [58].

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 [59] and 30% penetration in Southern China by 2050 [60]. We assume moderate levels of solar thermal cooling adoption in Chinese commercial buildings because larger shifts in the Chinese cooling market is

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

unlikely to occur without significant long-term policy changes targeting solar cooling technologies, which is not considered in this study.

We also assumed 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 [61]. Together with large use of air source heat pumps (48% by 2050) for commercial water heating, solar water heating can provide almost 80% of the water heating need under this scenario.

3.4 Efficiency, Fossil Fuel Switch and All Renewable Scenario

Building off the previous scenario that includes demand-side renewables, this scenario helps evaluate the total impact of renewables by adding in a decarbonized power sector with growing penetration of renewable and non-fossil generation. The total final energy demand for this scenario is the same as the previous scenario of Efficiency, Fossil Fuel Switch and Demand-side Renewables Scenario but the generation profile for the power sector is markedly different. Table 2 compares the installed capacity between the two scenarios. Energy storage technologies are not considered beyond limited capacities for pumped hydro in the power sector.

Table 2. Assumptions for Power Sector Installed Capacities

Unit: GW of installed capacity	**Reference; Efficiency and Fossil Fuel Switch; Efficiency, Fossil Fuel Switch and Demand-side Renewable Scenario**					**Efficiency, Fossil Fuel Switch and All Renewables; All Strategies Plus Accelerated Electrification Scenarios**				
	2010	**2020**	**2030**	**2040**	**2050**	**2010**	**2020**	**2030**	**2040**	**2050**
Distributed Solar PV	0	15	48	120	251	0	19	69	223	504
Geothermal	0	0	0	0	0	0	0	0	0	1
Biomass	4	15	25	34	47	4	15	19	22	34
Solar	0	95	216	432	704	0	124	313	801	1,416
Wind	30	210	366	559	721	30	271	482	1,002	1,217
Nuclear	11	58	130	220	350	11	58	100	155	221
Hydro	216	380	398	444	501	216	380	410	444	501
Natural Gas	17	110	133	157	207	17	110	161	225	294
Diesel	9	13	17	19	17	9	11	11	10	6
Coal	559	1,051	1,358	1,449	1,274	559	855	904	833	442

3.5 All Strategies Plus Accelerated Electrification Scenario

In order to evaluate the additional CO_2 reduction from accelerating electrification in all demand sectors beyond cost-effective efficiency and renewable technologies, the All Strategies Plus Accelerated Electrification scenario considers additional electrification beyond the level of the Reference Scenario for all end-use sectors. Increased electrification across all end-uses is first 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 [38]. Then, additional assumptions about maximized technically feasible electrification of selected key building end-uses, transport modes, and industrial processes were developed based on evaluation and analysis of international adoption rates and policy trends. This scenario assumes that accelerated electrification will only occur in step with an increasingly decarbonized power sector, consistent with the increasingly popular concept of "environmentally beneficial electrification.[5]"

3.5.1 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 [62]. Supporting policies and infrastructure are also needed to rapidly increase private EV adoption from now through 2050. Recently, 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 [63]. Similarly, accelerated penetration of battery electric vehicles are also considered for both heavy-duty and light-duty intracity buses. 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.

3.5.2 Industry

The maximum 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:

1. Replacing fossil fuel melting with electricity in the Glass sector
2. Replacing coal firing with electricity in the Food and Beverage sector
3. Replacing heat dryers with electricity in the Pulp and Paper sector

Although none of these applications are currently commercially available, studies expect these to be deployed in large-scale after 2030 [64-66]. Our specific assumption rates for China are shown in Table 3 below, and 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.

In addition, electric arc furnace (EAF) process has historically been responsible for around 15% share of Chinese steel production, although its share has experienced a decline in recent years [67]. China

[5] The concept of environmentally beneficial electrification was first introduced in [8], and refers to the electrification of energy end-uses that have been powered fossil fuels in order to reduce greenhouse gas emissions.

currently depends heavily on import for steel scrap, the main raw material for the EAF production process. This lack of adequate scrap contrasts with large reserves for coking coal, the dominant Basic Oxygen Furnace production process (BOF). Combined with newly added BOF production capacities, we expect BOF to remain dominant through 2050, with 10 percentage point increase in EAF production to 40% share of steel production by 2050.

3.5.3 Buildings

For commercial buildings, geographic limitations and different climate zone conditions are considered in developing the maximum technically feasible adoption of air source and ground source heat pumps for heating and cooling, respectively, since current technologies for air source heat pump are not effective under very cold 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 3). Similarly, the adoption of air source heat pumps for residential heating is also maximized taking into consideration geographic limitations and local climate zone conditions.

Table 3 summarizes the key assumptions of the selected sectors with maximized electrification under the Accelerated Electrification scenario.

