International Energy Analysis Department
Energy Analysis and Environmental Impacts Division
Lawrence Berkeley National Laboratory

Pathways for Accelerating Maximum Electrification of Direct Fuel Use in China's Building Sector

Drivers, Impacts, Barriers, Prospects, and Policy Recommendations

Wei Feng, Nan Zhou, Wenjun Wang, Nina Khanna, Xu Liu, Jing Hou

September 2021

Acknowledgements

The work described in this study was conducted at Lawrence Berkeley National Laboratory and supported by the U.S. Department of under Contract No. DE-AC02-05CH11231.

The authors thank the following experts for reviewing this report (affiliations do not imply that those organizations support or endorse this work):

Max Wei	Lawrence Berkeley National Laboratory
Jeffrey Deason	Lawrence Berkeley National Laboratory

Table of Contents

List of Figures

Executive Summary

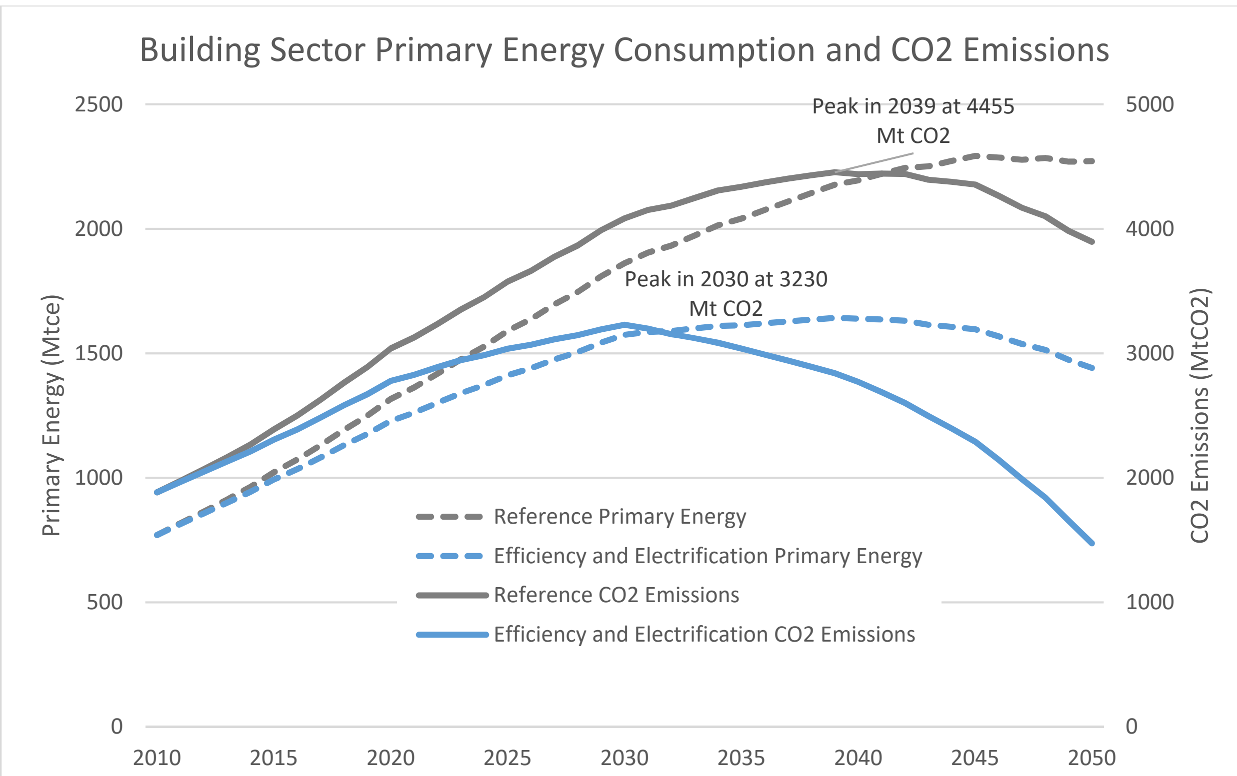
The building sector accounted for 22% of the primary energy consumption in China in 2018, and its energy consumption is projected to continue to grow. Fossil fuels—especially coal—still dominate the building final energy use in existing buildings. Electrification of energy end uses in the building sector will improve energy efficiency and reduce air pollution and carbon emissions. Even as the supply of renewable energy in the power grid continues to grow, making use of clean electricity in buildings is extremely important for achieving future zero emission buildings.

We identified promising and emerging electric technologies that could be used in the building end use sectors, especially space heating and cooling, water heating, and cooking. Those electric technologies include:

- Heat pumps for space heating
- Heat pumps for water heating
- Electric stoves for cooking
- Efficient air conditioners
- Rooftop photovoltaic (PV) and other renewables

Surveys were conducted among stakeholders and experts in the building sector to understand general acceptance and evaluation of the potential for future electrification in buildings. The survey results showed an optimistic attitude toward electrification in the building sector in China. The results indicated a consensus on electrification of space heating, as well as a high potential for water heating and cooking stoves in the near future. The possibility of electrifying district heating systems in China was also addressed. Experts indicated that challenges may still exist for electrification in the rural China due to low and stable energy demand, low household income, and the traditional cooking habits and consumer preferences.

To quantify the impacts of electrification on primary energy use and carbon dioxide (CO_2) emissions in the building sector in China, we conducted scenario analysis using a bottom-up model to model the impact of increasing the use of electric technologies and of improving the energy efficiency of those technologies. The electrification of building sector is developed under a high penetration of renewable energy (80% by 2050) over the power grid (Appendix A). By 2050, in our accelerated electrification scenario 83% of energy use in commercial buildings and 85% of energy use in residential buildings would be electrified[1]. That accelerated scenario was compared with a business-as-usual pathway in which only policies in place by 2010 continue to have an impact and autonomous technological improvement occurs (Reference scenario). Results showed a more rapid electrification in the building sector with increasing use of air source heat pumps and electric cookers with faster efficiency equipment penetration (Electrification and Efficiency scenario), which would help CO_2 emissions peak nine years earlier, in 2030, at 3,230 metric tons (Mt). By 2050, accelerated electrification and efficiency improvement combined to achieve more than a 2,400 $MtCO_2$ emission reduction in buildings by 2050. More than 70% of this reduction could be attributed to electrification, especially electrification in residential sectors. Efficiency improvement further reduced CO_2 emissions in both residential and commercial building sectors by about 300 Mt each. Carbon dioxide emissions in building sectors in 2050 would be 1,437 Mt, 62% lower than the Reference scenario (Figure ES1).



[1] The electrification rate is calculated by the total amount of electricity final energy consumption divided by the total building final energy consumption.

Figure ES1. Building sector primary energy consumption and CO_2 emissions under different scenarios (Mtce: million tons of coal equivalent)

The modeling results indicate that electrification rates could reach to 83% in the residential sector and 85% in the commercial sector in 2050 (Figure ES2). This includes enhanced penetration in buildings of electrical space heating, water heating, and cooking technologies. However, electrification itself is insufficient to decarbonize China's building sector. Continuous improvement of the efficiency of electrical technologies, including technologies that already have been electrified, is also extremely important.

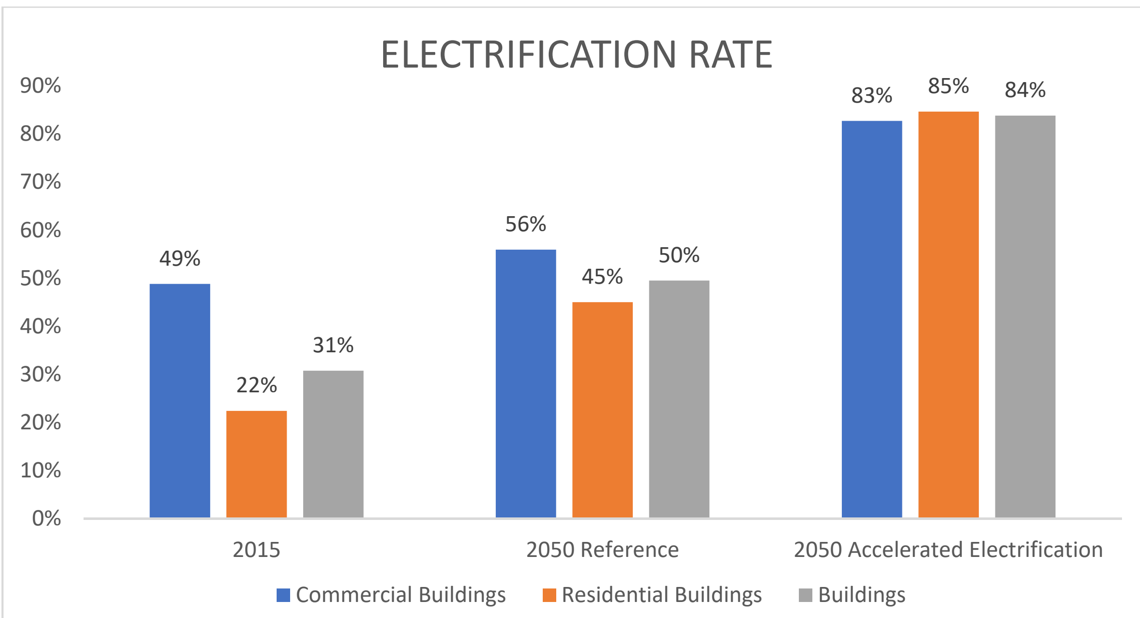


Figure ES2. Electrification rate potential in China's residential and commercial sector calculated using final energy

Overall, electrification in the building sector could save 1.8 billion tons of CO_2 in 2050. Together with electrical technology efficiency improvements, the CO_2 abatement potential is 2.4 billion tons of CO_2 (Figure ES3), which is 48 times the amount of New York City's CO_2 emissions each year.

