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Aging, generational shifts, and energy consumption in urban China

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China is recognized as the largest energy consumer and is also the country with the largest and fastest-aging population. Ongoing demographic changes may reshape China's household-based energy consumption patterns because of the large gap in consumption behavior between the elderly and the young as well as varying attitudes toward the environment among generations. However, when the impact of China's aging population on energy consumption is projected, the heterogeneous cognitive norms of generations in the process of demographic transition are not well understood. In this study, we assessed the future impact of China's demographic transition on energy consumption using a proposed theoretical framework to distinguish between age and generational effects. Specifically, we used age–period–cohort (APC) detrended analysis to estimate age and generational effects based on China's urban household survey data from 1992 to 2015. The results indicated large differences in energy use propensity across ages and generations. The elderly and younger generations tended to be energy-intensive consumers, resulting in higher energy consumption in this aging society. Our results consequently show that future changes in China's elderly population will result in a substantial increase in energy consumption. By 2050, the changing consumption share of the elderly population will account for ∼17 to 26% of total energy consumption in the residential sector, which is close to 115 million tons of standard coal (Mtce). These findings highlight the need to interlace environmental education policies and demographic transitions to promote energy conservation behavior in children and youth for low-carbon, sustainable development.

age-period-cohort | aging population | demographic transition | energy consumption patterns

Two fundamental changes are occurring in societies around the world: climate change caused by fossil fuel consumption and demographic transition, including changes in population size, age structure, and generational shifts. Demographic transition nested with socioeconomic development affects energy consumption through the bulk of forces such as economic growth, technological development, urbanization, and behavior modification (1, 2). Among them, behavior modification is most closely related to household energy consumption and is affected by age and generational shifts. Age is an endogenous determinant of biological, psychological, economic, and social characteristics that affects individual energy consumption behavior. Several studies have shown that older people spend more time at home and need more heating services in winter (3, 4), whereas young people spend more time online and use more electronic devices. According to the subcultural theory, a generation born in the same historical period and experiencing the same events will share a unique set of values, beliefs, and expectations that remain relatively stable throughout their lifetime and affect their daily energy end-use activities. Studies have found that people born during World War II or the energy crises of the 1970s have frugal behavior and consciously limit their overall energy use (5–8).

Considering the study results outlined above, it can be expected that aging and generational shifts will play an important role in influencing future energy consumption. However, studies have traditionally focused on population size and confounded age and generational effects when considering the impact of demographic factors on energy use (9–17). These studies examined the effects of age on energy consumption based on the underlying assumption that different generations living in different political, economic, and social periods have the same behavior at the same age stage. This is one reason why existing studies could not yield consistent results regarding the effect of age structure on energy use. For example, some studies have reported that the working-age (ages 15 to 64 y) population is associated with higher energy consumption (9–11), others have reported the opposite effect (13–17), and still others have reported that there is no significant impact (18–20). Confounding age and generational effects not only biases the estimation of age effects but also biases the projection of the impact of

Significance

Dynamic changes in environmental awareness and energy use habits rooted in generations and age cohorts can affect energy consumption. However, existing studies on the impact of demographic transitions on energy consumption have either ignored these changes or treated age structure in a simplified manner that has confounded generational effects. In this paper, we found that growth in the elderly population is likely to substantially increase China's energy consumption, largely influenced by generational shifts in the ensuing decades. Our analysis provides quantitative assessments and insights into the links between population aging, generational shifts, and residential energy consumption, suggesting that ignoring the effects of age and generational shifts will result in a significant underestimation of total future energy demand.

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population aging on residential energy consumption. Although most studies on energy consumption scenarios have considered demographic assumptions, they have focused on energy consumption prospects and did not explicitly examine the individual effects of demographic factors on future energy consumption (21, 22). Moreover, their population scenarios have been limited to factors such as population size, age structure, or household size (23), and detailed analysis of the future impact of generational shifts on residential energy consumption is extremely limited.

Recently, an exploratory study attempted to differentiate the effects of age and generation on residential energy consumption in Italy using an OLS (Ordinary Least Squares)-estimated log–log demand model (24). However, this method attributes the increase in energy consumption caused by socioeconomic development to age and generational effects, which may overestimate the impact of demographic transition on energy consumption due to a failure to distinguish social progress effects from age and generational effects. Several previous studies also contributed to understanding the different effects of age and generation, but they focused on carbon emissions and developed countries (24–26). By contrast, there is insufficient knowledge regarding the impact of aging and generational shifts on energy consumption in China, where the population is rapidly aging, such that by 2025, people over 65 y old will account for 26.1% of the total population (~366 million) (27).

To gain insights into the impact of China's aging population on energy consumption, this study used Chinese household survey data to investigate age and generational effects and to explore the future impact of demographic transition on residential energy consumption. More specifically, we focused on direct energy consumption in urban China, such as the consumption of electricity, natural gas, and coal, to better understand how China's rapidly aging population and generational shifts will reshape energy consumption behavior and affect future energy use.

The novelty of this study is threefold. First, a conceptual and mathematical analysis framework was proposed to identify the mechanism responsible for the impact of the demographic transition on energy consumption, which is important as it provides a guide for separating the impact of the demographic transition on energy consumption from the impact of socioeconomic development to avoid overestimation bias. Second, we utilized a detrended age–period–cohort (APC) model to identify the age and generational effects of energy consumption in China to compensate for the lack of empirical analysis in developing countries. Third, we projected changes in energy consumption caused by China's aging process, considering generational shifts, declining trends in household size, and China's future low fertility rate scenario.

The remainder of this paper is organized as follows. First, we explain the mechanism of the impact of demographic transition on energy consumption. Second, we present the facts on China's demographic transition and energy consumption. Third, we assess age and generational effects, providing projections for population and household size in *SI Appendix, SI Text*. Based on the above results, we project changes in residential energy consumption caused by demographic factors. Finally, we conclude and discuss the implications of the findings.