Table 3. Key Sectoral Technology Adoption Assumptions in Scenario Analysis

	2010	**2050 Reference**	**2050 with Accelerated 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
Buses	3% EV share of heavy-duty buses	24% EV share of heavy-duty buses, 16% EV share of light-duty buses	35% EV share of heavy-duty buses, 22% EV share of light-duty buses
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
Steel Production	13% share for Electric Arc Furnace (EAF)	30% share for EAF	40% share for EAF
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. Results

We present our results in two ways: first in terms of the energy impacts of the two key strategies of maximizing supply and demand-side renewable deployment and accelerating electrification, and then by comparing the CO_2 results of different scenarios modeled to understand the CO_2 implications of different low carbon strategies.

4.1 Energy Results

4.1.1 Maximum Renewable Deployment

Maximizing the deployment of demand-side renewable technologies in China's commercial and industrial sectors results in the additional utilization of 216 Mtce of renewable energy by 2050, compared to the Efficiency and Fuel Switching Scenario without additional renewables. Renewable heat use in industry (as shown in red) 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 (Figure 2). 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 industries that are able to utilize low grade temperature, renewable heat. In particular, food, beverage and tobacco, transport equipment and machinery manufacturing are some of the leading industries utilizing greater shares of renewable heat under this scenario.

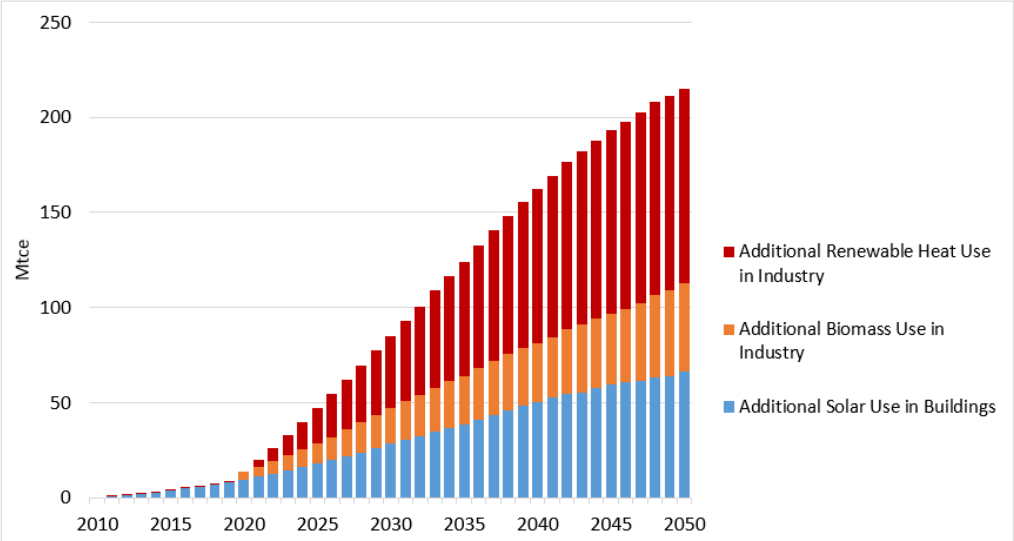

Figure 1. Additional Renewable Energy Utilization under Maximum Demand-side Renewable Scenario to 2050

From the sectoral perspective, the commercial building sector holds greater potential for utilizing new solar thermal technologies that are already commercialized prior to 2022. After 2022, however, the growing adoption of renewable heat and biomass technologies in the industrial sector overtakes the steady deployment of solar thermal technologies in commercial buildings. By 2050, the industrial sector holds 69% of the additional renewable heat utilization potential, compared to 31% in commercial buildings for heating. Most of the additional industrial renewable utilization potential is from increased renewable heat use generated from biomass (63%), solar thermal (30%) and geothermal heat (7%).

Most of the additional renewable energy utilized replaces coal and coke, fossil fuel generated heat, and natural gas, with smaller amounts used to replace 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 on an annual basis by the 216 Mtce of solar thermal, biomass and renewable heat energy (Table 4). This translates into 634 Mt of CO_2 reduction per year in 2050, or 13% reduction when compared to the Efficiency and Fossil Fuel Switch Scenario.

Table 4. CO_2-emitting Fuels Displaced by Additional Demand-side Renewable Utilization

Unit: Mtce	**2020**	**2030**	**2040**	**2050**
Coal and Coke	4.1	43.8	65.4	87.0
Natural Gas	2.7	15.9	36.9	54.1
Oil Products	-	2.6	4.6	4.3
Heat	1.0	12.6	30.4	45.0
Electricity	3.0	8.6	20.5	26.2
Total Displaced	10.8	83.6	157.8	216.5

4.1.2 Accelerated Electrification

We find that for all four sectors, there is significant near-term potential for increasing electrification cost-effectively beyond the Reference level. 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. Most of the increased electrification will occur as a result of technological change, such as the increasing adoption of electrical appliances in residential buildings as a result of urbanization and growing household incomes (Figure 3). This is reflected in the higher electrification rates across all sectors and overall electrification rate of 38.6% in a previous study that only considered adoption of today's cost-effective technologies under [38].

However, our additional scenario analysis finds that when considering the increasingly decarbonized power sector expected in coming years, *additional* electrification can occur in all four sectors to varying degrees (Figure 3). Under the Accelerated 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 to 83% and 25% by 2050, respectively.

