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Implications of maximizing China's technical potential for residential end-use energy efficiency: A 2030 outlook from the bottom-up

Nina Khanna, David Fridley, Nan Zhou and Jing Ke
China Energy Group
Environmental Energy Technologies Division
Lawrence Berkeley National Laboratory

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Executive Summary

China has committed to reduce energy and CO₂ intensity through 2020 but whether and how specific energy efficiency measures can help achieve these goals is unclear. One area with significant energy and emissions reduction potential is residential end-uses, as urbanization and rising incomes continue to drive household ownership, usage and demand for residential energy services. However, because China only recently started focusing on energy efficiency and has followed an iterative regulatory approach to raising equipment efficiency levels, there is significant remaining – but not yet quantified - technical savings potential from residential end-use efficiency improvements.

In this paper, we evaluated the technical potential of maximizing China's residential equipment efficiency and the subsequent energy demand and CO₂ emissions implications through 2030. A detailed LBNL bottom-up, end-use energy model is used to highlight residential end-use energy linkages between urbanization, economic development and China's growing buildings sector. Scenario analysis with a reference energy efficiency scenario and a maximum technically feasible efficiency improvement (Max Tech) scenario is used to evaluate two possible pathways of energy and emissions reduction and the efficiency gap by residential end-use through 2030. Relative to the reference scenario, achieving Max Tech residential efficiency improvements could save 3.91 EJ and 395 million tons of CO₂ per year by 2030. Energy savings opportunity varies across end-uses, with major appliances having the largest savings potential despite a smaller share of total energy demand followed by space heating and cooking efficiency improvements. Electricity savings and the associated CO₂ reduction from equipment efficiency improvements can be magnified by power sector efficiency improvements and fuel switching, underscoring the dual importance of end-use efficiency improvements and power sector decarbonization in China's future.

Table of Content

Executive Summary.....	i
1. Introduction.....	3
2. Modeling Methodology	3
2.1. Model Scenarios.....	4
3. Basis for Residential Energy Demand Outlook	5
4. Efficiency Improvement and Technology Outlook.....	5
4.1. Appliance Technology Outlook	6
Room Air Conditioners.....	6
Standby Power.....	6
Fans.....	6
Refrigerators	6
Televisions	6
Clothes Washers	7
4.2. Residential Heating Technology Outlook.....	7
4.3. Residential Lighting Outlook	7
4.4. Residential Cooking Outlook.....	7
4.5. Residential Water Heating Technology Outlook.....	7
4.6. Household Other End-Use Energy Intensity Trends.....	8
5. Residential Sector Energy and CO₂ Emissions Findings	8
5.1. Analysis of Residential Savings Potential	9
6. Conclusions and Discussion	10
Acknowledgments	11
References.....	11

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1. Introduction

After over two decades of staggering economic growth and soaring energy demand, China began taking serious actions to reduce both its economic energy intensity (energy consumption per unit of gross domestic production) and carbon intensity (CO₂ emissions per unit of GDP). The 11th Five Year Plan (FYP) target of reducing economic energy intensity by 20% from 2006 to 2010 was followed by new and revitalized policies and programs to improve efficiency across all sectors. In November 2009, China committed to reduce its carbon intensity by 40% to 45% below 2005 levels by 2020. After achieving 19.1% reduction in economic energy intensity during the 11th FYP period, binding targets of 16% and 17% reductions in energy and carbon per unit of GDP, respectively, have been set for the 12th FYP period of 2011-2015.

Against this backdrop of short and medium-term targets for reducing energy demand and emissions, it is important to consider where the largest opportunities for efficiency gains and emissions reduction lie from sectoral and end-use perspectives and how they may contribute to the achievement of these targets. One area with significant energy and emissions reduction potential is residential end-uses, particularly for urban households. China added 210 million new urban residents between 2000 and 2010 and expects to add another 300 million by 2030 (NBS 2012). Rising urbanization and increasing household income levels are expected to continue to drive household ownership, usage and demand for residential energy services over the next two decades. At the same time, the targets need to be contextualized in terms of how far they will place China in attaining the highest possible efficiency levels and adopting the most advanced technologies. To understand China's possible energy and emission pathways and the efficiency gap by residential end-use through 2030, this study uses a bottom-up, end-use model and two scenarios to represent energy supply and demand sectors.