Mechanism of Demographic Transition on Energy Consumption

The impact of the demographic transition on energy consumption behavior is related to changes in people's thinking and action systems. Thinking and action systems often influence each other and ultimately determine cognitive norms and energy practices. Although it is difficult to predict how people will think about and act on something at a particular time, people form persistent patterns of thought, perceptions, and actions throughout their lives. Bourdieu (28) uses the concept of "habitus" to encapsulate these common and persistent patterns. Stephenson et al. (29) introduced habitus into the study of energy consumption behavior. They stated that energy consumption behavior is a product of interactions between objective materials and subjective habitus. Objective materials are affected by socioeconomic development, and subjective habitus is affected by people's age and their formative experiences in childhood. From this perspective, Fig. 1 presents the energy consumption influence mechanism determined by socioeconomic development and demographic transition. Socioeconomic development affects energy consumption by improving the living material environment; it includes increases in household income, available technologies, and larger houses. Demographic transition affects energy consumption by changing the habitus rooted in people's age and generation.

Based on the conceptual framework, we applied a mathematical analysis to further clarify the mechanism. Specifically, we introduced habitus and "material" into the household energy consumption determination function

$$y_{ij} = f(H_{ij}; M_i), \qquad [1]$$

where y_{ij} is the i-th household's demand for energy j, such as electricity, natural gas, or liquefied petroleum gas (LPG), H_{ij} denotes the energy use habitus of the i-th household head for energy j (*SI Appendix, SI Text* further discusses the acceptability of the behavior of the head of the household on behalf of the entire household), and M_i is a set of factors that affect the energy material environment, including household income, housing area, and educational level of the head of the household.

The formation of habitus is complex and is affected by various unobservable factors such as local culture, physiology, and social practice. Changes in these intertwined factors reshape thinking and activities at all stages of the life cycle. Although we could not measure how these unobservable factors affect energy consumption behavior, we assumed that the habitus changes with age, specifically,

$$\frac{H_{ij}(age+1) - H_{ij}(age)}{H_{ij}(age)} = \gamma_{ij}(age), \qquad [2]$$

where $H(\cdot)$ denotes the energy use habitus and $\gamma(\cdot)$ is the rate of changes in energy use habitus. As this change is continuous, Eq. **2** can be rewritten as follows:

$$H'_{ij}(age) = H_{ij}(age) \times \gamma_{ij}(age). \qquad [3]$$

By solving the above differential equations, we obtained Eq. **4**:

$$H_{ij}(age) = H_{ij}(t_{i0}) \times exp[\int_{t_{i0}}^{t_{i0}+age_i} \gamma_{ij}(\tau) d(\tau)] \qquad [4]$$

where t_{i0} denotes the year of birth for the head of the i-th household and $\exp(\cdot)$ is the natural logarithm. Eq. **4** shows that energy use habitus is affected by two factors: birth year and age. To facilitate the model estimation, we made a strict assumption that the effects of habitus and materials on energy consumption are logarithmically additive, that is,

$$\ln(y_{ij}) = \ln\Big(H_{ij}(t_{i0})\Big) + \int_{t_{i0}}^{t_{i0}+age_i} \gamma_{ij}(\tau) d(\tau) + g(M_i) \qquad [5]$$

where $g(\cdot)$ is a control function for a set of covariables M_i. $\ln(H_{ij}(t_{i0}))$, determined by the year of birth of the household

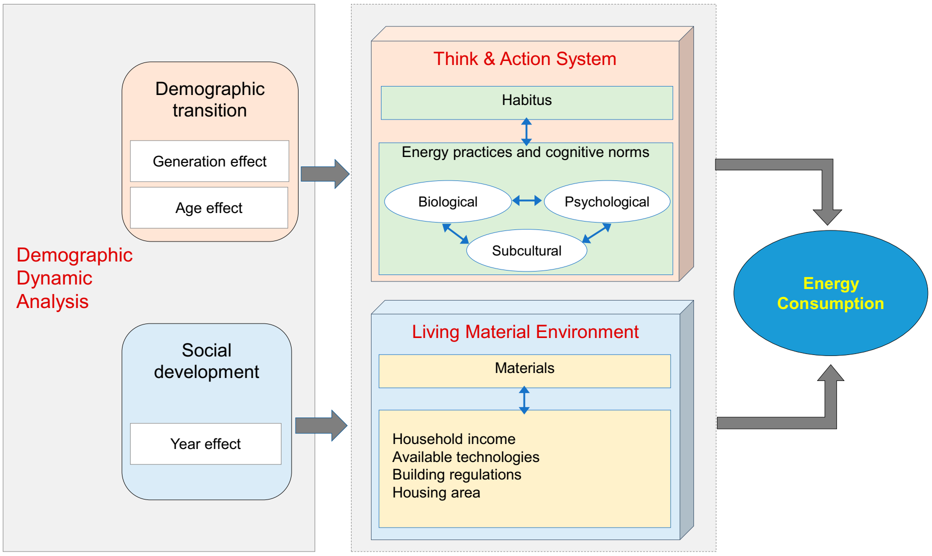

Fig. 1. Influence mechanism of demographic transition on energy consumption.

head, is defined as the generational effect, and $\int_{t_{i0}}^{t_{i0}+age_i}\gamma_{ij}(\tau)d(\tau)$, which varies with age, is defined as the age effect. Thus, we could incorporate the unobservable habitus that affects energy consumption behavior into age and generational effects.

Demographic Transition and Energy Consumption in China

China's population reached 1.41 billion in 2020, exceeding that of all developed countries (30). This population giant is now becoming an "aging giant." With the implementation of the one-child policy and improvements in living standards, China's total fertility rate decreased from 2.2 in 1990 to 1.3 in 2020 (31, 32), while life expectancy increased from 69 to 77 y (33, 34). Consequently, population aging has rapidly increased. In 2020, the proportion of the population over age 65 y was 13.5%. According to the United Nations, this proportion will almost double to 26.1%, ∼366 million people, by 2050. China's society is also experiencing changes in social values in the aging process. By 2020 to 2050, people born between 1955 and 1985 will successively enter old age. Their shared formative experience differs from that of earlier generations, forming their unique intergenerational values (35).