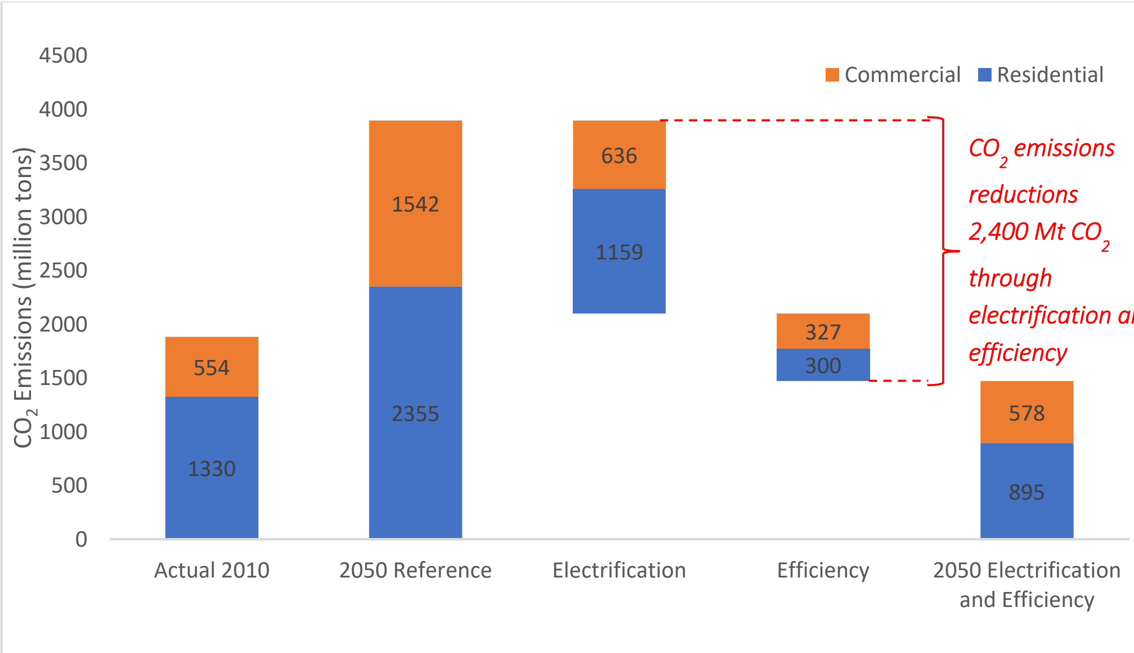


Figure ES3. CO_2 emission reductions through electrification and electrical technology efficiency improvement

The report proposes future policy recommendations to encourage electrification in the building sector:

- Set specific targets for electricity penetration in the building sector.
- Develop building codes and standards that have a minimum threshold of electrical load penetration in residential and commercial buildings.
- Conduct technology research, development, and demonstration for advanced electric technologies for building end uses with high efficiency.
- Provide incentives for electrical technology development, comprehensive consideration of electric heating tariffs, and building retrofits.
- Design an appropriate electricity rate to encourage electricity use in buildings.
- Develop demand response programs to better manage electricity load and integrate technologies with the power grid.
- Increase public awareness of the benefits of electrification in buildings.

1. Introduction

1.1 Purpose and scope

This report reviews the prospects for electrification of energy end uses in buildings in China. It focuses on the electrification of end uses where direct use of other fuels has a substantial market share, especially space heating and cooling, water heating, and cooking. The remainder of Section 1 identifies the potential benefits of electrification. Section 2 offers a brief literature review on building sector electrification studies. Section 3 describes the current trends of primary energy use and the electrification status of Chinese building sectors, and identifies several promising or emerging electric technologies for specific end uses. Section 4 shows LEAP model estimation results for electrification rates, primary energy use, and CO_2 emissions in residential and commercial building sectors in China by 2050. Section 5 provides a high-level assessment of the literature on economic potential for electrifying end uses in buildings. Section 6 identifies the barriers of electrification, and Section 7 proposes potential policy approaches to encourage beneficial electrification. Section 8 summarizes survey results and concludes with key findings and recommendations.

1.2 Benefits of electrification

Previous research (Deason et al. 2018) has demonstrated that electrification in buildings benefits the U.S. market in several ways: grid support, ancillary services, flexibility for integration of variable energy resources, friendliness to electric vehicles and storage, and air quality. Electrification also can provide additional unique benefits for the building sector in China, beyond those of the U.S. building sector:

Greenhouse gas (GHGs) reductions. Studies have shown that electrification, when combined with low or zero carbon electric generating technologies, can serve as an important pathway to decarbonize the energy system (Williams et al. 2012; Wei et al. 2013). China's building sector still relies on coal and natural gas being used directly. Electrification will not only reduce China's CO_2 emissions, it will also help to reduce non-CO_2 GHG emissions such as methane from natural gas and coal mining, transport, and end uses.

Balance of trade for fuels and energy security. Currently, China's energy structure heavily depends on natural gas imports. Increasing the use of domestic renewable energy resources such as wind and solar to meet high demand driven by electrification may reduce dependence on imported fuels and improve energy security.

Infrastructure construction. Much of China's natural gas is imported from Russia over land, and as liquefied natural gas (LNG) over the sea. Electrification of the building sector would reduce natural gas demand and use, therefore bringing benefits such as reduced infrastructure investment in natural gas pipelines.

1.3 Literature review

According to the Electric Power Research Institute (EPRI), electrification is the process through which end uses such as heating and cooling appliances that are currently directly powered by solid, liquid, or gaseous fossil fuels (e.g., natural gas or fuel oil) are powered by electricity instead.

Electrification may be desirable for a number of reasons. It directly benefits the energy system through better grid support and ancillary services (Weiss et al. 2017; Alstone et al. 2017), more flexibility for integration of variable energy resources (Weiss et al. 2017; Dennis 2015; Alstone et. al. 2017), and valuable synergies with electric vehicles and distributed generation and energy storage (Chaouachi et al. 2016; Deason et al. 2018). Beyond those benefits, it also introduces significant non-energy and indirect benefits, such as improving air quality (Peng et al. 2018), decarbonizing the energy system (Williams et al. 2012; Wei et al. 2013), reducing fuel price risks (Deason et al. 2018), and reducing consumer cost in some applications (Nadel 2016).

According to a recent Lawrence Berkeley National Laboratory (Berkeley Lab) report (Deason et al. 2018), in the United States, electricity's share of total energy use in buildings has generally been increasing since at least 1960 as the use of electrically powered devices (such as appliances and air conditioners) has grown.

Research of electrification in the U.S. building sector generally reflects the understanding that high rates of electrification in the building sectors is feasible. Although most studies do not directly forecast or assess either the technical or economic potential of electrification in the building sectors, they do frequently develop scenarios with notably high electrification rates in buildings and identify these scenarios as feasible pathways to meet specific policy goals. The assumed rates of electrification can sometimes be as high as 100%. For example, Weiss et al. (2017) and Steinberg et al. (2017) assume in their modeled scenarios that 100% of U.S. residential and commercial end uses will be electrified by 2050. A recent Berkeley Lab report by Deason et al. (2018) also points out that the technical potential for electrification in residential and commercial buildings is nearly 100% of all energy use in buildings, and the primary challenges to electrification are economic.

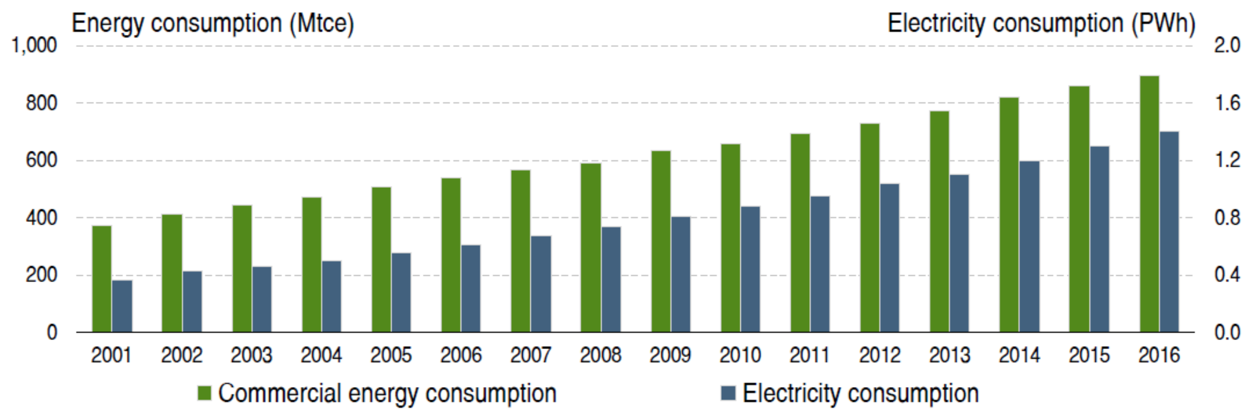
In summary, the literature suggests that electrification of end uses generally is relatively cost-effective in new (versus existing) buildings, in residential (versus commercial) buildings, in settings where a single heat pump can replace the need for the capital cost of an air conditioning unit as well as a space heating unit, and in areas with milder winters. However, electrification may in some cases be cost effective for any building type in any location.