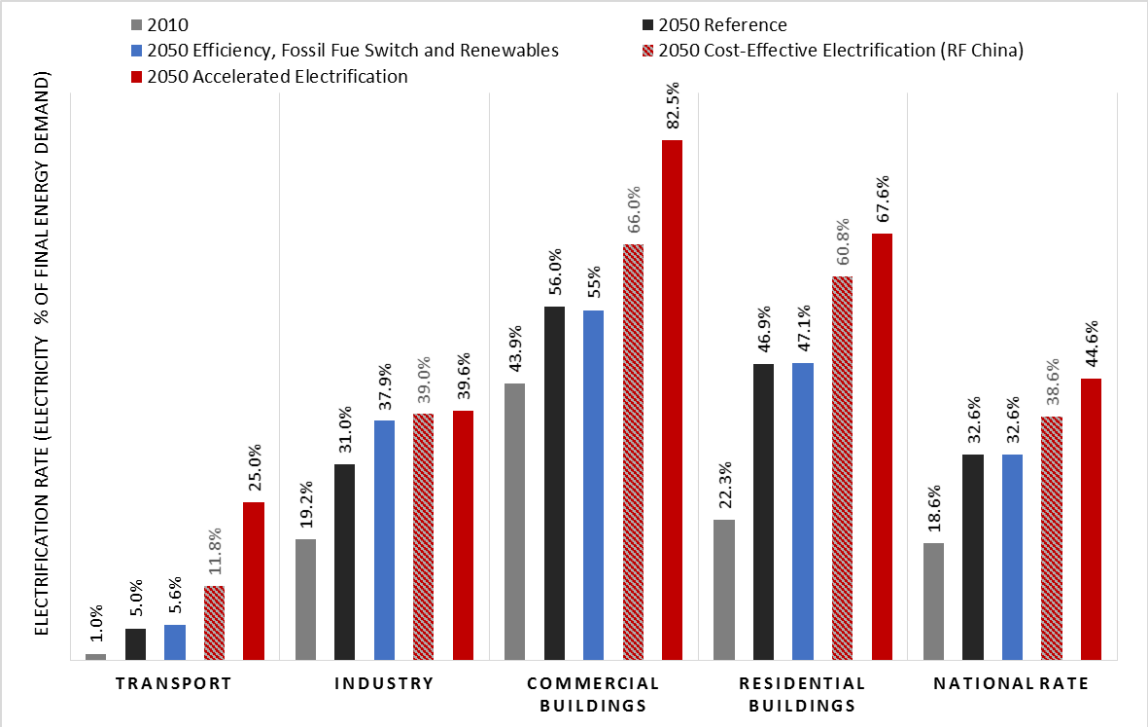

Figure 2. 2010 and 2050 Sectoral Electrification Rates by Scenario

Note: Electrification rate is electricity's share of total final energy demand. RF China is the Reinventing Fire: China study [38].

We also find lower total final energy demand under the Efficiency and Fossil Fuel Switch and Accelerated 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 (Figure 4). China's total final energy demand is the lowest under the Accelerated Electrification Scenario with 2718 Mtce of total annual energy demand in 2050, compared to demand of 4266 Mtce under the Reference Scenario and 2732 Mtce under the Efficiency, Fossil Fuel Switch and Demand Side Renewables Scenario, due to additional adoption of higher efficiency electrical equipment. These results suggest that the CO_2 impact associated with accelerated electrification and decarbonized power 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.

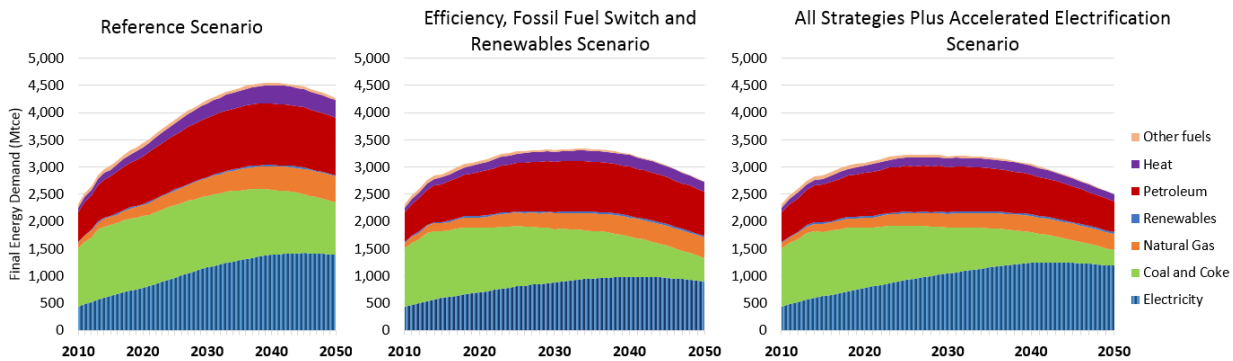

Figure 4. Final Energy Demand by Fuel by Scenario, 2010 to 2050

The energy benefits of accelerating electrification are shown by the relatively small increase in electricity demand due to additional electrification, which can be offset by reduction in the consumption of coal, gasoline, natural gas, heat, coke and other fossil fuel resources (Figure 5). By 2050, there is a net reduction of 231 Mtce of final energy demand, with the increased demand for 293 Mtce of electricity offset by 522 Mtce savings in fossil fuel consumption.