Individuals born in the Republican Era (1912 to 1949) experienced dramatic changes in Chinese society. More than 2,000 y of feudal monarchy ended, and China entered a modern way of life. This period also saw extreme poverty, war, and political instability. The Second Sino–Japanese War broke out in 1931, and the Chinese endured a 14-y-long Japanese occupation. This turbulent period ended when the Communists won the 1945 to 1949 civil war (35). Teens who came of age during the years before the war witnessed the traditional way of life being uprooted and replaced by a modern lifestyle characterized by the pursuit of freedom and comfort (36). Teens growing up in the war era predominantly experienced poverty and starvation as a fact of life and invariably learned from their parents to be frugal. The generations born during the Consolidation Era (1950 to 1965) also experienced hardship. The Great Leap Forward (1958 to 1960) and the Great Chinese Famine (1959 to 1961) led to extreme commodity shortages (37). The commodity ration system further reinforced the population's childhood memories of scarcity, and the era of self-denial and simplicity that people experienced in childhood profoundly influenced their thrift habits in later life. Generation X (1965 to 1980) lived in an era of tremendous rapid industrialization and modernization. China's Open Door policy (1978 to the present) created a solid foundation for economic and social reforms, resulting in unprecedented economic growth and the revival of individualism and new materialism (38). The generations who have lived in the time of social reform have experienced an abundance of materials and have focused more on individual needs. Their sense of thrift is significantly lower than that of the Consolidation and Republican generations.

Changes in lifestyle patterns across ages and generations affect energy practices. Fig. 2 shows Chinese urban household energy consumption patterns across ages and generations. Here, we constructed a pseudopanel dataset to track the "generations" of households, with generations defined according to the year the head of the household was born (see *Materials and Methods* for details). The profile of each line shows changes in energy consumption behavior across the life cycle, whereas the shifts in the lines within the same age group indicate changes in the consumption behavior by generation. In Fig. 2*A*, the overall age–energy consumption profile shows an increasing trend with aging, with this trend plateauing at ∼70 y and declining thereafter. Later-born generations generally consumed more than earlier-born generations, but there are some exceptions. For example, people born during the period 1920 to 1929 consumed more than their peers born during the period 1930 to 1939. Coal consumption (Fig. 2*B*) shows that older people consumed more coal, with no clear differences between generations. In contrast to coal consumption, gas (Fig. 2*C*) and electricity (Fig. 2*D*) consumption not only increased with age but also showed a clear growth trend between generations. Thus, younger generations will consume more gas and electricity than older generations.

Assessing Age and Generational Effects

The above descriptive figures of China's demographic transition and energy consumption show a mixture of year, age, and generational effects, as time trends are present in the long-term dataset. In an economy growing as rapidly as China's, the technologies available for end-use energy devices develop quickly, particularly home appliances and electronics, resulting in rapid growth in electricity consumption over time. In addition, the growing importance of low-carbon transition has led to the Chinese government's ongoing energy regulation policies, which over time will prompt households to replace coal with electricity and natural gas consumption. Therefore, to identify age and cohort effects that are not affected by social progress (including technological advances and policy evolution), we not only need to control for time effects but also remove linear trends for age and generational effects. We can capture the detrended effects by assuming zero slopes for the age and generation variables, while establishing a series of new variables for age and generation to capture the linear trend (more details can be found in *Materials and Methods*).

Age Effect

Fig. 3 *A*–*C* shows the estimated age profile of energy consumption (statistical results are shown in *SI Appendix*, Table S8). The solid line is the age effect, and the dotted lines indicate the 95% CI. To clarify the analysis, households with the head aged 30 to 45 y are defined as young households, those aged 46 to 60 y are defined as middle-aged households, and those over 60 y are defined as elderly households. The results show that the age effects of electricity and gas consumption are similar (Fig. 3 *A* and *B*), with the consumption of young and middle-aged households increasing and that of elderly households decreasing with age. The household consumption of electricity and natural gas peaks at age 60 to 65 y. This result is consistent with the findings of Belaïd et al. (39) in France. Their findings show that residential electricity consumption has an inverted U-shaped distribution with age.

To account for the change in energy consumption across the life cycle, we can think of it in terms of household lifestyles. Household energy consumption has a direct correlation with time spent at home. Middle-aged households with children tend to spend more time on energy-consuming household activities, such as cooking and cleaning, than younger households without children and who work outdoors. Consequently, young to middle-aged households increase their energy consumption. As households age, the children grow up and move out. Household members do not need to work from home after retirement and often go to bed early owing to biology. When they retire, their income is reduced, and they are also motivated to develop energy-saving habits for financial reasons (40). All of these changes reshape the elderly household's energy habitus and reduce its household energy consumption.

Our coal consumption result shows an increasing trend with age over one's life cycle (Fig. 3*C*). The increase in coal use in later years is due to the increasing need for a higher indoor temperature by elderly people to ensure health and comfort (41). In most of our study years (1992 to 2015), clean heating policies that primarily promoted household use of natural gas instead of coal as heating fuel were not widely implemented