2. Pathways of Electrification Opportunities

2.1 Current trends

In China, total energy consumption and electricity consumption in building sectors have been increasing significantly for decades. As of 2016, the total building energy consumption accounted for about 20% of the total primary energy consumption of China. From 2001 to 2016, the primary energy consumption in China's building sector more than doubled, and electricity consumption increased more than 200% (Tsinghua 2019). Since 2010, new building construction in China, driven by continuing rapid urban growth, has comprised closed to half of the world's growth in new construction. This trend of building stock and area expansion is expected to continue for years to come. Such rapid construction of buildings comes with substantial increases of energy use in buildings. However, there are reasons to believe that these trends will saturate in the first two or three decades and then level off or decline. Reasons include saturation for household appliances and other energy-use equipment slowing, and ultimately the end of mass migration to urban areas, low population growth, and other factors.

Electricity's share of total energy use in buildings has been increasing steadily since 2001 as the use of electrically powered devices (such as appliances and air conditioners) has grown. Figure 1 shows the evolution of building sector commercial energy and electricity consumption from 2001 to 2016. As of 2016, electricity was the main energy carrier in public buildings and commercial buildings. However, natural gas, coal, liquefied petroleum gas (LPG), and oil are also used for space heating, water heating, cooking, and other end uses.



Source: China Building Energy Use 2018, BERC Tsinghua, 2018

Figure 1. China's buildings sector commercial energy consumption (2001–2016)[2]

Both past trends and future projections show gradual movement toward the electrification of additional end uses in China's building sector. Space heating uses the significant majority of non-electric energy in buildings. For example, space heating energy use in regions with centralized district heating networks are dominated by coal and natural gas, while electricity only comprises a small share of the total energy consumption, leaving a huge potential for electrification. Additionally, huge amounts of biomass are still used for heating and cooking, especially in rural areas. Such traditional use of biomass will likely be replaced by electricity over time, driving electrification rates to higher levels.

Technological improvement plays an essential role in the process of electrification, and electric technologies have experienced rapid development during the past decades. As of now, technically, almost 100% of energy use in the building sectors, including both residential and commercial buildings, can be electrified. The three major fields for electrification are space heating, water heating, and cooking, for which direct fuel combustion constitutes a substantial market share. Electric alternatives for these end uses are not only commercially available but also provide similar service. Such electric technologies include heat pumps for space heating and cooling, electric water heaters, electric stoves, and more. Each of these technologies will be discussed in detail in the following subsection.

[2] Commercial energy means all energy consumption excluding distributed renewable energy such as solar PV, solar thermal, biomass, and biogas in buildings.

2.2 Candidate electrification technologies in China

Space heating accounts for about 25% of China's building sector energy use. Unlike the U.S. building sector, where heating is mainly provided by distributed technologies such as boilers in individual buildings, buildings in China, especially in the northern climate zones, are heated by centralized city-scale district heating systems. Chinese district heating systems are often fueled by natural gas and coal. Electrifying the district heating systems in China is a key component of decarbonizing China's building sector. As China is using different types of district heating systems with a mix of fuel sources and heat sources, the district heating electrification will focus on community, campus and building block scale district heating systems which currently use coal or natural gas. For large city scale district heating systems based on steam or utilizing industrial waste heat, the focus to decarbonize large scale district heating systems is to switch from using coal or natural gas to utilizing waste heat from power plants or industrial facilities.

Heat pumps are a promising technology to replace coal and natural gas use in China. Generally speaking, heat pumps are much more energy efficient than electric resistance technologies. Recent advances in technologies also enable air-source heat pumps to operate at lower temperatures (DOE 1, n.d.). For example, cold-climate heat pumps now perform even in outdoor temperatures well below freezing (Alpine, n.d.; Rheem, n.d.). Electric heat pumps for space heating and cooling enjoy increasing market share in the United States in the past few years (EIA). Also, advanced technologies such as a ground source heat pumps (GSHP) can further boost heat pump efficiency, even when operated in a cold outdoor environment. It is widely believed that heat pump technologies will become the dominant space heating technology in the future.

Domestic hot water (DHW) accounts for about 15% of the residential building energy use in China. The existing DWH systems primarily consume natural gas. In small towns and rural areas, LPG- and coal-based DHW systems are still commonly used. In urban households, electric resistant heating devices are becoming more and more common. While their capital costs are lower, electric resistance technologies are much less energy efficient than heat pumps, and thus more expensive to operate (EIA 2017). Using a heat pump water heater can greatly boost DHW system efficiency compared to resistant electric water heaters.

Electric resistance stoves and electric induction stoves are two major kinds of electric stoves that can be installed in all kinds of buildings. Electric induction cookstoves generally have slightly higher capital costs compared to their gas counterparts, while electric resistance cookstoves are similar in capital cost to their gas alternatives. According to a recently published report on California (Energy and Environmental Economics, Inc. 2019), electric stoves, both electric resistance and induction, have moderately higher operation costs compared to gas stoves (up to $80 per year). However, electric resistance stoves could serve as a lower-cost option than gas stoves in new buildings since installing electric resistance stoves in new construction can avoid the cost of connecting gas lines to the kitchen. It is also noticed that Chinese cooking features high temperature cooking associated with oil stir-frying. Such cooking techniques also require using round-bottom pans so there is a large cooking pan surface to stir food. The development of electric cooking technologies also will need to accommodate Chinese cooking techniques.

Rooftop photovoltaic (PV) systems make use of solar energy to generate electricity. The electricity is then used to satisfy the building's local energy consumption. As penetration levels of solar PV systems increase over time, the potential for overproduction of solar power has increased (Mills and Wiser 2015). This problem applies to other renewables as well. Electrification, expanding the demand of electricity use that could be shifted, makes better use of these resources. Also, the addition of rooftop PV to electric storage offers a great value by providing resilience that enables buildings to operate during critical events.

2.3 Summary

Total energy use and electricity consumption in China's building sectors have increased significantly for decades. This trend is expected to continue for years to come, then saturate in two or three decades, and finally level or decline. Electricity is enjoying an increased share of total energy use in buildings. However, natural gas, coal, LPG, and oil also are used for space heating, water heating, cooking, and other end uses, leaving considerable potential for electrification.

Technological improvement plays an essential role in the process of electrification. In buildings, electric technologies exist for almost all major end uses and have experienced rapid development during the past decades. The three major fields for electrification are space heating, water heating, and cooking. Heat pumps are by far the most promising technologies that can be used for electrifying space heating, space cooling, and water heating. Importantly, a single heat pump can provide both heating and cooling. Air source heat pumps are by far the most common type of heat pump. Another readily available technology is electric resistance. Electric resistance technologies enjoy a substantial market share in water heating. However, while their capital costs are lower, electric resistance technologies are much less energy-efficient than heat pumps, and thus more expensive to operate. Electric resistance stoves and electric induction stoves could be installed in all kinds of buildings.

Electric resistance stoves could serve as a lower-cost option than gas stoves in new buildings since installing electric resistance stoves in new construction can avoid the cost of connecting gas lines to the kitchen.

3. Survey Results

We conducted a survey with stakeholders in the building sector using a questionnaire (Appendix A). It posed 13 questions on electrification of building energy use, covering the importance of accelerating electrification, applicable technologies, technical potentials, major barriers, and policy recommendations for both the U.S. and China. Two survey rounds were conducted. In the first round, 11 responses were collected from high-level decision makers in U.S. technology companies. In the second round, a workshop was held in China involving a mix of experts from the policy-making sector, a design institute, utilities, technology companies, professional associations, and research institutes. The results of both surveys are summarized below.

During the first round of the U.S. survey (Figure 2), more than half the participants (54.5%) agreed that electrification could help reduce a building's carbon footprint, while the remaining 45.5% were not sure. However, no one responded with a definite "no." Similar results were drawn from the expert workshops. It is generally agreed that electrification in the building sector is important because it not only reduces pollution and delivers fewer safety concerns but also increases energy efficiency in the end use side. However, electrification is a systemic issue and it requires a comprehensive solution that considers both technical and economic concerns.

Of the applicable technologies in China, space heating seems to be the most promising: 100% of the survey participants (8 of 11 participants answered this question) believe space heating could be electrified in the near future in China. The percentages for water heating and cooking stoves are 50% and 37.5%, respectively. For the United States, the responses were a bit different. Of the respondents, 77.8% believe space heating and water heating could be electrified in the near future, while 55.6% believe cooking stoves could be electrified. This difference may result from different cooking traditions and customer preferences between the United States and China. Of the participants, 63.6% think electrical storage technology improvements and its associated cost reduction would likely promote building sector electrification, while the remaining 36.4% do not think so. During the expert workshop, it was emphasized that large public buildings have higher electrification rate than residential buildings and that space heating (especially heat pumps), cooking stoves, and water heating are the major targets for electrification of China's building sectors.