2. Modeling Methodology

The basis for evaluating China's future energy and emissions trajectory and the span of cross-sectoral efficiency gains lies in the Lawrence Berkeley National Laboratory (LBNL) China Energy End-Use Model, a bottom-up, end-use model of the Chinese economy to 2030 developed using the Long-range Energy and Alternatives Planning (LEAP) software platform. The China Energy End-Use Model forecasts diffusion of detailed end use technologies, the macroeconomic and sector-specific drivers of energy demand, and the energy required to extract fossil fuels and produce energy, while also

modelling the power sector with distinct generation dispatch algorithms. The LEAP platform enables detailed consideration of technological development—equipment efficiency, residential appliance usage, power sector efficiency, lighting and heating usage—as a way to evaluate China’s energy and emissions reduction development pathway below the level of its macro-relationship to economic development. By adopting an end-use approach to energy and emissions modelling, this study is able to separate out and decompose different magnitudes of potential efficiency gains by sector and by technology. At the same time, scenario analysis enables the modelling of a pathway where efficiency improvements are maximized to reach the highest technically feasible levels (irrespective of costs) by 2030 in order to assess the combined effects of efficiency on energy and emissions reduction.

2.1. Model Scenarios

Two key scenarios – Reference and Maximum Technology (Max Tech) – were developed to assess efficiency gains in terms of energy savings and CO₂ mitigation potential by measure and by sector. Both scenarios share the same demographic and macroeconomic characteristics and assumptions, including population growth to 1.46 billion by 2030 based on United Nations projections, 70% urbanization by 2030 and annual average GDP growth of 7.7% from 2010 to 2020 and 5.9% from 2020 to 2030 based on Chinese projections. LBNL’s assumed population growth and urbanization rates are similar to those used in other recent modelling studies by China’s Energy Research Institute (ERI) and McKinsey & Co., but has slightly lower GDP annual average growth rates after 2010 than the other two studies (Zheng et al. 2010). The two scenarios in this study also share the same subsectoral drivers of energy demand such as building floorspace and appliance ownership and usage, which are linked to changes in household sizes and household income levels¹. The two scenarios differ primarily in efficiency improvements as measured by terms such as equipment unit energy consumption (kWh/year) as well as technology mix (such as compact fluorescents versus light-emitting diodes for lighting) and fuel mix.

In particular, the Reference scenario was developed to represent a pathway in which the Chinese economy continues a moderate pace of “market-based” improvement in all sectors and adopts all announced policies and goals related to efficiency improvement, such as continuing the recent pace of appliance standard revisions. Unlike a frozen scenario, which is unrealistic given China’s recent commitments to energy and carbon intensity reductions, the reference scenario reflects what is likely to happen and thus serves as the baseline for measuring savings from efficiency improvements.

The Max Tech scenario serves as an alternative pathway for development in which efficiency improvements are maximized to the highest technical potential across residential end-uses by 2030 as a result of aggressive policies and programs. This scenario only takes technical feasibility into consideration and does not consider current economics of the technology such as high costs or commercial deployment barriers. For specific end-uses such as residential appliances, heating and cooling equipment, the Max Tech scenario means adopting the best known efficiency level that is technically feasible or the saturation of cutting edge technology such as all organic light-emitting diode (OLEDs) televisions that are not yet commercially deployed by 2030. A literature review and internet search of best available technologies and efficiency levels in international standards and labelling programs (e.g., EU Ecodesign, U.S. ENERGY STAR) and product markets as well as

¹ Due to space constraints, details on the residential drivers of energy demand are not covered here. More information on these drivers and their basis can be found in Zhou et al. 2012 and Fridley et al. 2011.

discussions with U.S. appliance experts served as the basis for determining the maximum technically feasible efficiency levels for residential end-uses.