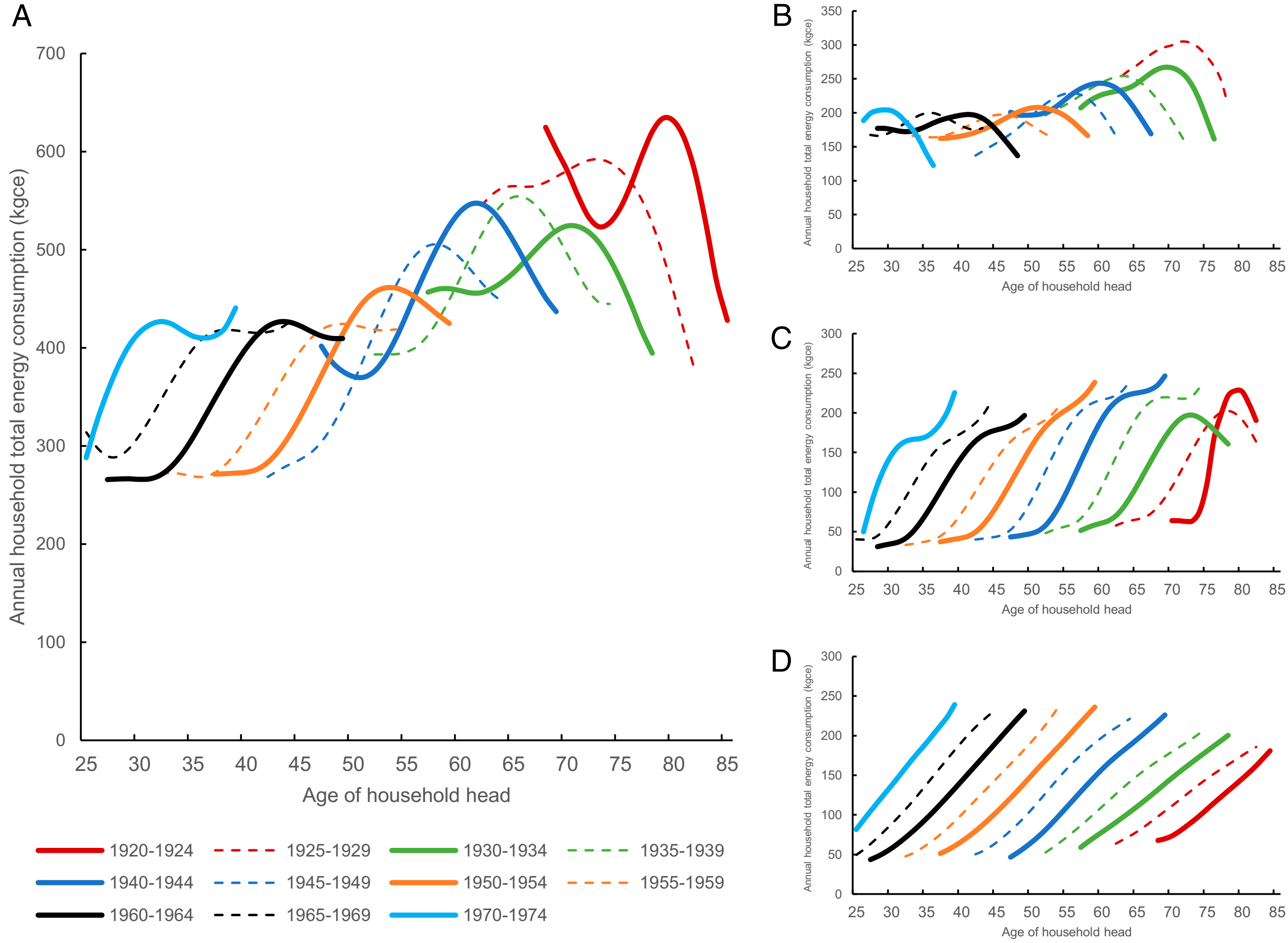

Fig. 2. Energy consumption for life cycle and different generations (unit: kgce). (*A*) Total energy consumption. (*B*) Coal consumption. (*C*) Gas consumption. (*D*) Electricity consumption.