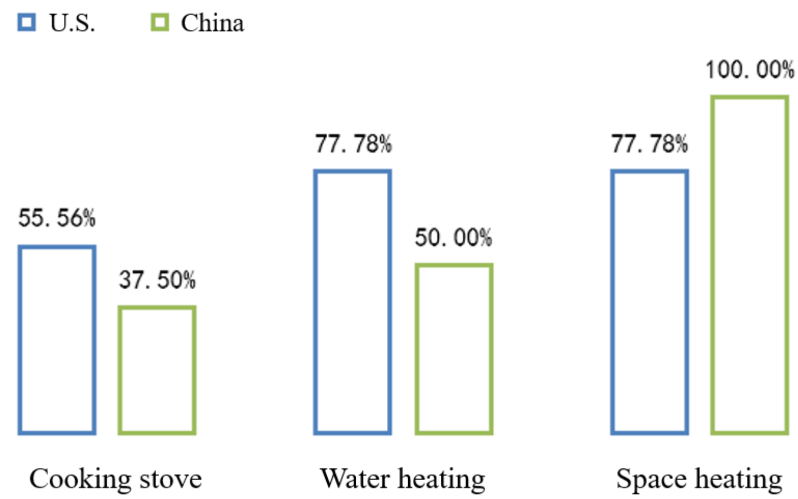


Figure 2. Questionnaire results on technologies that can be electrified in the near future

When it comes to the potential to electrify district heating systems in China, more than half (57.1%) of the participants believe it is partially possible, 14.3% believe it is highly possible, while the other 28.6% stated that it would be difficult to accomplish on a large scale. However, no one claimed that it would be almost impossible to electrify district heating systems in China. The results seem to reflect a generally optimistic attitude toward electrifying district heating systems. However, the predicted percentage of district heating respondents believe could be electrified in China by 2030 and 2050 ranged broadly, from 20% to 80% (Figure 3). Experts in the workshops estimated a 43%–82% electrification in the public buildings sector and 22%–67% in the residential buildings sector. In general, respondents believed that 60%–70% electrification can be achieved in the building sector by 2050.

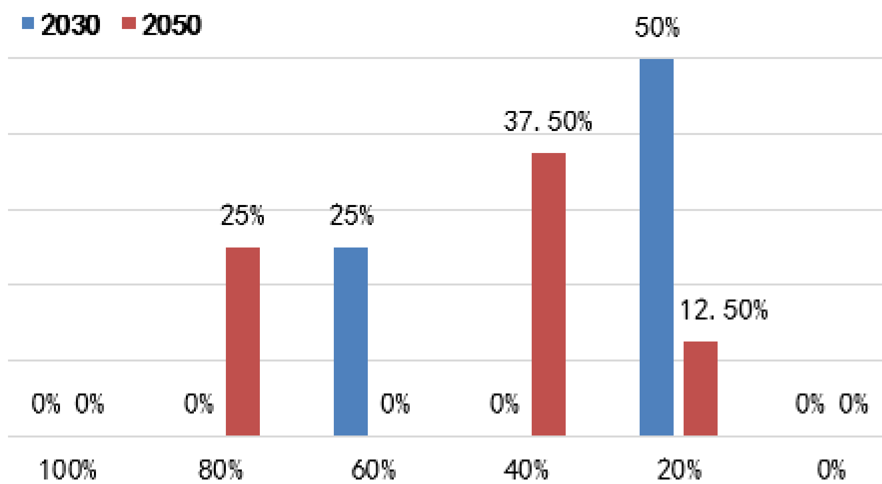


Figure 3. Questionnaire results on the expected percentage of district heating electrification in China in 2030 and 2050

The questionnaire results on the potential for electrification in the rural part of China seems relatively pessimistic. More than half (55.5%) of the participants think it would be difficult to electrify the rural part of the country, and an additional 11.1% think it would be very difficult. Only 11.1% think it would be easy to implement. The results reflect the difficulty of electrification in rural China. Experts partially explained the difficulty of electrification in the rural part of China by low and stable energy demand, low household income, and traditional cooking habits and preferences. But the experts also mentioned the possibility of district heating electrification in cold rural areas.

Survey results suggest that lack of end-user awareness and lack of government/utility policies and incentives are the two leading barriers to building electrification in China (Figure 4). Requirements for technology installation and transformer/substation capacity updates, high technology costs, and low fuel prices (e.g., for coal, natural gas) also play significant roles. High electricity cost and the lack of technology availability, though mentioned less frequently than the others, constitute notable barriers to building electrification. Experts in the workshop emphasized the importance of high electricity costs (rural electricity costs in particular), consumer energy preferences, and market mechanisms as leading barriers, and suggested revising relevant standards and updating transformer/substation capacity. The next subsections will discuss each barrier in more detail. The results are quite different for the United States—low fuel prices, high technology costs, lack of government/utility policies and incentives, and high electricity costs are the four major barriers. Lack of technology availability, requirements for technology installation and transformer/substation capacity upgrades, and lack of end-user awareness only play limited roles.

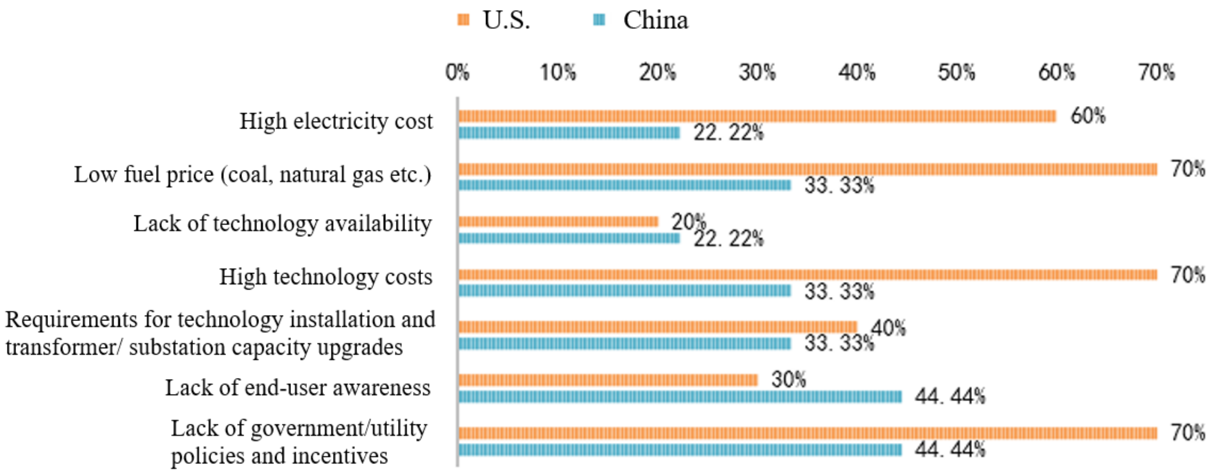


Figure 4. Questionnaire results on the major barriers to building electrification

The questionnaire also asked respondents what they thought the barriers were to transition from coal to electricity for rural heating. The results show that technology cost, energy costs, and lack of long-term supporting policies on technology installation and energy are the major barriers. In addition, the coal to electricity transition in rural heating would be more applicable to new construction, since retrofits would be very expensive without significant subsidies and incentives.

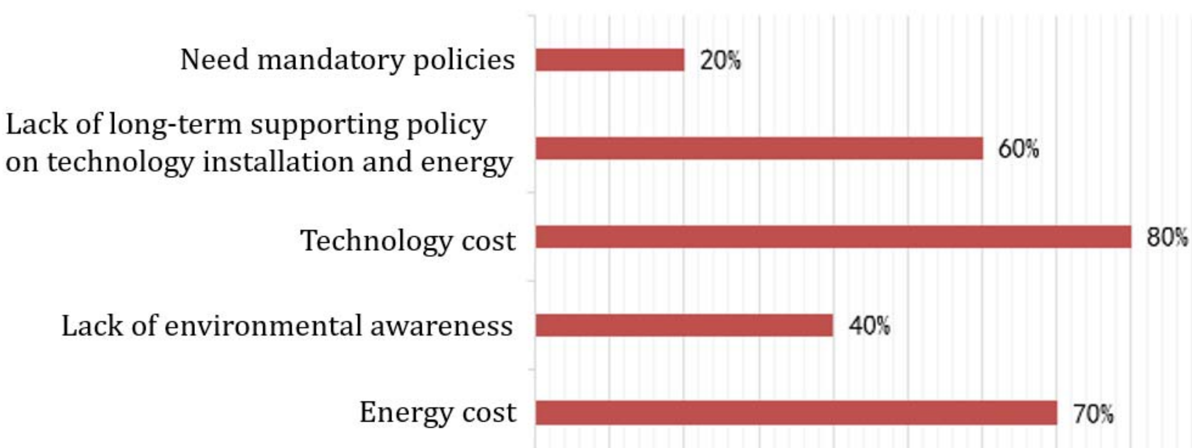


Figure 8. Questionnaire results on the barriers for coal to electricity in rural heating

Some useful suggestions were collected on how to accelerate electrification of building energy use in China and the United States. First, more policy rebate and incentives will promote electrification. Government incentive programs can play an essential role in accelerating electrification of building energy use. Second, increased research into electric heating efficiencies for northern climates will be helpful, too. In addition, China needs to focus on increased power generation from green and other sources to handle the increased demand. Moreover, investing in building energy efficiency and building-grid integration, as well as focusing more on commercial buildings and hybrid solutions, may help accelerate electrification of building sector energy use.

4. Impacts of Electrification of China's Building Sector

The electrification modeling was conducted by using Berkeley Lab's previous Reinventing Fire China (RFC) project building sector modeling structure (Zhou et al. 2018). This research further refined the model to capture electrification rate change in end use technologies, as well as efficiency improvement for technologies that will be electrified or have been electrified. Such modeling efforts are carried out in residential, commercial, and rural sectors across all building climate zones in China.