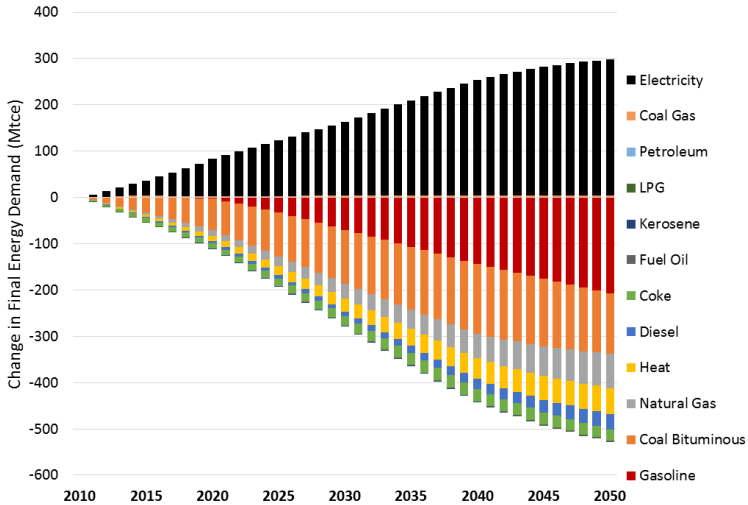

Figure 5. Final Energy Demand Impacts of Accelerated Electrification

However, despite an increasingly decarbonized power sector, the additional electricity generated to meet more aggressive electrification is still mostly derived from coal-fired generation. This is because despite rapid increases in installed capacities for renewables, there is still insufficient renewable-based power generation to meet the additional electricity demand associated with increased electrification. Under the Accelerated Electrification Scenario, additional electricity generated to meet accelerated electrification is all generated by coal-fired power through 2044 because all of the new incremental non-fossil power generation has already been used to meet the higher electricity demand (Figure 6). Compared to the Efficiency, Fossil Fuel Switch and All Renewables Scenario, there is a slow-down in the decline in use of fossil fuels such as coal, with larger amount of coal not displaced by the growth of renewables due to extra demand for electricity. Based on our assumed installed capacity for non-fossil generation – which already accounts for the maximum supply-side renewable capacities in the Efficiency, Fossil Fuel Switch and Renewables Scenario - and accelerated electrification rates, the year 2045 appears to be a turning point where there is finally sufficient non-fossil power generation to offset the increase in electricity demand from accelerated electrification. After 2045, more of the additional electricity generated can be met by solar power (both on-grid and distributed photovoltaic) and biomass power, resulting in greater offset of coal-fired power. This suggests that managing the pace of electrification in tandem with the roll-out of additional non-fossil power generation is crucial in the resulting CO_2 impact of electrification as further discussed in the next section.

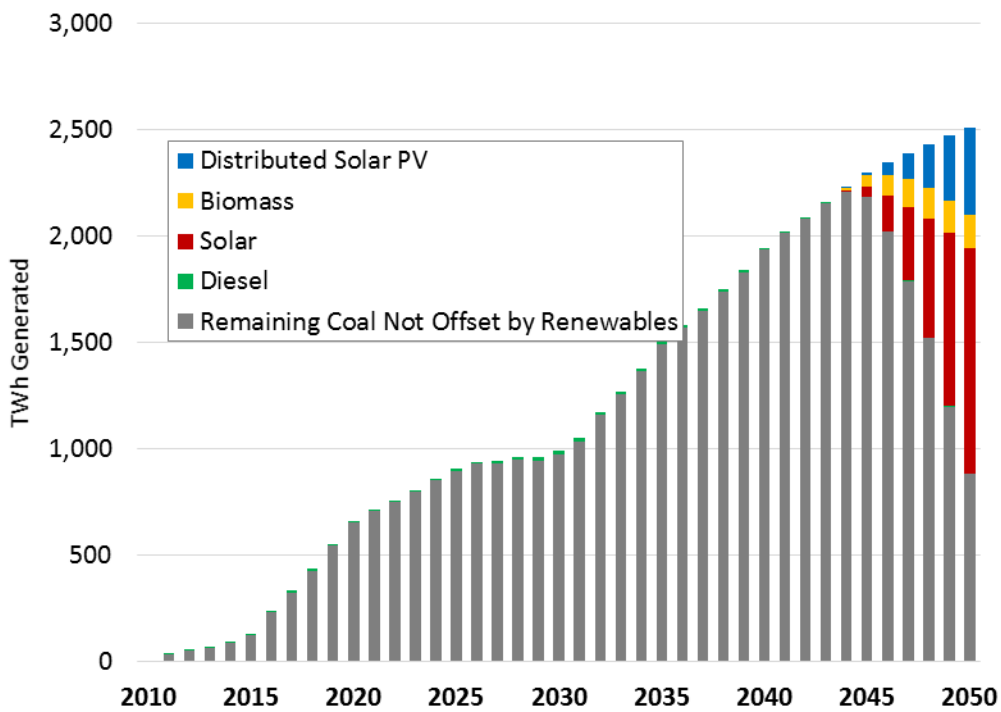

Figure 6. Generation Fuel Mix of Additional Electricity Demand under Accelerated Electrification Scenario