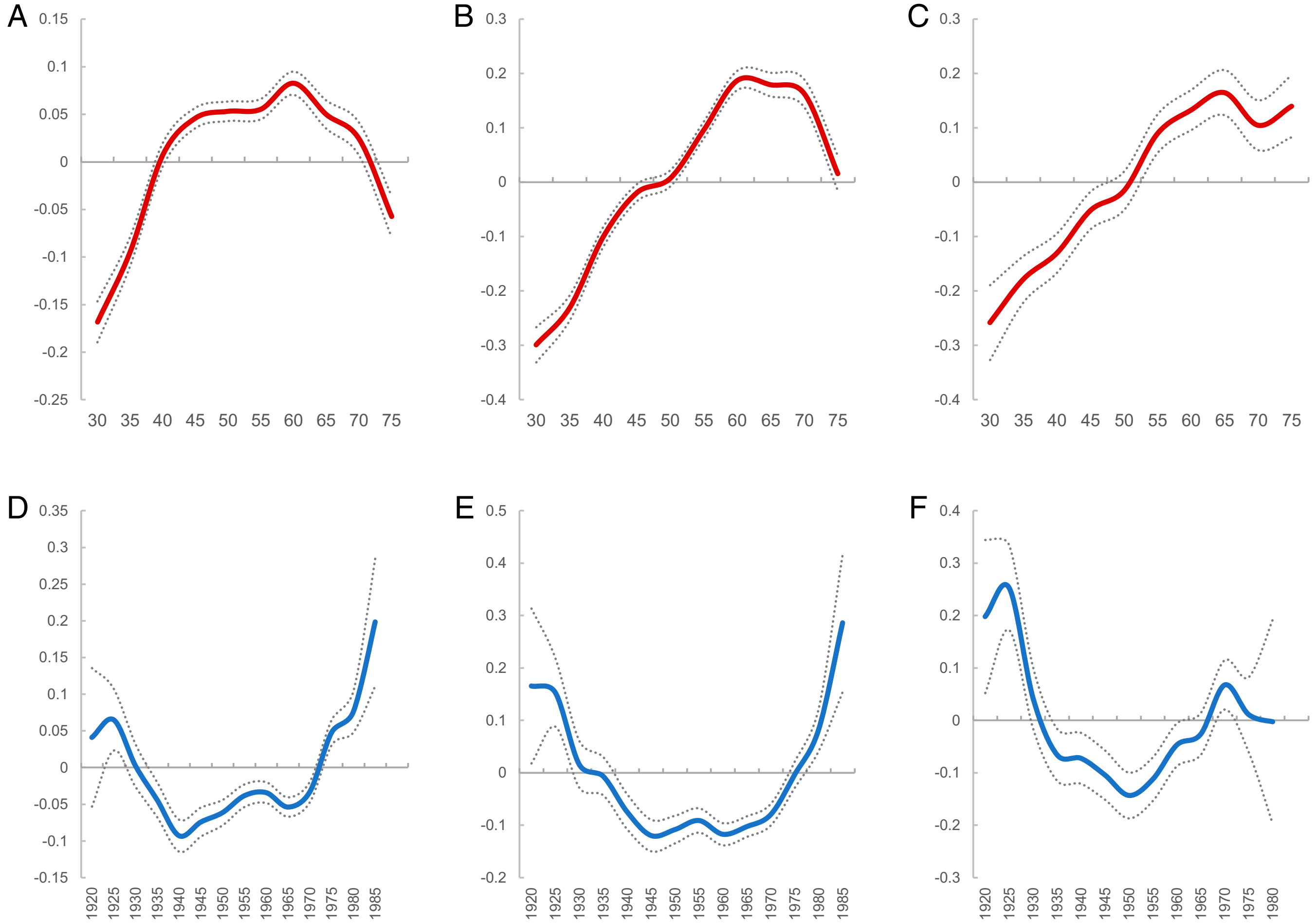

Fig. 3. Estimated results of APC model. (*A*) Age effect of electricity. (*B*) Age effect of gas. (*C*) Age effect of coal. (*D*) Generation effect of electricity. (*E*) Generation effect of gas. (*F*) Generation effect of coal. As the 1985 cohort had fewer than 500 households using coal, we excluded that cohort.

(42). Therefore, during our study period, fire stoves were often the main choice for households to access heating services when district heating systems were not available (43). Because heating fuels could not be distinguished in our data, we consulted previous studies to verify our conclusions. From 1990 to 1995, coal accounted for ∼90% of household terminal heating fuels (44). From 1999 to 2002, the share of coal in urban household energy use declined (including coal, electricity, natural gas, and LPG) but was still the largest (∼46 to 57%) (45). In the early 2010s, the proportion of urban households using coal as heating fuel was 15.6%, which was the third-most common heating method after central heating and electric heating (46). At the end of 2016, decentralized heat using coal as the heating fuel accounted for ∼40% of the urban heating area, whereas only 8% of the urban heating area used natural gas (42). The data provided in the literature showed that coal was the most important fuel for household heating compared to natural gas during our research period. Therefore, as people age, they need more heating services, and the consumption of coal as a primary heating fuel also increases.

Generational Effect

Fig. 3 *D*–*F* shows the estimated generation profile of energy consumption. The solid line shows the estimated generational effects, and the dotted lines indicate the 95% CI. The results indicate that the generation–energy consumption patterns of each energy source exhibited a U-shaped trend, and there were significant differences across generations. Overall, the generations that experienced hardship had a lower propensity for energy consumption than the generations born in the era of great abundance. This result is consistent with the findings of Yang et al. (47) in China. They found that the older generation exhibited more energy-saving behaviors than the younger generation.

More specifically, in this study, the energy consumption propensity of Republican and Consolidation generations exhibited a downward trend as the generation shifted. Pre-1931 Republican generations (before the Second Sino–Japanese War) maintained a relatively high propensity for energy consumption. This may be because they witnessed the “golden age” of the Chinese bourgeoisie, and the bourgeois lifestyle they experienced in their childhood and early adulthood left a deeper imprint on them than the social turmoil they experienced later (48, 49). The energy habitus of the later Republican and Consolidation generations became increasingly frugal as the generation shifted, especially for those who experienced the Second Sino–Japanese War and the Great Famine during childhood.

Relative to their Republican and Consolidation generation peers, Generation X has shown a higher propensity for energy consumption. This is the result of the interaction of their individualistic, materialistic, and hedonistic ideas with the rich materiality of their era. Although Generation X's propensity for energy consumption has increased compared to that of its predecessors, it shows differences across energy sources. Electricity and natural gas consumption increased with generational shifts (Fig. 3 *D* and *E*), whereas the propensity for coal consumption was lower in the Generation X cohort born after 1970 than in the cohort born before 1970 (Fig. 3*F*). This is unsurprising because generations born in the late 1970s and 1980s were exposed to more environmental-related curricula and media coverage about the harms of coal use on health and climate change. Consequently, they were more willing to pay for access to clean energy services and more receptive to new approaches to protecting the environment, forming proenvironmental habits that differed from those of older generations.

Projection

We explored the future impact of urban population aging on China's energy consumption. Fig. 4*A* shows the change in residential energy consumption in those over age 60 y in the coming decades compared to 2015. The results show that energy consumption is projected to increase by 2050, primarily gas and electricity. The change in total consumption caused by demographic transition was 9 million tons of standard coal (Mtce) in 2020, of which the change in electricity and gas consumption accounted for 89%. By 2050, the change in total consumption caused by demographic transition is expected to reach 115 Mtce, with 92% of the change coming from electricity and gas consumption. The increment accounts for ∼17 to 26% of the projected energy consumption in the residential sector in 2050 (50). This quantity is more than the energy consumption of Hungary's residential sector in 2019 (106 Mtce) (22). The overall annual growth rate increases rapidly from 5.7% in 2020 to 10.8% in 2035, stabilizing at around 11% in subsequent years. Small changes in the growth rate after 2035 mean that the impact of population aging on residential energy consumption will gradually weaken. One possible reason for this is that after 2035, the population over the age of 60 y will primarily comprise those born after 1975—a cohort with a small population size that was primarily affected by the family planning policy (51).