3. Basis for Residential Energy Demand Outlook

Residential energy demand is driven simultaneously by urbanization and growth in household incomes. Whereas urban households tend to consume more energy than rural households, particularly in non-biofuels, household income growth also affects the size of housing units and subsequent heating and cooling loads, and increase in ownership and use of energy-consuming equipment such as appliances, lighting and electronics.

With respect to the basis for rising residential energy demand, key assumptions underlying the Reference and Max Tech scenario include household size, residential floorspace per person, and ownership of key energy-consuming appliances. International experience has shown that household size tends to decline with rising income and urbanization, while per capita floorspace is expected to rise². The decline in household size leads to an increase in the total number of households which, together with the increase in living area, will multiply the contribution of energy demand from households. LBNL's projections for household sizes, residential space per person and total residential building floorspace are within the range of the ERI and McKinsey modelling studies, with 39.8 billion m² of urban residential floorspace and 17 billion m² of rural residential floorspace³.

In terms of ownership, Chinese urban appliance ownership rates were only at around 50 units per 100 households for refrigerators and televisions and negligible for air conditioners in the early 1990s. Within twenty years, nearly every urban household now owns a clothes washer and refrigerator with ownership of multiple units of air conditioners and televisions common in urban households (NBS 2012). In forecasting future ownership trends for the largest household energy-consuming appliances, an econometric model correlating historical ownership rates to incomes and using these to predict future trends is used. Significant growth in ownership, especially in the rural sector, is expected and saturation effects will become important in urban households in the near future as growth in per household electricity consumption is expected to slow⁴. Some growth is assumed to continue as incomes continue to rise, resulting in increased usage (especially air conditioners), larger refrigerators, more lighting and more devices using standby power. Meanwhile, space heating intensity and usage also increases with dwelling area and wealth. In addition, the model takes into account prevailing trends in space heating equipment choice, such as an increase in the use of electric heat pumps in China's Transition climate zone, and the phase-out of coal boilers.

4. Efficiency Improvement and Technology Outlook

Opportunities for reducing energy consumption in households primarily fall in the improvement of equipment efficiency, which rises as the stock turns over and newer, more efficient units replace the retirement of old, inefficient units. In recent years, minimum energy performance standards (MEPS)

² See Zhou et al. 2012 for more information on the specific model assumptions for these drivers.

³ See Zheng Zhou and Fridley 2010 for a more detailed comparison of residential drivers and assumptions.

⁴ Historical appliance ownership rates are taken from the annual China National Statistical Yearbook. LBNL projected appliance ownership rates can be found in Fridley et al. 2011.

and voluntary and mandatory energy labeling have driven equipment efficiency improvements in China and is expected to continue in the future. The current schedule of Chinese MEPS, with revisions occurring every 4 to 5 years, is explicitly accounted for in the Reference and Max Tech scenarios and is specific to each type of equipment.

4.1. Appliance Technology Outlook

Room Air Conditioners

Room air conditioner usage is expected to increase significantly with rising household incomes, as illustrated by the boom in ownership since the mid-1990s, and air conditioner MEPS have been implemented since 1999 with subsequent revisions in 2004 and 2010 in China. The Reference scenario expects the current pace of revisions to continue, reaching an Energy Efficiency Ratio (EER) of 4 by 2030 while accelerated MEPS revisions under the Max Tech scenario help reach the maximum technically feasible EER of 6 by 2030 (Zhou et al. 2011).

Standby Power

For standby power, the assumed standby electricity consumption per plug-load is expected to decrease as more product MEPS begin to incorporate maximum standby power consumption requirements. Under the reference scenario, per unit standby power consumption is reduced by 80% from the base level to 1 watt (W) by 2030 based on existing standby requirements in many countries including the U.S. and Korea. The Max Tech scenario considers a much lower per unit standby power consumption of only 0.1 W by 2030 based on the lowest proposed limits for standby in the European Union Ecodesign requirements.