To model the impact of electrification in buildings, it is very important to properly model future power grid fossil fuel energy composition and the trajectory to decarbonize the power sector. Although this effort is not within the scope of this research, the power sector model is critical and provides important input data for a building sector electrification impact assessment. This study adopted the power sector model through the Reinventing Fire China project, and refined the RFC model through collaboration of power sector modeling with the Energy Research Institute (ERI) and State Grid Energy Research Institute (SGERI). In general, the power sector captures the trend of the power grid to adopt clean and renewable energy through 2050. A detailed building sector and power sector modeling assumption can be found in Appendix A.

Three scenarios were created in the Low Emissions Analysis Platform (LEAP) model to evaluate the building sector's electrification impact in China:

- *Reference scenario:* a business-as-usual energy and emissions pathway in which only policies in place by 2010 continue to have impact and autonomous technological improvement occurs
- *Electrification scenario:* more rapid electrification in the building sector, such as increasing use of air source heat pumps for heating and water heating and electric cookers for cooking, with decarbonization in the power generation sector.
- *Electrification and Efficiency scenario:* efficient equipment using electricity penetrates the market at a faster rate on the base of the Electrification scenario. Specific assumptions for the last two scenarios are shown in Appendix A of this report.

The results show significant potential for building electrification; up to 85% of energy use could be electrified by 2050 with accelerated electrification. Figure 8 shows the electrification rate estimates under different scenarios. Under the Reference scenario, the electrification rate in the commercial building sector would increase only slightly, from 49% in 2015 to 56% in 2050, while the electrification rate in the residential building sector would more than double, from 22% in 2015 to 45% in 2050. However, the electrification rate in the residential sector would remain lower than that in the commercial sector by 2050. On the other hand, with accelerated electrification, both the residential and commercial building sectors would experience a huge increase in electrification rates. By 2050, 83% of the energy use in commercial buildings and 85% of the energy use in residential buildings would be electrified, with the electrification rate in the residential sector slightly exceeding that in the commercial sector.

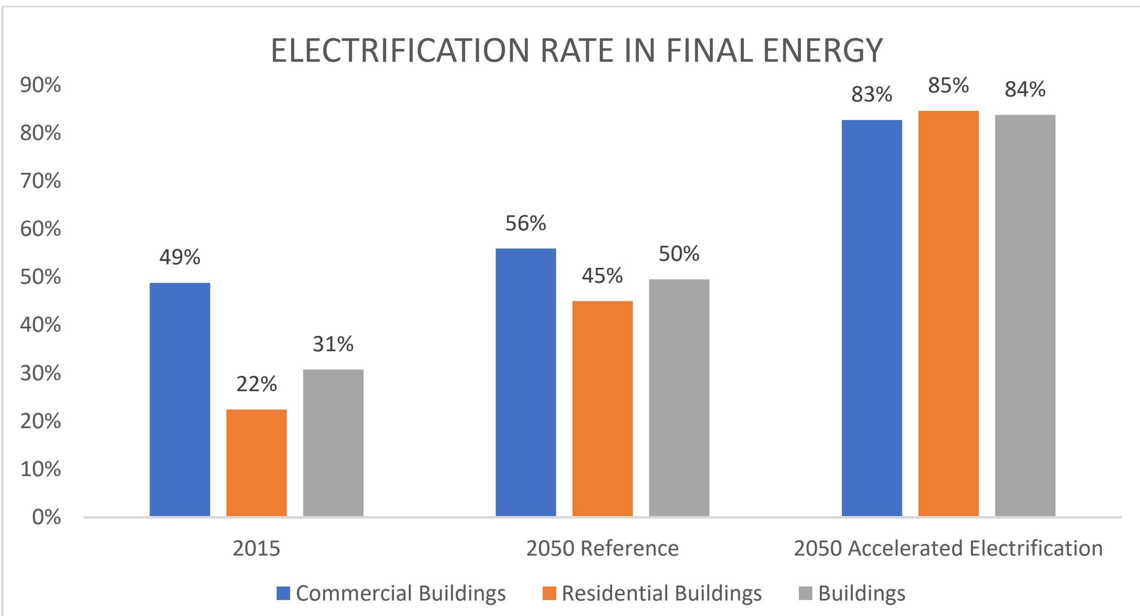


Figure 8. The electrification rate in the residential and commercial building sectors

In the Electrification and Efficiency scenario, CO_2 emissions peak in 2030 at 3,230 Mt, both earlier and at a lower level compared to its Reference counterparts, where the CO_2 emissions peak in 2039 at 4,455 Mt. Similar patterns apply to primary energy consumption in the building sector. Primary energy consumption would increase slower and peak earlier in the Electrification and Efficiency scenario than in Reference scenario. For both the Reference and the Electrification and Efficiency scenarios, the model simulations align with the expected trend that energy consumption and CO_2 emissions in China's building sectors will first increase, then level off, and finally decline in the next few decades. Figure 9 shows the simulated building sector primary energy consumption and CO_2 emissions from 2010 to 2050 under different scenarios.

In the scenario, accelerated electrification and efficiency improvements combine to achieve more than a 2,400 Mt CO2 emission reduction in buildings by 2050 (Figure 5). Over 70% of this reduction can be attributed to electrification, especially electrification in residential sectors. Carbon dioxide emissions in the residential sector would be cut by half with electrification compared to the Reference counterpart, and commercial building CO2 emissions would be reduced by about 40%. Efficiency improvement would further reduce CO_2 emissions in both residential and commercial building sectors by about 300 Mt each. The final estimated CO_2 emissions in building sectors in 2050 are 1,437 Mt; 62% lower than the Reference counterpart (Figure 6).

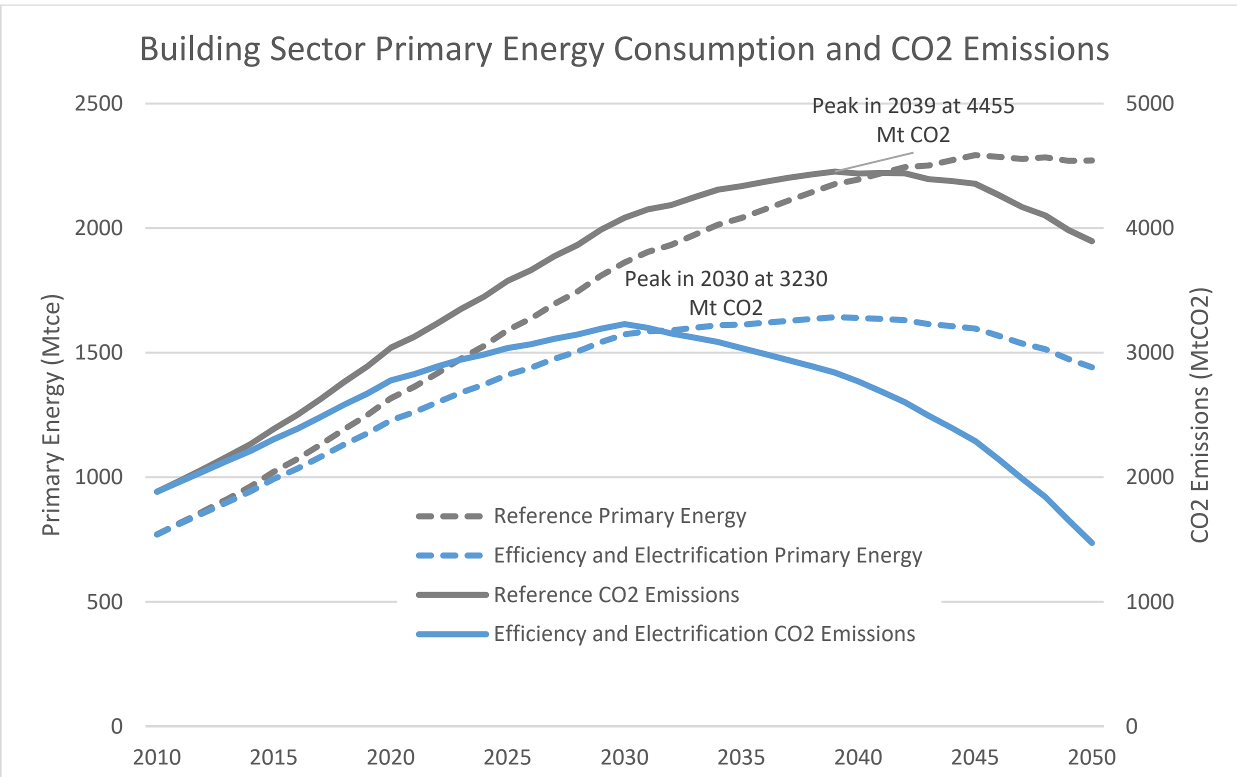


Figure 5. Building sector primary energy consumption and CO_2 emissions under different scenarios