Fig. 4*B* shows the contribution of population, household size, and generational effects to changes in residential energy consumption. Compared with 2015, the increase in energy

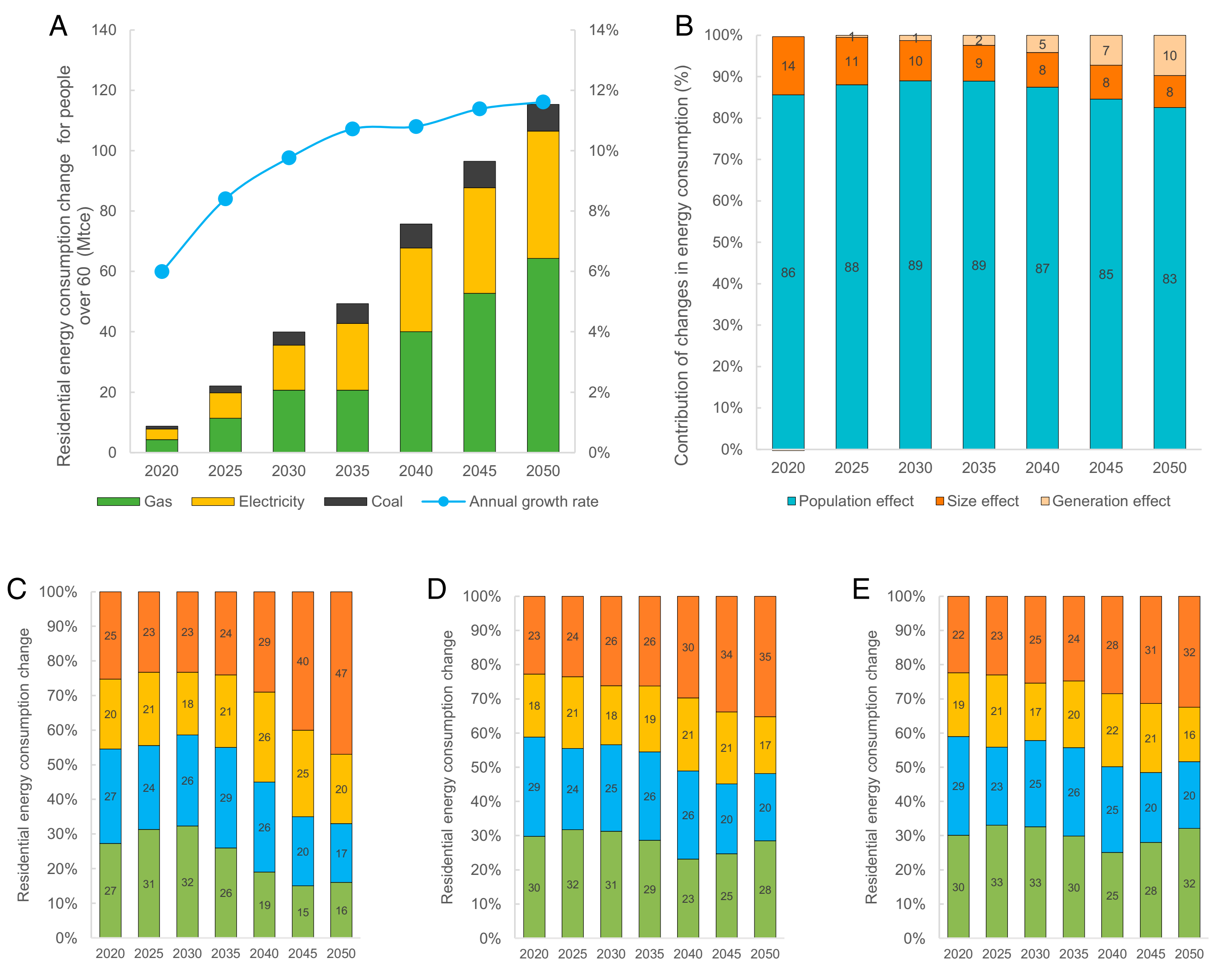

Fig. 4. Projection results. (*A*) Changes in residential energy consumption caused by demographics. (*B*) Contribution of population, household size, and generational effects in projected residential energy consumption. (*C–E*) Projected proportion of changes in residential energy consumption for the elderly across each age group. (*C*) Coal consumption. (*D*) Electricity consumption. (*E*) Gas consumption.

consumption caused by changes in the size of the elderly population accounts for the largest proportion, which is ∼83 to 89% in 2020 to 2050. However, it exhibits a downward trend resulting from future shrinking of this population. The contribution of household size effects is ∼8 to 14%, and it also exhibits a declining trend in the period 2020 to 2050. A possible reason is that the trend of changes in household size will retard annually in the future (*SI Appendix*, Fig. S3), and its impact on household energy consumption will gradually decrease. Conversely, generational shifts will contribute to increases, from less than 1% before 2025 to a positive 10% in 2050. People born before 1965 will be over 60 y old in 2020 to 2025. They experienced the same historical events in the Consolidation Era, and the generational effects are not significant because of their shared subculture. As members of Generation X (1965 to 1980) enter old age sequentially, they will consume more energy than their predecessors, and this effect will increase with generational transitions.

Fig. 4 *C–E* shows the proportion of change in energy consumption caused by each age group. The results show that for 2020 to 2050, with the population aging, the most important contributor to changes in consumption shifts from the 60- to 69-y age group in 2020 to the above 70-y age group in 2050. In Fig. 4*C*, the proportion of changes in coal consumption in the 60- to 69-y age group falls from 54% in 2020 to 33% in 2050. Correspondingly, this proportion for the 70- to 79-y age group increases from 45% in 2020 to 67% in 2050. There is also an increase in natural gas (Fig. 4*D*) and electricity (Fig. 4*E*) consumption caused by changes in the population over the age of 70 y compared with the age group of 60+ y from 2020 to 2050, but the change is smaller than with coal consumption.