Fans

As an alternative to room air conditioners, fans have already saturated in terms of ownership and relatively small incremental improvements in efficiency are expected as a result of further MEPS revisions. The reference scenario assumes unit energy consumption will drop from the base level of 10 kWh/year to 8.7 kWh/year by 2030, while Max Tech assumes greater reductions to 6.1 kWh/year by 2030 (Zhou et al. 2011).

Refrigerators

New MEPS were recently implemented for refrigerators and the expected efficiency gains are modeled in both the Reference and Max Tech scenario, with an 11% and 15% improvement in unit energy consumption between 2010 and 2020, respectively. After 2020, the Max Tech scenario will reflect more aggressive efficiency improvements of 40% from 2020 level by 2030, compared to only 20% in the Reference scenario. In both scenarios, the average size of refrigerators grows over time (Zhou et al. 2011).

Televisions

Unlike other appliances, efficiency improvements in televisions are expected as a result of both MEPS and technology shift towards more efficient TVs illuminated by Light-Emitting Diodes (LED) instead of Cold Cathode Fluorescent Lamps (CCFL) used in most LCD televisions. Since China introduced flat panel television MEPS in December 2010, both scenarios assume the same pace of MEPS revisions. By 2026, both scenarios will meet U.S. ENERGY STAR version 5 specifications with 35% efficiency gain. In addition to efficiency gains from MEPS, television efficiency is also expected to rise over time

as a result of the technology shift towards LED and cutting-edge organic LED illuminated displays, which are 40% more efficient than CCFL-LCD TVs. Based on published market forecasts, the relative share of LCD televisions that are OLEDs is expected to reach 50% by 2030 since it will take a few years for the technology to be commercially deployed under the reference scenario, and 100% by 2030 under the Max Tech scenario – a significantly faster improvement over historic efficiency improvement trends (Stokes 2009).

Clothes Washers

Efficiency gains for clothes washers largely result from MEPS revisions, with 15% improvement from current levels by 2030 under Reference scenario and nearly 50% improvement by 2030 under the Max Tech scenario (Zhou et al. 2011).

4.2. Residential Heating Technology Outlook

Three technologies are considered for residential space heating: gas boilers, heat pumps, and electric heaters. Gas boilers under the Reference scenario is expected to reach 88% efficiency by 2030 and the highest technically feasible efficiency of 99% by 2030 under Max Tech (ACEEE 2010). For heat pumps, the coefficient of performance (COP) is expected to reach 2.6 by 2030 under the Reference scenario and the highest known COP of 4 by 2030 under Max Tech (ACEEE 2010). Lastly, small efficiency improvements of 5% and 14% are expected for electric heaters under the reference and Max Tech scenarios, respectively.

4.3. Residential Lighting Outlook

As with televisions, residential lighting efficiency improvements are also the product of technology shift to LED and advanced LED lighting technology, as well as incremental efficiency improvements within LED technology. Under both scenarios, the proposed phase-out of incandescent lighting will be implemented before 2030 and CFLs will dominate lighting in the short term. Over the long-term, LEDs are assumed to replace 50% of CFLs by 2030 under the Reference scenario, and 100% under Max Tech. In addition, within LEDs, the Max Tech scenario assumes growing technology shares of more efficient advanced LEDs that use 4.7 kWh/year instead of 7.6 kWh/year after 2015 to 100% advanced LEDs by 2030 (Letschert et al. 2010).

4.4. Residential Cooking Outlook

Both electric and gas stoves are assumed to improve by 18% from now to 2030 under the Reference scenario, and by a much higher 54% under the Max Tech scenario (Zhou et al. 2011).