The overall energy impact of accelerated electrification is shown in Figure7, which compares the change in primary energy use by fuel type of All Strategies Plus Accelerated Electrification Scenario with the Efficiency, Fossil Fuel Switch and All Renewables Scenario. The reduction in crude oil, gasoline, and

natural gas from additional electrification is offset by the net increase in coal use for power generation when compared to the Efficiency, Fossil Fuel Switch and All Renewables Scenario. As discussed previously, this net increase in coal use results from offset to the decline in demand for fossil fuels made possible in other scenarios because of the need for additional coal-based generation to meet higher electricity demand.

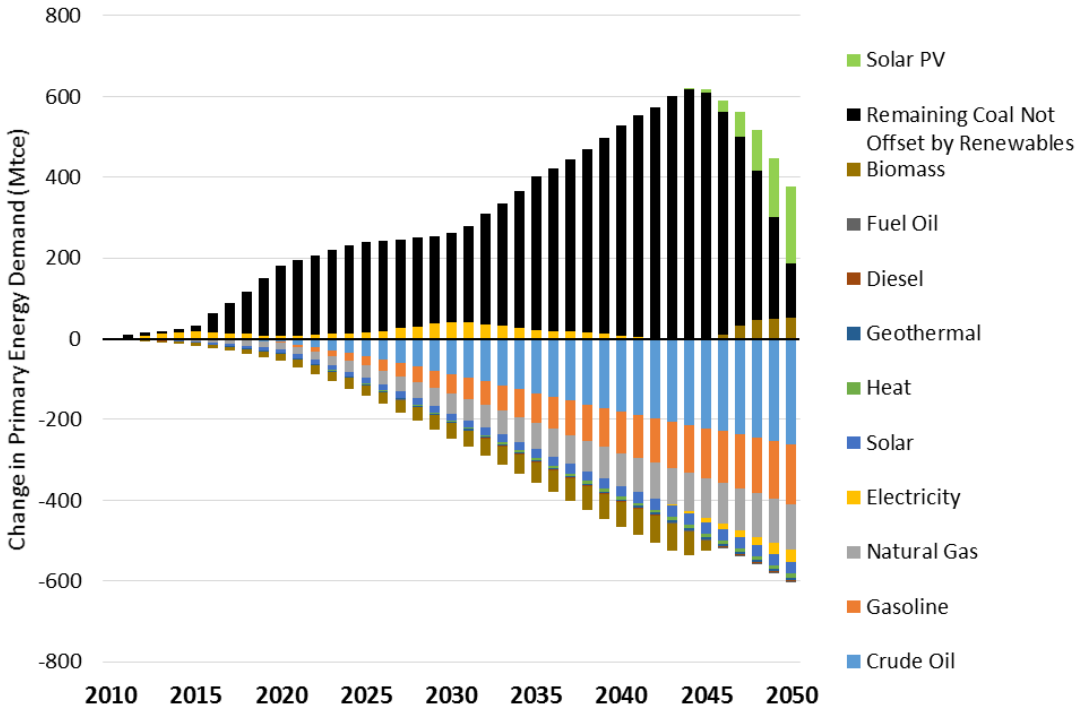

Figure 7. Primary Energy Demand Impacts of Accelerated Electrification by Fuel Type

4.2 CO_2 Results and Implications

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 (Figure 8). The four alternative scenarios follow similar CO_2 emissions trajectory from 2010 through 2030, with all four scenarios reaching a CO_2 peak in 2025, eleven years earlier than the Reference CO_2 peak year of 2036. The CO_2 peak level varies slightly between the four scenarios, with the lowest CO_2 peak level of 10.17 Gt CO_2 achieved under the Efficiency, Fossil Fuel Switch and All Renewables scenario and the highest peaking level of 10.73 Gt CO_2 reached under the Efficiency and Fossil Fuel Switch scenario. After 2030, there is greater divergence between the CO_2 pathways of the four alternative scenarios, with the Efficiency and Fossil Fuel Switch scenario having the highest CO_2 emissions and the Efficiency, Fossil Fuel Switch and All Renewables Scenario having the lowest CO_2 emissions of the four alternative scenarios. Accelerating electrification in all sectors with maximized electrification for key end-uses under the All Strategies Plus Accelerated Electrification scenario results in generally higher CO_2 emissions than the Efficiency, Fuel Switch and All Renewables Scenario through 2045, as a result of the increased coal-fired power generation to meet additional electricity demand seen in Figure 6. By 2050, however, the All Strategies Plus Accelerated Electrification scenario results in slightly lower annual CO_2 emissions. In 2050, the combination of efficiency, fuel switching including aggressive electrification and

maximized renewable deployment embodied in the All Strategies Plus Accelerated Electrification Scenario results in total annual CO_2 emissions of 4.39 Gt CO_2, or 62% reduction from the total annual emissions of 11.57 Gt CO_2 under the Reference Scenario.