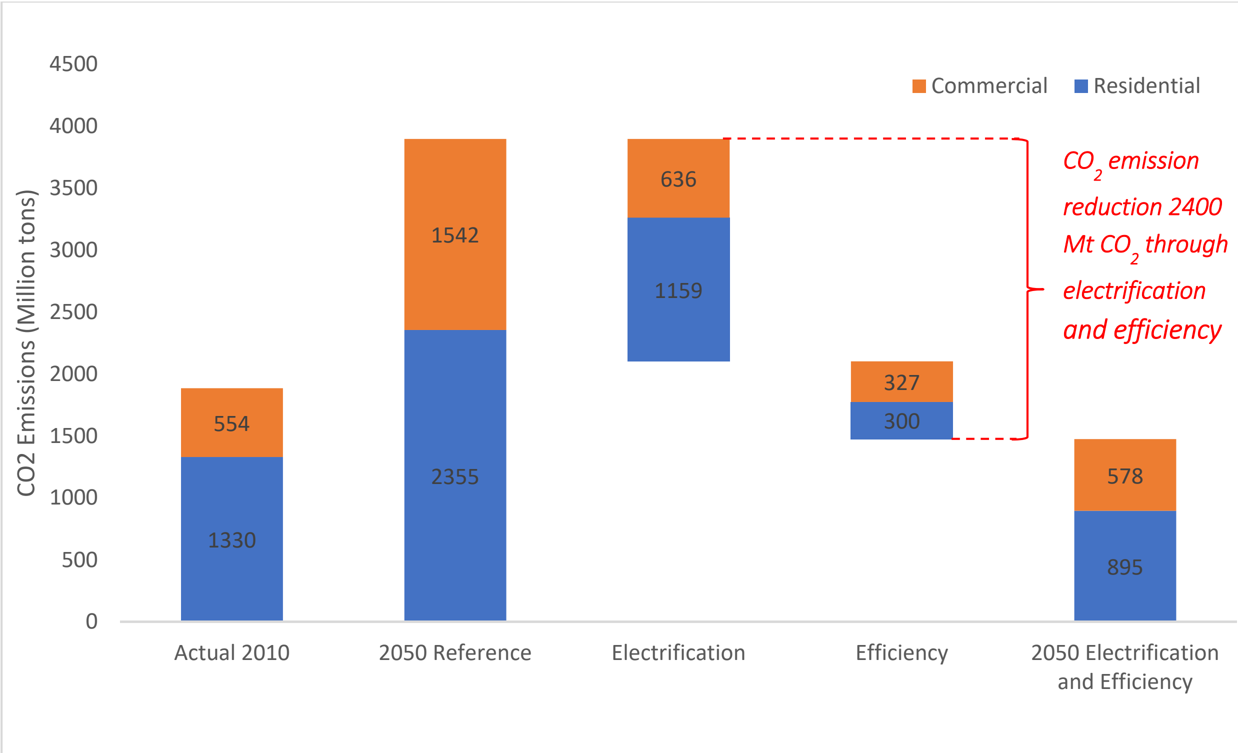


Figure 6. CO_2 emission abatement through electrification and electrical technology efficiency improvement

5. Policy Recommendations to Enable Electrification in China's Building Sector

China has developed comprehensive building energy efficiency and renewable energy integration policies since the 11th Five-Year Plan (FYP). However, electrification has never been mentioned in China's building sector polices. Many policy opportunities may be used to promote electrification in China's building sector. The questionnaire results offer some useful suggestions.

First, more policy rebate and incentives will promote electrification. Government incentive programs can play an essential role in accelerating electrification of building energy use. Second, increased research into electric heating efficiency for northern climates also will be helpful. In addition, China needs to focus on increased power generation from clean energy and other sources to handle the increased demand. Moreover, investing in building energy efficiency and building-grid integration, as well as focusing more on commercial buildings and hybrid solutions, may help to accelerate electrification of building sector energy use. Besides these suggestions, lessons from the United

States identify two emerging approaches that hold particular promise: (1) time varying electricity rates (charging lower prices for off-peak electricity use) and (2) electricity market designs that reward flexibility (rewarding the grid services that newly electrified end uses would offer).

A previous Berkeley Lab study (Deason et al. 2018) identified a number of policies to promote building and industrial sector electrification in the United States. This report adopts the policy analysis framework and discusses the policy opportunities in China's building sector.

5.1 Target-setting

Setting policy targets in the national and provincial level FYPs could be an effective way to drive electrification in China. Previous policy development has focused on energy efficiency targets and distributed renewable penetration policy settings. As China is planning a carbon peaking and carbon neutral pathway, the role of electrification in China's building sector decarbonization should be clearly identified. One key question of target setting is to clarify the building sector electrification rate. The modeling research of this paper uses final energy as the unit to calculate the building sector electrification rate. Given that China tends to use primary energy consumption as the major unit to calculate its energy efficiency and renewable energy utilization targets, with high penetration of renewable energy on the power grid and continuous end use technology electrification, using final energy is more appropriate to illustrate China's building sector electrification progress.

In the current China's FYP policy setting, there is no policy mention of building electrification. There is an opportunity for future policy development (e.g., the 14th FYP) to specify electricity penetration targets in buildings for both new and existing construction. With such target development, it can better drive local government, industry, and building owners to adopt electrical technologies in China's building sector.

5.2 Codes and standards

China began to develop and enforce its building codes and standards in late 1990s. Building energy efficiency standards establish minimum energy performance for buildings regardless of the energy source used, while appliance and equipment standards are developed separately for combustion-fueled and electric devices. The existing codes and standards are based on prescriptive measures, and the overall building energy performance is often calculated through simulation tools. Given that whole building performance simulation is still not very common in new construction analysis, the current building energy efficiency standards do not provide an explicit whole building energy performance compliance path. Instead, the use of prescriptive measures is still common, and easy to enforce in China's building energy standards compliance process. To include electrification targets in China's building energy efficiency standards, a whole building performance compliance path is needed to allow buildings to comply with standards requirements by calculating a building's energy use intensity (EUI) values. On specific technological measure requirement, building energy efficiency standards need to be further developed to eliminate non-electric technologies, especially those using coal in the residential and commercial building sectors. An effective way to incentivize electric technologies and the whole building electrification rate is to include a whole building final energy electrification rate in the building's energy performance compliance path. The whole building electrification rate is calculated as: the building's annual electricity compunction divided by its annual final energy consumption, to indicate how much of a building's energy consumption comes from electricity. Such an electrification rate can vary across China's different climate zones and grid region by considering the nature of heating and cooling energy use, as well as clean energy penetration over the power grid. Similarly, building retrofit standards and green building standards also should develop criteria to prescribe the adoption of electrical end use technologies.

5.3 Technology research, development, and demonstration (RD&D)

Technology innovation is crucial to persuade building owners and occupants to adopt electric technologies. China has set up a comprehensive national research and development (R&D) program to improve building technology efficiency. The current R&D program also shifts the focus from single technology development to the integration of multiple technologies in building systems. For example, to electrify residential building space heating and DHW systems, an integrated heat pump solution has been developed for the Chinese market, to offer both space heating and hot water using the same heat pump unit. The integration of technologies can offer many benefits, such as reducing cost and saving the space, both indoors and outdoors, required for installations.

To electrify building end use technologies, technology development should focus on not only efficiency improvement, but also on how to accommodate an occupant's usage preference. Take cooking, for example. There is an immediate need to develop cooking technologies that meet the various cooking needs in China, both in the home kitchen and the commercial kitchen. Demonstrating the effectiveness of these technologies to stakeholders is also critical, to showcase not only their efficiency, but also to show there is no loss of performance compared with traditional fossil fuel technologies (Figure 11). Through the demonstration, user feedback is critical, to help technology developers further refine the technologies based on the actual user experience.

Figure 11. A chef in Shanghai demonstrating how to cook with an electric stove and a round-bottom pan

5.4 Incentives for technology deployment

Beginning in 2016, China began to implement ambitious policies to switch coal heating to electric heating in Northern China's rural areas. The policies are characterized as central and local subsidy to cover a part of the installation cost electric heating technologies in rural houses, together with local bans on selling heating coal in Northern China rural areas. Such policies proved effective to reduce pollutant emissions from burning scattered coal in winter seasons, but they also showed that rural residents need to pay a significant amount of their electricity bill for heating. How to lower the long-term operation cost is a key policy question that needs to be addressed for the long-term operation of electric heating systems in rural China. Incentive policies should switch from a single focus on subsidizing installation costs of a technology to a more comprehensive consideration of introducing a lower electric heating tariff for rural heating—as well as electrical distribution system infrastructure upgrades in rural areas to meet the increase of electricity demand. Finally, as much rural housing is not energy efficient, priority also should be paid to retrofitting existing rural housing, upgrading the thermal integrity of the building envelope and reducing the building heating load.

5.5 Electricity rate design

China's residential electric rate features a flat tariff around 0.6 renminbi per kilowatt-hour (RMB/kWh) (0.09 USD/kWh), while the commercial building electric rate peak, off-peak tariff, and the peak price can reach to 1.4 RMB/kWh (0.22 USD/kWh). In addition, the local power company only offers one tariff structure for residential and commercial buildings, respectively, and buildings do not have another alternative tariff structure to choose. As more and more electric technologies penetrate in buildings, the electricity time of use patterns in the residential and commercial sectors will inevitably change over time. More electricity rates need to be designed to offer people the flexibility to choose the rate suitable for their building's electricity demand. The electricity rate design also should consider the affordability for urban buildings versus rural dwellers. Especially for rural electrical heating, certain electricity structures could be introduced to encourage rural residents to use electrical heating with an affordable electricity cost. Given that China is advancing distributed PV polices, the impact of building integrated PV (BIPV) should also be considered in the electric rate design.

5.6 Demand response program and electricity market design

China does not have a mature electricity market yet. The demand response is not 100% triggered by market signals, but more driven by critical events such as heat waves and shortage of electricity generation. An immediate challenge for electrification of the building sector is the expansion of local power distribution to accommodate the increase of building electricity demand increase. Such distribution network infrastructure expansion could require significant capital investment. To foster a mature electricity market in the long run, policies should be developed to encourage building users to shift or curtail their peak demand. The utility companies would reap huge benefits and potentially reduce the amount of money they need to invest in power distribution system expansion. As mentioned in the discussion on electricity rate design, demand response programs also should consider distributed solar policies and study the impact of distributed solar generation on curtailing buildings' peak loads. A comprehensive incentive structure for demand response needs to be designed in conjunction with the incentives provided for distributed PV.