4.5. Residential Water Heating Technology Outlook

Residential water heating is comprised of electric and gas water heaters, both of which are expected to improve as a result of MEPS revisions. For gas water heaters, the energy factor is assumed to improve from 0.86 to 0.92 by 2030 under the reference scenario and to 0.96 by 2030 under Max Tech, based on levels comparable to the U.S. Department of Energy's assumed Best Available Technology in the most recent water heating standard setting process (US DOE 2010). For electric water heaters, continued efficiency improvements are expected under reference and Max Tech, with the energy factor rising from current level of 0.76 to 0.88 and 0.95 in 2020, respectively. From 2020 to 2030, a technology switch from electric water heaters to heat pump water heaters with energy factor of 2.5 is expected to bring significant energy savings in both scenarios (Letschert 2010).

4.6. Household Other End-Use Energy Intensity Trends

In order to account for growing ownership and active use of miscellaneous end-uses such as hot water dispensers, entertainment electronics such as DVD players and stereo systems, rice cookers, microwaves, computers and printers, the “other end-use” category was created. Under both scenarios, other end-use energy intensity in urban households is expected to rise from 400 kWh per year per household to 730 kWh per year per household in 2030, or 2 kWh per day. Rural household other end-use energy intensity is expected to remain lower than urban households, with 50% lower growth through 2030.

5. Residential Sector Energy and CO₂ Emissions Findings

As Figure 1 shows, residential primary energy demand will not peak before 2030 under the Reference scenario with rapid growth of 2.7% per year from 2010 through 2020 and then slowing down to only 0.5% per year by 2030. This slowing of growth is largely due to saturation effects, as the process of urbanization will be largely complete and most households will own all major appliances by 2030. The impact of the aggressive efficiency improvements under the Max Tech scenario is to both cap demand growth in the residential sector and to achieve a reduction in total energy demand after 2020. Under Max Tech, residential primary energy demand peaks after growing at 1.6% per year and reaches a significantly lower level of 23% below the reference case by 2030, after declining at nearly 1% per year after 2020. Compared to the 8% average annual increase in residential primary energy demand from 2000 to 2010, the much lower growth rates under Reference and Max Tech scenarios highlight the potential impacts of efficiency policies targeted at the residential sector. Effects of this magnitude in any sector are significant, and show that policy actions taken now to cap energy intensity in non-industrial sectors can contribute greatly to China’s ability to cap energy demand in the long term. In terms of primary fuel, coal for electricity and steam is increasingly replaced by primary electricity and natural gas with only 35% coal share of primary energy under the decarbonized and more efficient Max Tech scenario.

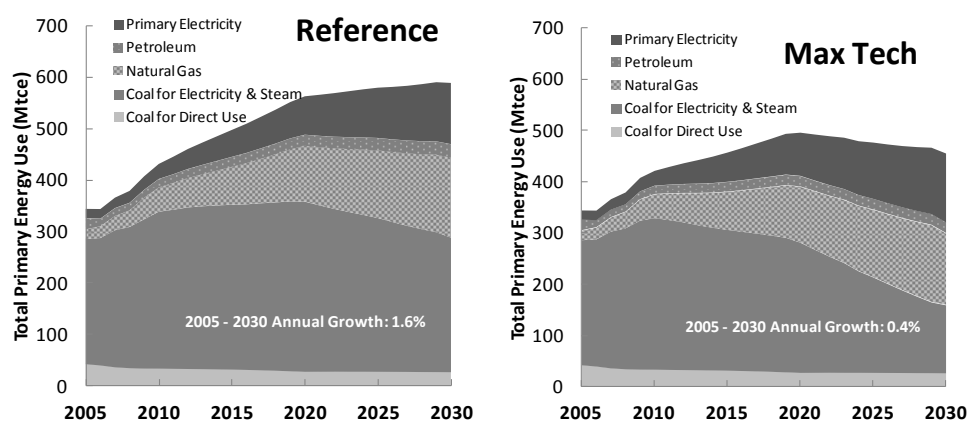


Figure 1. Residential Primary Energy Consumption by Fuel, Reference and Max Tech Scenario