Discussion

This study analyzed the impact of China's demographic transition on residential energy consumption and projected the future impact up to 2050. Our analysis indicates that aging and generational shifts can affect household energy consumption by changing the habitus rooted in people's life cycles. The empirical results show that age–electricity and age–gas profiles generally exhibited an inverted U shape. The age–coal profile is an exception, however, as it increased after the age of 60 y. The results of the impact of generational shifts on energy consumption show that there is a U-shaped trend for each energy source. The historical events and specific social backgrounds experienced by a generation shape their generational energy habitus, affecting their energy consumption throughout their life cycle.

To investigate the future impact of age and generational shifts on household energy consumption, we projected changes in residential energy consumption due to demographic transitions. The results show that by 2050, a change in residential energy consumption for the elderly will account for ∼17 to 26% of total energy consumption in the residential sector (50), with ∼115 Mtce, of which population and household size effects explain ∼90 to 95%, but will show a downward trend. Generational effects explain ∼5 to 10% of the change in residential energy consumption and show an increasing trend. Note that by 2050, the generational effect will exceed the effects of household size and become the second-largest demographic factor affecting household energy consumption.

One caveat is that our projection of the impact of demographic transitions on household energy consumption relies on future urban population trends. In the field of social trends involving human behavior, the future can never be projected with certainty. In our multistate model for population projection, all three components of population change (i.e., future fertility, mortality, and migration trends) are uncertain. Changes in each of these components could lead to uncertainty in our results. For fertility rate, we adopted a low total fertility rate without considering the two- and three-child policies, which may result in an underestimation of household size and thus an overestimation of the number of households and total household energy consumption. For mortality, our settings are conservative and do not consider the impact of future disruptive medical innovations on life expectancy, which may result in underestimation of the aging population and associated energy consumption. For migration trends, we assumed that rural-to-urban migration would decline in the coming decades, which is supported by the literature (52, 53), but uncertainty remains about the setting of the decline rate. This creates uncertainty in the annual urban population size projection, affecting corresponding energy consumption.

Although there is some uncertainty about our specific results, the findings allow us to share insights into household energy consumption in China from a demographic perspective. First, generational shifts may result in a significant increase in energy consumption by Chinese households in the future. Environmental education methods and policies therefore need to be developed to guide the younger generation to adopt new sustainable ideas, shape positive environmental values, foster environmentally friendly behaviors, and reduce energy consumption. Second, population aging will increase Chinese energy demand in the future. Improved energy efficiency policies for the elderly are needed in an aging society. For example, policies that promote the trade-in of old appliances in elderly households and efficient technology could be introduced. Finally, demographic policies may indirectly impact energy consumption. Thus, attention should be paid to China's upcoming new retirement policy, which will likely affect energy consumption of elderly households by affecting household income and lifestyle.

Materials and Methods

Dataset and Cohort Construction. In this study, we accessed a large sample of 412,050 observations in 18 provinces from the China Urban Household Survey (CUHS) dataset for the period 1992 to 2015. The CUHS survey is conducted by the National Bureau of Statistics of China to monitor dynamic changes in the living conditions of urban households (54). It provides China's most representative urban household data, with extensive geographic coverage and the longest duration. CUHS obtains data through the bookkeeping method, and survey respondents include all family members. The CUHS data provide detailed information on demographic characteristics, housing situation, household income, and expenditures. In the expenditures information, the expenditure amount and quantity information of household energy consumption, such as electricity, coal, and natural gas, are recorded in detail.

We used CUHS data incorporating household energy consumption, personal information on the household head, and household characteristics (*SI Appendix*, Table S1 provides more details). We processed the dataset as follows. For energy consumption data, if both usage and expenditures on a specific type of energy were missing, we replaced it with "0" because we considered that the household did not use this type of energy. If only the usage was missing, we filled in the missing value based on the consumption of households in the same region with similar energy expenditures. We used conversion factors to convert each energy source into a standard quantity and then summed them to calculate the household's total energy consumption (*SI Appendix*, Table S2 describes the conversion factors). For households with unidentifiable household heads, we chose the middle-aged male with the highest income as the head of the household. To capture the impact of temperature on energy consumption, we collected weather data from the National Oceanic and Atmospheric Administration and merged them with the CUHS data based on geographic information. We calculated the heating and cooling degree days (HDDs and CDDs), which is a measure of how cold or hot the temperature is over several days. The base temperature for HDDs was set at 18 °C, and for CDDs at 26 °C (55). Moreover, all monetary variables were deflated to the 2015 constant price. *SI Appendix*, Table S3 presents the mean values of the variables used in this study.

We grouped households based on the age of the household head and tracked the cohorts over time, with cohorts defined by date of birth. To construct the cohort dataset, we performed the following steps. First, we included only those households whose head was between 30 and 80 y old. The youngest and oldest observations were excluded to avoid sample selection problems caused by small sample sizes. Second, to avoid extreme outliers that could affect outcomes, we excluded the highest and lowest 1% of the observations. Third, we set the bandwidth to 5 y to calculate cohort means, which is the most common setting in the literature for trade-off between the number of observations per cohort and intracohort heterogeneity (54). We grouped observations into 14 five-year birth cohorts for our analyses through this procedure. In our sample, the oldest cohort member was born in 1920, and the youngest was born in 1985. The data structure is listed in *SI Appendix*, Table S4.

Empirical Strategy. APC analysis was used to estimate the age effect (α_a) and generational effect (namely, cohort effect) (β_c) on energy consumption. The empirical model is as follows:

$$y_i^{apc} = \mu + \alpha_a + \beta_c + \gamma_p + BX_i + \varepsilon_i, \quad [6]$$

where y_i^{apc} is the energy consumption of household i, γ_p is the period effect, and $\boldsymbol{X_i}$ is a set of control variables.