5.7 Awareness, education, and outreach

Occupants are the core stakeholders who adopt electric technologies. During our survey and in communications with stakeholders, it was often heard that occupants tend to stick with technologies they are familiar with, and that they are reluctant to switch to new technologies. Take electrification of cooking, for instance. Occupants tend to think the traditional natural gas or coal cooking stock can offer high temperature for traditional stir-frying using a round-bottom pan and help maintain the taste of the cooked food. Some public awareness has been launched in China to educate people on the performance of electric alternatives. The green electricity procurement certification (a program in which occupants can purchase green electricity through their social network account and demonstrate to their friends) is an effective way to persuade occupants to use clean electricity in buildings. The government procurement program is also an impactful way of using government buildings to demonstrate the efficiency and effectiveness of using electrical technologies. Future building energy policies should encourage the use of public (e.g., government) buildings in showcasing successful examples of electric technology adoption.

To provide necessary training on electric system design, operation and maintenance is also critical. Building owners, design engineers, contractors need to be familiar with electric system requirements. Electric engineers need to actively work with HVAC and other engineers to make sure a fully electrified building can be safely designed and built.

6. Conclusions

This research report illustrates the benefits and policy solutions of electrifying China's building sector. In terms of target technologies, space heating, water heating, and cooking are three key building end use sectors that can be greatly electrified in the future. The survey results from this study identified some common barriers to electrifying China's building sector, such as: high energy cost, high up-front technology investment, a lack of incentives, and building users unfamiliar with new technologies. The modeling results show that electrifying the building sector in China would result in 50% CO_2 savings. To promote building sector electrification, a few policy measures are recommended, such as: target-setting, code and standards, technology development, incentives, electricity rate design, demand response, and public awareness education. These measures should be considered for inclusion into China's future building energy efficiency policies and FYP.

7. Acknowledgement

The authors acknowledge the Energy Foundation for their support on this research project. The authors also thank Max Wei and Jeff Deason for their review and valuable comments on this report.

References

Alpine. (n.d.) Specifications: BLUERIDGE BMKH12-15YN4GA 15 SEER Single Zone Ductless Mini-Split Heat Pump System. Alpine Home Air Products.

Alstone, Peter, Potter, J., Piette, M. A., Schwartz, P., Berger, M. A., Dunn, L. N., Smith, S. J., Sohn, M. D., Aghajanzadeh, A., Stensson, S., Szinai, J., Walter, T., McKenzie, L., Lavin, L., Schneiderman, B., Mileva, A., Cutter, E., Olson, A., Bode, J., Ciccone, A., & Jain, A. (2017). *2025 California Demand Response Potential Study, Final Report and Appendices on Phase 2 Results: Charting California's Demand Response Future.* Lawrence Berkeley National Laboratory. Prepared for California Public Utilities Commission. April.

Chaouachi, A., Bompard, E., Fulli, G., Masera, M., De Gennaro, M., & Paffumi, E. (2016). Assessment framework for EV and PV synergies in emerging distribution systems. *Renewable and Sustainable Energy Reviews*, *55*, 719–728. https://doi.org/10.1016/j.rser.2015.09.093.

Deason, J., Wei, M., Leventis, G., Smith, S., & Schwartz, L. C. (2018). *Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches.* Lawrence Berkeley National Laboratory. March.

Dennis, Keith. (2015). Environmentally Beneficial Electrification: Electricity as the End-Use Option, *The Electricity Journal,* 28 (9), November, 100–112. ISSN 1040-6190. https://doi.org/10.1016/j.tej.2015.09.019.

Energy and Environmental Economics, Inc. (2019). *Residential Building Electrification in California: Consumer economics, greenhouse gases and grid impacts.* Retrieved from https://www.ethree.com/wp-content/uploads/2019/04/E3_Residential_Building_Electrification_in_California_April_2019.pdf.

Mills, Andrew, & Wiser, Ryan H. (2015). Strategies to mitigate declines in the economic value of wind and solar at high penetration in California. *Applied Energy* 147, 1 June 2015, 269–278. ISSN 0306-2619. https://doi.org/10.1016/j.apenergy.2015.03.014.

Nadel, Steven. (2016). Comparative Energy Use of Residential Furnaces and Heat Pumps (No. A1602). ACEEE.

Peng, W., Yang, J., Lu, X., & Mauzerall, D. L. (2018). Potential co-benefits of electrification for air quality, health, and CO_2 mitigation in 2030 China. *Applied energy*, 218, 511–519. https://doi.org/10.1016/j.apenergy.2018.02.048.

Rheem. (n.d.). Classic Series Heat Pump (RP14 Series). Product Manual.

Steinberg, David, Bielen, Dave, Eichman, Josh, Eurek, Kelly, Logan, Jeff, Mai, Trieu, McMillan, Colin, Parker, Andrew, Vimmerstedt, Laura, & Wilson, Eric. (2017). *Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization* (No. NREL/TP-6A20-68214). Retrieved from https://www.nrel.gov/docs/fy17osti/68214.pdf.

Tsinghua University Building Energy Research Center. (2018). *China Building Energy Use 2018*.

U.S. Department of Energy. 1 (n.d.). Air-Source Heat Pumps. https://www.energy.gov/energysaver/heat-pump-systems/air-source-heat-pumps.

U.S. Department of Energy. 2 (n.d.). Demand Response. https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response.

U.S. Energy Information Administration. (2017). *Annual Energy Outlook 2017* (No. AEO2017). Retrieved from

U.S. Energy Information Administration. (2017). *Residential Energy Consumption Survey (RECS): Table HC8.1 Water heating in U.S. homes by housing unit type, 2015.* Energy Information Administration (EIA).

U.S. Energy Information Administration. (2017). State Energy Data System (SEDS). https://www.eia.gov/state/seds/.

Wei, Max, Nelson, James H., Greenblatt, Jeffrey B., Mileva, Ana, Johnston, Josiah, Ting, Michael, Yang, Christopher, Jones, Chris, McMahan, James E., & Kammen, Daniel M. (2013). Deep carbon reductions in California require electrification and integration across economic sectors. *Environmental Research Letters*, *8*(014038), 10. https://doi.org/doi:10.1088/1748-9326/8/1/014038.

Weiss, Jürgen, Hledik, Ryan, Hagerty, Michael, & Gorman, Will. (2017). *Electrification: Emerging Opportunities for Utility Growth* (White Paper). The Brattle Group. Retrieved from https://brattlefiles.blob.core.windows.net/system/news/pdfs/000/001/174/original/electrification_whitepaper_final_single_pages.pdf?1485532518.

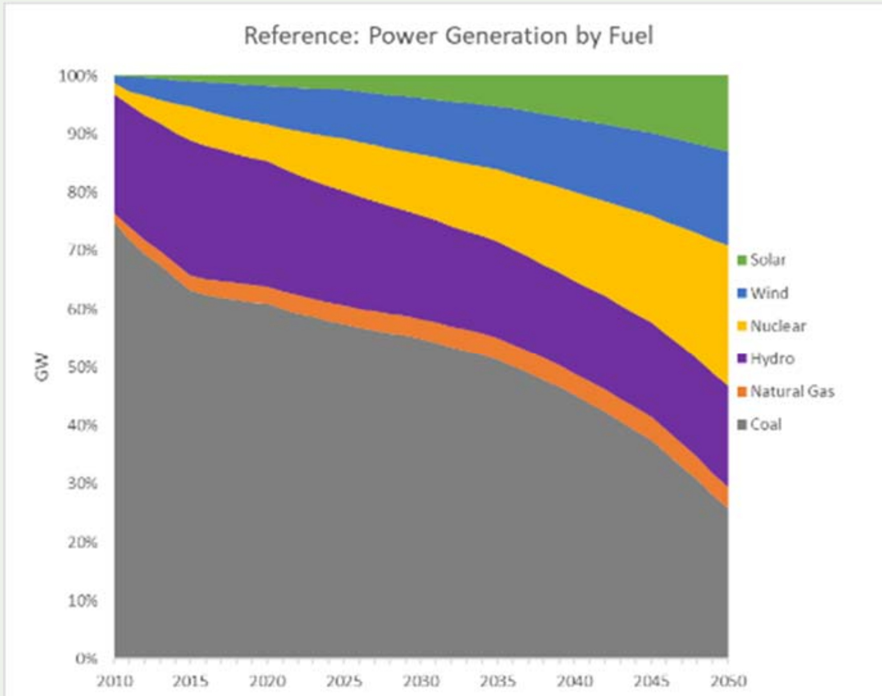
Williams, James H., DeBenedictis, Andrew, Ghanadan, Rebecca, Mahone, Amber, Moore, Jack, & Morrow III, William R. (2012). The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity. *SCIENCE*, *335*(6 January 2012), 53–59. https://doi.org/10.1126/science.1208365.