Within the residential sector, primary energy demand growth is driven primarily by space heating and appliances, which together comprise of 60% to 62% of total demand under the two scenarios (Figure 2). Under the Reference scenario, space heating energy use grows at 3% from 2005 to 2030 while appliances grow at a slower 1.6% through 2030 due to more efficiency improvements and

increased equipment saturation. While space heating grows at a slightly lower annual average rate of 2.6% in Max Tech relative to Reference, the growth of energy use from appliances is much slower with only 0.8% due to more aggressive efficiency improvements and technology switching. After initial growth between 2010 and 2020, energy use from water heating, cooking, and other uses remains relatively constant after 2020.

As a result of the significant decline in coal primary energy demand under Max Tech, residential CO₂ emissions actually plateaus after 2010 and declines rapidly after 2020. In contrast, reference residential CO₂ emissions continue rising at annual average rate of 1.5% before peaking at 1.2 billion tonnes (Bt) and then declining slowly through 2030. Because CO₂ emissions growth is capped after 2010 under Max Tech, the 2030 annual residential emissions under Max Tech is 35% lower than under reference with cumulative reduction of 4.6 Bt CO₂.

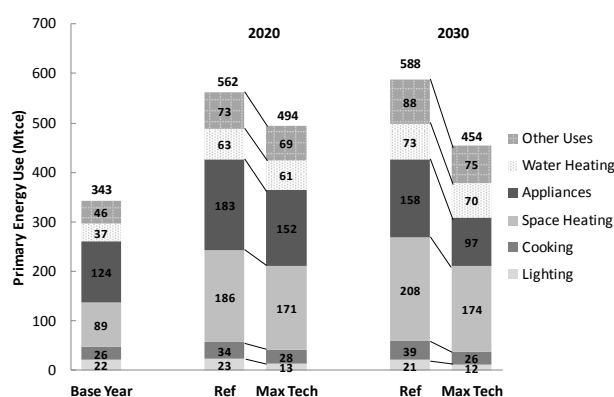


Figure 2. Residential Primary Energy Consumption by End-Use

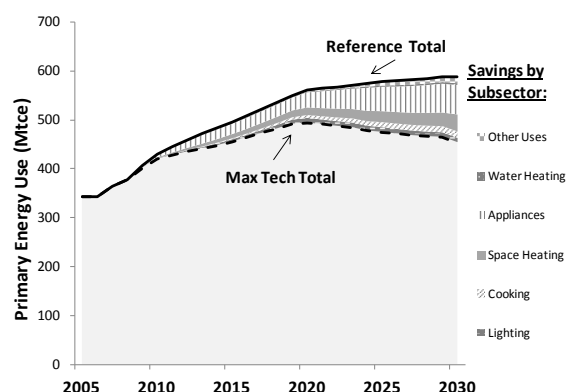


Figure 3. Residential Primary Energy Use Savings Potential by End-Use

5.1. Analysis of Residential Savings Potential

The energy savings opportunity in the residential sector varies across end-uses, with appliances having the largest savings potential followed by space heating and cooking over time (Figure 3). Appliances' high savings potential can be traced back to major residential energy end-uses including refrigerators and air conditioners, as well as aggressive efficiency improvements such as in OLED televisions and standby power (Figure 4).

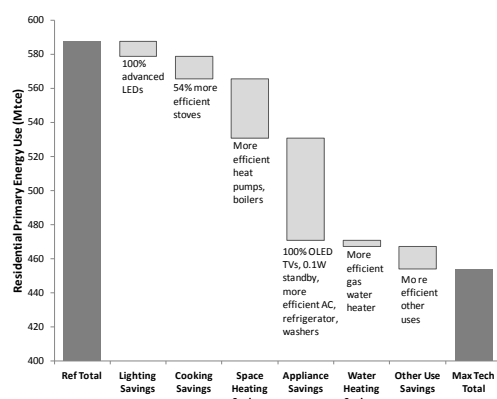


Figure 4. 2030 Residential Primary Energy Savings by End-Use

Note: Y-axis not set to zero.