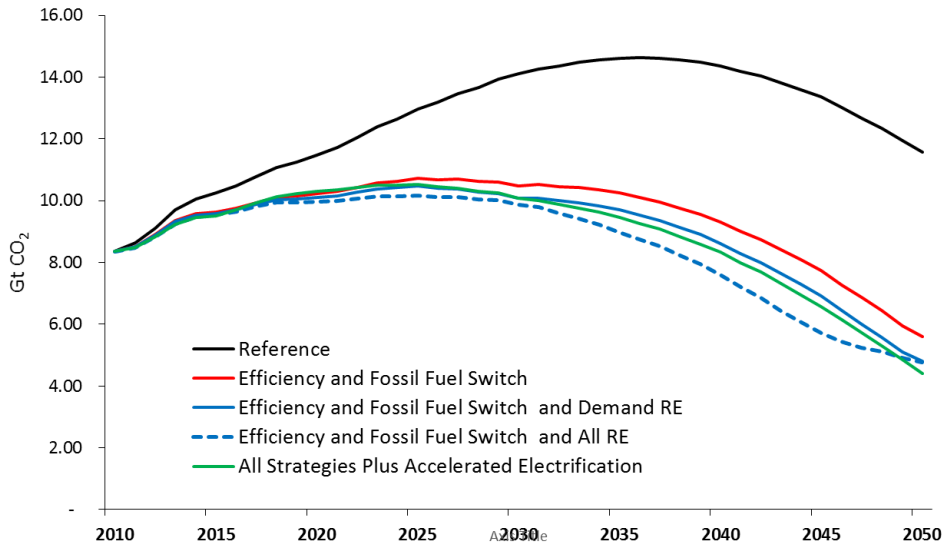

Figure 8. China's Projected CO_2 Emissions from 2010 to 2050 under Different Scenarios

Compared to renewables and electrification, adopting cost-effective efficiency improvements and switching to cleaner fossil fuels will result in the largest annual and cumulative CO_2 emissions reduction from 2010 through 2050 (Figure 9). In 2050, adopting additional efficiency improvements and fossil fuel switching will lower annual total CO_2 emissions by 52% compared to the Reference Scenario. Further integrating demand-side renewables will result in an additional 0.79 Gt CO_2 emissions annual reduction in 2050, with additional 0.04 Gt CO_2 emissions reduction if supply-side renewables are also successfully deployed. Cumulatively from 2010 through 2050, introducing demand-side and supply-side renewables will result in total CO_2 emissions reductions of 16.8 Gt CO_2 and 18.5 Gt CO_2 emissions, respectively.

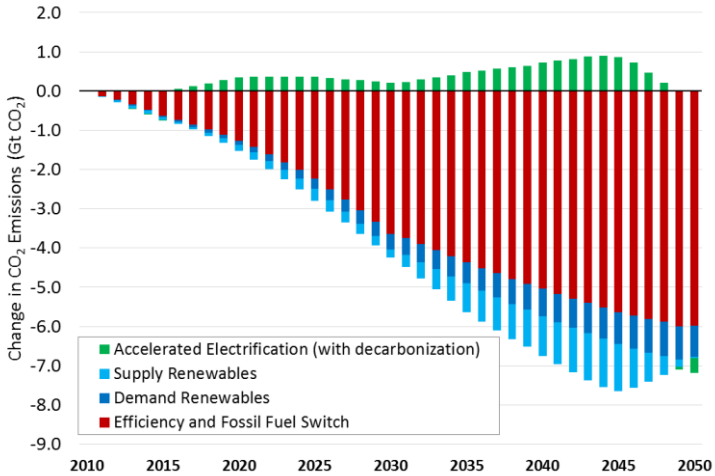

Figure 9. CO_2 Emissions Impacts of Efficiency, Fuel Switch, Renewables and Accelerated Electrification Strategies

Note: the emissions impact is calculated relative to the previous scenario without the specific strategy as shown in Table 1.

Accelerating electrification for all end-uses with maximized electrification for some end-uses, on the other hand, will result in net CO_2 emissions increases through 2048 despite an increasingly decarbonized power sector based on our assumed non-fossil capacity growth shown in Table 2. This net CO_2 increase results from offsets in the decline of coal-fired power generation made possible in other scenarios with increased renewable capacities. The higher electricity demand resulting from accelerated electrification results in more coal-fired power generation being deployed compared to the Efficiency, Fossil Fuel Switch and All Renewable Scenario, after all non-fossil capacities have already been fully deployed. While the fossil fuel replaced by electricity – notably gasoline, diesel and coke - will result in CO_2 emissions reductions, the greater increase in CO_2 emissions from coal use for power generation will result in net CO_2 increase from 2010 through 2048 (Figure 10). By 2050, accelerated electrification will result in a slight net reduction of 0.38 Gt CO_2 emissions. However, there is a net increase of 14.31 Gt CO_2 emissions cumulatively from 2010 through 2050 associated with accelerated electrification under our assumed pace of power sector decarbonization. This shows that if accelerated electrification does not match the pace of non-fossil generation expansion, it can lead to unintended consequences such as a slow-down in the decline in the use of fossil fuels and particularly coal for power generation.