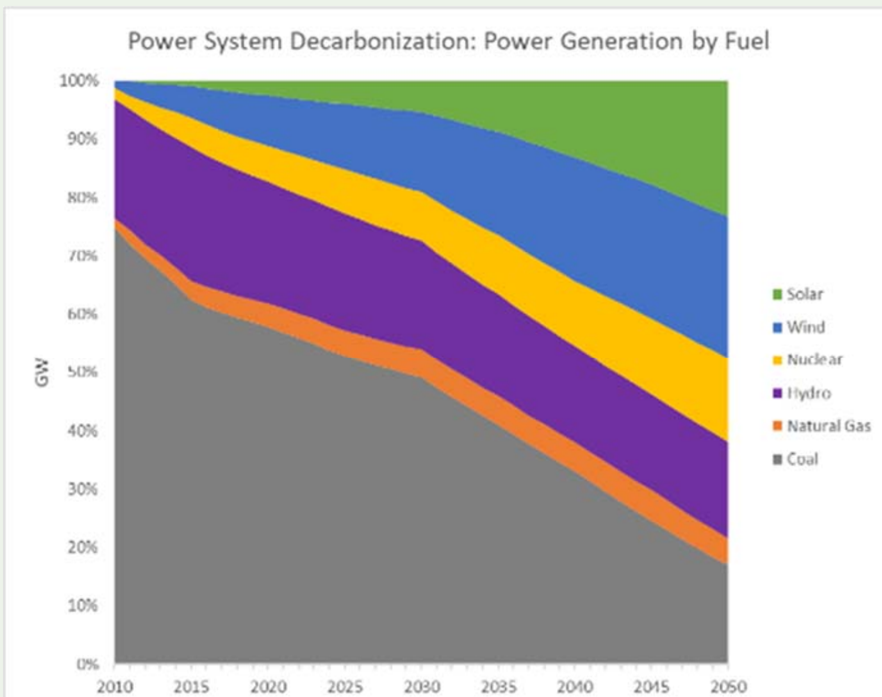
Zhou, N., Khanna, Nina, Feng, Wei, Ke, Jing, & Levine, Mark. (2018). Scenarios of energy efficiency and CO_2 emissions reduction potential in the buildings sector in China to year 2050. *Nature Energy*, 3: 978–984.

Appendix A. Modeling Assumption and Input Parameters

Categories	Measures
Electrification technologies for buildings	- Heat pump water heating, integrated with renewables (50% penetration, potentially with solar thermal for coefficient of performance [COP] > 7) Commercial: 60% air sourced heat pump (ASHP) in 2050 Urban: 50% ASHP in 2050 - Electrification for space heating, rural and urban (COP 4.47, rural 100%, urban 50%) ASHP Urban Residential North: 50% in 2050; Transition: 80% in 2050; South: 100% in 2050 Rural North: 60% in 2050; Transition/South: 80% ASHP Commercial North: 60% in 2050; Transition: 90% in 2050; South: 100% in 2050 - High efficiency cooking stove (penetration 60% for cooking) Urban: 80% in 2050 Rural: 60% in 2050 - DC buildings (15% energy efficiency and carbon reduction, better control and smart system) - High efficient cooling (residential air-conditioner seasonal energy efficiency ratio [SEER]: 38) penetration 100% - Improve energy efficiency of lighting and home appliances
Energy efficient and grid-friendly buildings: policy opportunities	- Net/nearly zero energy buildings and ultra-low energy buildings - Deep energy efficiency retrofits to buildings - Increase appliance/equipment energy efficiency and encourage to use electric appliances - Smart building electric system grid friendly control through demand response (DR) - Efficient equipment penetration rate (0 in 2010 to 100 in 2050) faster than the Reference scenario (0 in 2010 to 40 in 2050) - Residential - Heating: ASHP - Cooling: room air conditioner (AC) - Cooking: electric cooker - Water Heating: ASHP - Appliances: clothes washer, color TV, refrigerator, stand by - Lighting - Commercial - Heating: ASHP - Cooling: centralized AC, room AC, geothermal heat pump

<table>
<tr><td></td><td>- Water Heating: ASHP
- Lighting and Equipment</td></tr>
<tr><td>Decarbonization of the power generation sector under both the Electrification scenario and the Electrification and Efficiency scenario</td><td>-





Coal share in power generation drops more quickly in the Electrification and Efficiency scenario (63% in 2015 to 17% in 2050) than in the Reference scenario (63% in 2015 to 26% in 2050).</td></tr>
</table>

	Wind and solar accounts for 48% in 2050 in the Electrification and Efficiency scenario, compared with 29% in 2050 in the Reference scenario. The nuclear share in the Electrification and Efficiency scenario grows relatively slower compared with that in the Reference scenario. In 2050, nuclear accounts for 14% in 2050 in the Electrification and Efficiency scenario, while it accounts for 24% in 2050 in the Reference scenario. The hydro share is approximately the same under all scenarios.

Appendix B. Electrification Survey Questionnaire

1. Do you think electrification is an effective strategy to help buildings reduce their carbon footprint?
Yes
No
Not sure
Please provide a brief explanation for your answer here:

2. Please identify which of the following you think are major barriers of doing building electrification in the United States (Please select all that apply).
1) high electricity costs
2) low fuel prices (coal, natural gas, etc.)
3) lack of technology availability
4) high technology costs
5) requirements for technology installation and transformer/substation capacity upgrades
6) lack of end-user awareness
7) lack of government/utility policies and incentives
8) other (write in)
Please provide a brief explanation for your answer here:

3. Please identify which of the following you think are major barriers of doing building electrification in China (Please select all that apply).
1) high electricity costs
2) low fuel prices (coal, natural gas, etc.)
3), lack of technology availability
4) high technology costs
5) requirements for technology installation and transformer/substation capacity upgrades
6) lack of end-user awareness
7) lack of government/utility policies and incentives
8) other (write in)
Please provide a brief explanation for your answer here:

4. What technologies do you think can be electrified in the near future in the United States?
1) cooking stove
2) water heating
3) space heating
4) other (write in)
5) Please write in any specific technologies (brand, make, model, etc.) that your company can provide, or that you recommend, that are highly efficient and cost-effective for electrification in the United States:
Please provide a brief explanation for your answer here:

5. What technologies do you think can be electrified in the near future in China?
1) cooking stove
2) water heating
3) space heating
4) other (write in)
5) Please write in any specific technologies (brand, make, model, etc.) that your company can provide, or that you recommend, that are highly efficient and cost-effective for electrification in China:
Please provide a brief explanation for your answer here:

6. Do you think electrical storage technology improvements and associated cost reduction would likely promote building sector electrification? If so what are the most promising storage technologies/improvements on the horizon and associated technology unit prices ($/kWh)?
1) Select one: YES, NO
2) Provide promising storage technologies/improvements and associated technology unit prices (write in):

Please provide a brief explanation for your answer here:

7. What do you think of the potential for electrification in the rural part of China? What are the barriers for coal to electricity in rural heating?
1) Potential (select one): difficult; possible; easy to implement
2) Barriers (multiple choices): energy cost; lack of environmental awareness; technology cost; lack of long-term supporting policy on technology installation and energy; need mandatory policies

Please provide a brief explanation for your answer here:

8. What do you think is the potential to electrify district heating systems in China? What % of district heating do you think can be electrified in China in 2030, and 2050?
1) Potential (select one): Highly possible, partially possible, difficult in large scale, almost impossible
2) Percentage electrification possible by 2030 (select one): 100%, 80%, 60%, 40%, 20%, 0%
3) Percentage electrification possible by 2050 (select one): 100%, 80%, 60%, 40%, 20%, 0%

Please provide a brief explanation for your answer here:

9. What are your technology and policy recommendations for accelerating electrification of building energy use in China?
Please provide your answers and a brief explanation here:

10. What are your technology and policy recommendations for accelerating electrification of building energy use in the United States?
Please provide your answers and a brief explanation here:

Appendix B. Electrification Survey Questionnaire Responses

1. Do you think electrification is an effective strategy to help buildings reduce their carbon footprint?

Yes	54.55%
No	0.00%
Not sure	45.45%

2. Please identify which of the following you think are major barriers of doing building electrification in the United States (Please select all that apply).

high electricity cost	60.00%
low fuel price (coal, natural gas etc.)	70.00%
lack of technology availability	20.00%
high technology costs	70.00%
requirements for technology installation and transformer/substation capacity upgrades	40.00%
lack of end-user awareness	30.00%
lack of government/utility policies and incentives	70.00%

3. Please identify which of the following you think are major barriers of doing building electrification in China (Please select all that apply).

high electricity cost	22.22%
low fuel price (coal, natural gas etc.)	33.33%
lack of technology availability	22.22%
high technology costs	33.33%
requirements for technology installation and transformer/substation capacity upgrades	33.33%
lack of end-user awareness	44.44%
lack of government/utility policies and incentives	44.44%

4. What technologies do you think can be electrified in the near future in the United States?

cooking stove	55.56%
water heating	77.78%
space heating	77.78%

5. What technologies do you think can be electrified in the near future in China?

cooking stove	37.50%
water heating	50.00%
space heating	100.00%

6. Do you think electrical storage technology improvements and associated cost reduction would likely promote building sector electrification?

Yes	63.64%
No	36.36%

7. (Part1) What do you think of the potential for electrification in the rural part of China?

Easy to implement	11.11%
Difficult	55.56%
Very difficult	11.11%

7. (Part2) What are the barriers for coal to electricity in rural heating?

energy cost	70.00%
lack of environmental awareness	40.00%
technology cost	80.00%
lack of long-term supporting policy on technology installation and energy	60.00%
need mandatory policies	20.00%

8. (Part1) What do you think is the potential to electrify district heating systems in China?

Very likely	14.29%
Likely	57.14%
Unlikely	28.57%
Very unlikely	0.00%

8. (Part2) What % of district heating do you think can be electrified in China in 2030?

100%	0%
80%	0%
60%	25%
40%	0%
20%	50%
0%	0%

8. (Part3) What % of district heating do you think can be electrified in China in 2050?

100%	0%

80%	25%
60%	0%
40%	37.50%
20%	12.50%
0%	0%