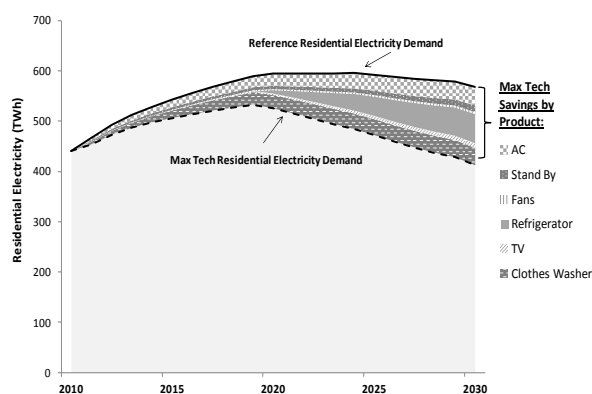


Figure 5. Max Tech Appliance Electricity Savings by Product

Although appliances do not have the largest share of residential energy consumption, they continue to be responsible for nearly half of all savings through 2030. Of all the appliances included in the model, refrigerators have the greatest electricity savings potential with a 37% share of total savings in 2030, followed by air conditioners at 24% and clothes washers at 22% (Figure 5). Refrigerators and air conditioners have the largest energy savings potential because they are the two largest energy consuming appliances within households so small relative efficiency gains can translate into large absolute energy savings. In contrast, televisions have smaller savings potential because their unit energy consumption is lower and they are already relatively efficient under the reference case with 50% of all televisions being OLEDs by 2030.

Space heating is responsible for the most energy use but has the second highest energy savings potential, with a 26% share in 2030. This is due to the smaller incremental efficiency gain in gas boiler efficiency (88% versus 99%) and heat pump COP (2.4 versus 4.0) between Reference and Max Tech scenario. Cooking, lighting and other uses have the next three largest efficiency savings potential, with water heating having the smallest savings potential in the residential sector.

6. Conclusions and Discussion

Although China nearly achieved its 20% energy intensity reduction target for 2006 to 2010, continued rapid economic growth and urbanization creates additional opportunities for efficiency improvements, especially in the residential sector. In evaluating China's energy savings and CO₂ mitigation potential over the next twenty years, it is important to contextualize and quantify the gap between current and expected technologies in use in China and the highest possible efficiency levels of the most advanced technologies. This study uses a bottom-up, end-use model with two scenarios (Reference and Max Tech) to evaluate China's possible energy and emission pathways through 2030. This study finds that relative to the Reference scenario, achieving Max Tech residential efficiency improvements could save 3.91 EJ and 395 million tons of CO₂ per year by 2030. Energy savings opportunity varies across end-uses, with major appliances having the largest savings potential despite a smaller share of total energy demand followed by space heating and cooking efficiency improvements.

Achieving these savings will not only require the continued strengthening and expansion of existing residential efficiency policies such as energy standards and labelling programs, but also the introduction of more market-based mechanisms such as incentives and rebate programs to accelerate market transformation. In recent years, in support of the national energy and emissions goal, the Chinese government launched several market-based programs targeted at improving equipment efficiency in the residential sector. These include subsidies for high efficiency appliances, a buy-back program for old inefficient appliances with a 10% discount on new efficient appliances, and rural household appliance subsidy programs. The overall efficiency of products covered by these financial incentive programs have increased, including a 7% rise in the average model-weighted energy efficiency of air conditioners and refrigerators, while the efficiency levels of water heating and cooking products not covered by the subsidy programs have stalled or remained flat (CNIS 2011). This suggests that much more significant policy action – both in bolstering existing mandatory programs such as the minimum energy efficiency

standards and energy labels and in the initiation of new incentive-based programs – are needed for all products to tap into the significant potential energy savings associated with reaching Max Tech efficiency levels by 2030. At the same time, the potential energy savings can be realized only with strengthened program implementation and evaluation for both mandatory policies and market mechanisms.

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