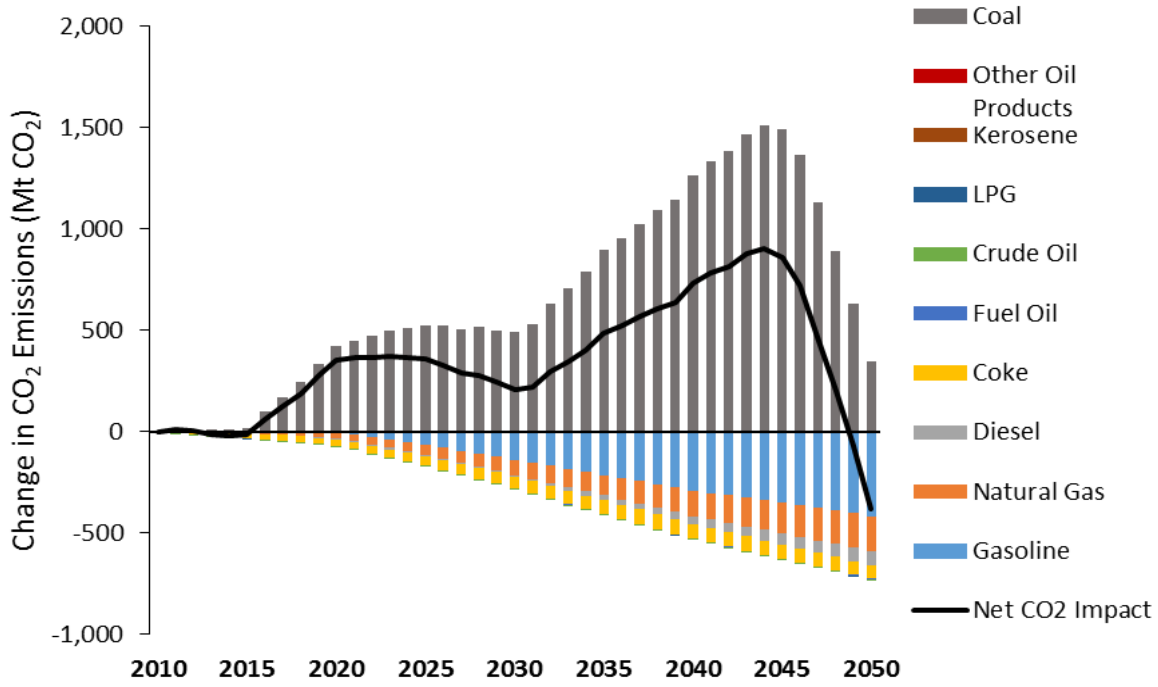

Figure 10. CO_2 Emissions Impact of Accelerated Electrification

Note: CO_2 emissions impact shown are compared to Efficiency, Fossil Fuel Switch and All Renewables Scenario, not compared to Reference Scenario

The close linkage between increased electricity demand and subsequent CO_2 emissions intensity of electricity generated is further illustrated in Figure 11. As total electricity demand is reduced from the Reference Scenario to the Efficiency and Fossil Fuel Switch Scenario, the CO_2 emissions intensity of the electricity generated decreases significantly because much of the electricity generated is coming from non-fossil resources. The CO_2 emissions intensity of electricity generated is further reduced with more aggressive deployment of supply-side renewables in the power sector under the Efficiency, Fossil Fuel Switch and All Renewables Scenario. However, when aggressive electrification is pursued as a strategy

across all end-use sectors, the CO_2 emissions intensity of electricity generation rises again to a level similar to the Efficiency and Fossil Fuel Switch scenario without additional supply-side renewables. This suggests that the increased electricity demand from accelerating electrification is offsetting any potential CO_2 reductions in the power sector from deploying additional supply-side renewables.

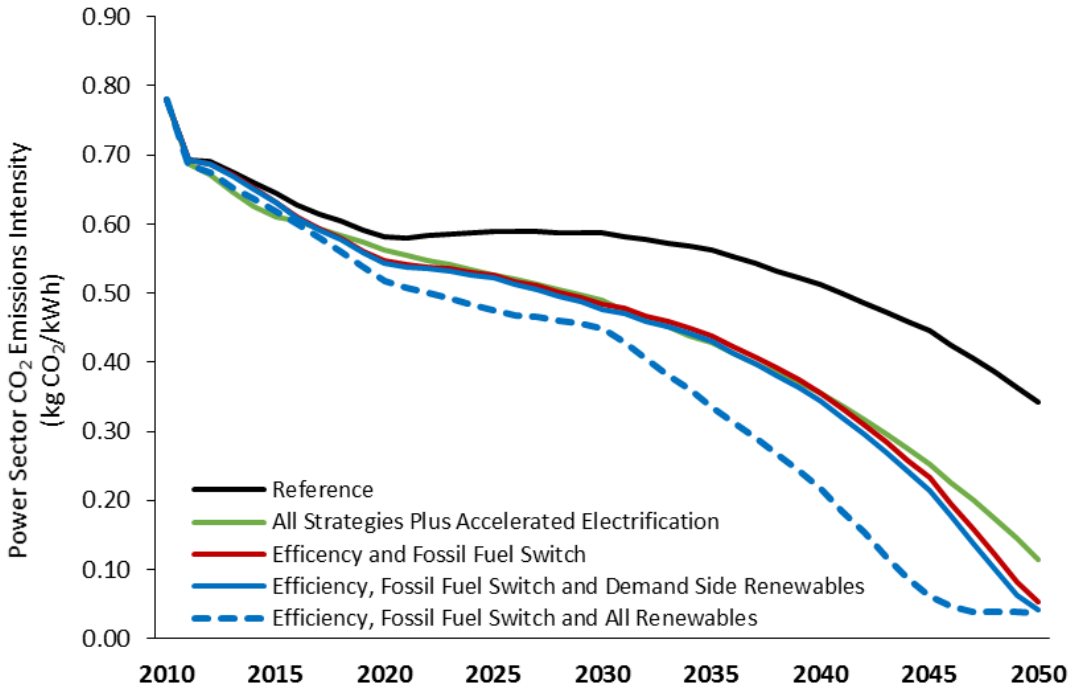

Figure 11. CO_2 Emissions Intensity Trends of Electricity Generation by Scenario

5. Discussion

Our results show that there are several different strategies for China to achieve its target of peaking its CO_2 emissions by 2030 or earlier, and a combination of all strategies including accelerated electrification can help significantly reduce China's future CO_2 emissions by as much as 62% annually by 2050 when compared to a Reference Scenario of no new policies. While China's CO_2 emissions can peak as early as 2025 by only pursuing cost-effective efficiency measures and fuel switching to cleaner fossil fuels, further integrating demand-side and supply-side renewables (including 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 Energy Efficiency and Fossil Fuel Switch 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 [38].

Beyond energy efficiency and fossil fuel switching, deploying more demand-side renewables and maximizing the adoption of non-conventional renewables such as renewable heat and biomass for industry and solar thermal applications for buildings can result in additional CO_2 emissions reductions

that is comparable in scale to traditional supply-side renewables for the power sector. Cumulatively from 2010 to 2050, maximizing the deployment of renewables in the demand sectors can contribute to CO_2 emissions reductions of 16.8 Gt CO_2 beyond efficiency and fossil fuel switching, with additional reductions of 18.5 Gt CO_2 possible from increased utilization of renewable power generation. However, 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 are 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 manufacturing 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 there may be applicable lessons learned from renewable deployment in other demand-side sectors such as buildings in European countries such as Finland, Sweden and Austria [52, 56, 69-69].

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 replace direct use of fossil fuels with electricity for key end-uses, but increasing electrification face key challenges. One key challenge highlighted by the modeling results is the CO_2 impacts of increased electrification with a power sector that is still transitioning to more non-fossil power generation sources. Our results show that even with rapid deployment of new wind and solar generation capacities, particularly after 2030, concurrently increasing electrification across all demand sectors will result in net CO_2 increase through 2045. Although non-fossil sources accounts for more than half of total power generation installed capacity by 2030, the incremental supply of electricity from these sources is insufficient to supply the incremental demand under this scenario; consequently, demand for thermal generation increases, increasing CO_2 emissions. Managing the pace of electrification in tandem with the pace of decarbonization of the power sector will be crucial to achieving CO_2 reductions from the power sector in a scenario of increased electrification. This interdependence between electrification and the successful decarbonization of the power sector—achieving “beneficial electrification”— constitutes a key barrier to minimizing the CO_2 emissions impact of rapid electrification in China and may require greater policy coordination across power sector planners and demand-side policymakers. In addition, there are also existing barriers to increasing electrification in China. For example, 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.

The four alternative scenarios included in this study represent four possible policy-driven pathways for China’s future energy and CO_2 emissions development that can help peak national total energy-related CO_2 emissions as early as 2025. While the extent that each of these strategies will be deployed in China remains to be determined, our attempt to quantify and compare the CO_2 impacts of each individual

strategy is intended to help guide policy development and prioritization. It sheds light on the possible role for demand-side renewables, particularly non-conventional renewables that are not yet widely considered in China, in contributing to additional CO_2 emissions reductions. It also emphasizes the possible challenges and uncertain CO_2 emissions impacts associated with rapidly increased electrification, including maximized electrification for key end-uses in the transport, buildings and selected industrial sectors, given expected developments in China's power sector. The need to manage the pace of electrification in tandem with the extent of power sector decarbonization will be crucial to mitigating possible net CO_2 emission increases that result from greater electrification.

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