APC analysis is widely used in the socioeconomic literature. However, there is an underlying predicament, the "identification problem." Age (a), period (p), and cohort (c) are completely collinear, which is derived from the equation $c = p - a$. In Eq. **6**, the collinearity between regressors α_a, β_c, and γ_p implies that the model does not have a unique solution and cannot be identified (56). Previous studies have solved the identification problem by imposing special restrictions on the model, including the APC intrinsic estimator, hierarchical APC, and APC-detrended (APCD) models. Among these methods, the APCD model separates linear and nonlinear trends for cohort, age, and period effects. The linear trends in age, period, and cohort cannot be identified because of the collinearity. Thus, the linear trend part of the model can be considered a blank linear parameter. The detrended age and cohort effect can be identified (57). The identification strategy of the APCD model is consistent with our study. Our study needed to identify age and cohort effects that were not affected by social progress but only related to their intrinsic properties. The APCD model used in this study can be expressed as follows (57):

$$\begin{cases} y_i^{apc} = \mu + \alpha_a + \beta_c + \gamma_p + \alpha_0 rescale(a) + \beta_0 rescale(c) + BX_i + \varepsilon_i \\ \begin{cases} \sum_a \alpha_a = \sum_c \beta_c = \sum_p \gamma_p = 0 \\ slope_a(\alpha_a) = slope_c(\beta_c) = slope_p(\gamma_p) = 0\,, \\ p = c + a \text{ and } \min(c) < c < \max(c) \end{cases} \end{cases} \quad [7]$$

where y_i^{apc} is the energy consumption of household i and μ is a constant term. α_a denotes the age effect vector indexed by age group a, β_c is the cohort vector, and γ_p is the period vector. These vectors are detrended as two sets of constraints are assigned. $\sum_a \alpha_a = \sum_c \beta_c = \sum_p \gamma_p = 0$ implies that the coefficients are centered, and the *slope* is a linear function that gives the linear slope of the regression coefficients. The terms $\alpha_0 rescale(a)$ and $\beta_0 rescale(c)$ absorb linear trends. *rescale* is a transformation that standardizes the age and generation from minimum to maximum to the interval -1 to $+1$. $\boldsymbol{B}$ is a set of coefficients of the control variables $\boldsymbol{X_i}$. Finally, $\min(c) < c < \max(c)$ denotes that the oldest cohort in the first survey and the youngest cohort in the last survey are excluded from the model to obtain more stable estimates.

This study estimated the influence of age and generational effects on energy consumption using the *apcd* module in Stata (58). Considering other energy consumption drivers, we controlled a set of variables, including family income, educational level of the head of the household, family size, housing area, and HDDs and CDDs at the regional level.

Projection Setup. We projected the impact of population aging on energy consumption by accounting for population changes, generational shifts, and changes in household size in urban China. First, we know that energy consumption by the elderly can be calculated as follows:

$$E_t = \sum_{a=1,\,\ldots,\,4} q_{a,t} \times HH_{a,t} \quad [8]$$

where E_t is the total energy consumption in year t for the elderly population. $a = 1, \ldots, 4$ represents four groups for the elderly: 60 to 64 y, 65 to 69 y, 70 to 74 y, and above 75 y. $t = 2020, 2025, \ldots, 2050$. $q_{a,t}$ is the average energy consumption by age group a in year t. $HH_{a,t}$ is the household number in year t for age group a.

Second, the household size by age group can be calculated using the following equation:

$$HH_{a,t} = \frac{Pop_{a,t}}{N_{a,t}} \quad [9]$$

where $Pop_{a,t}$ is the total population for age group a in year t, and $N_{a,t}$ is the household size for age group a in year t. The projected results for household size and age-specific population are shown in *SI Appendix*, Figs. S3 and S4. The projected methods are detailed in *SI Appendix, SI Text*.

Third, we assumed that the potential average energy consumption for each age group was q^* but the real energy consumption for different age groups was affected by their age and their generational culture. Therefore, the energy consumption of households for a specific age group at period t was calculated as follows:

$$q_{a,t} = q_t^* \times \alpha_a \times \beta_{t-a_{age}}, \quad [10]$$

where the symbol $q_{a,t}$ is potential average energy consumption for each age group in year t. If we assume that the period effect is γ_t, then $q_t^* = q^* \times \gamma_t$. The symbol α_a is the age effect for age group a, which measures the consumption affected by psychological or biological factors. The symbol $\beta_{t-a_{age}}$ is the generational effect for the generation born on $t - a_{age}$. Note that $\beta_{t-a_{age}}$ measures the consumption because of the habitus affected by different generational cultures.

According to Eqs. **9** and **10**, Eq. **8** can be reorganized to give Eq. **11**:

$$E_t = \sum_{a=1\ldots4} \left(\frac{Pop_{a,t}}{N_{a,t}} \times \alpha_a \times \beta_{t-a_{age}} \times q^* \times \gamma_t \right). \quad [11]$$

We chose 2015 as the base year. The potential average energy consumption of each age group in 2015 is $q_{2015}^* = q^* \times \gamma_{2015}$. We did not consider the impact of future social development on energy consumption, so the period effect is assumed to be the same as the base year. Thus, Eq. **11** can be rewritten as follows:

$$E_t = \sum_{a=1\ldots4} \left(\frac{Pop_{a,t}}{N_{a,t}} \times \alpha_a \times \beta_{t-a_{age}} \times q_{2015}^* \right), \quad [12]$$

where $Pop_{a,t}/N_{a,t}$ is the household number in each age group, which is affected by population and household size, and α_a and $\beta_{t-a_{age}}$ are age and generational effects, respectively, which can be obtained based on the estimated results.

Subsequently, changes in total energy consumption resulting from population aging can be calculated by summing the changes in energy consumption for each age group. The specific equation is as follows:

$$\Delta E_t = \sum_{a=1\ldots4} \Delta E_{a,t} = \sum_{a=1\ldots4} \left(\frac{Pop_{a,t} - Pop_{a,2015}}{Pop_{a,2015}} - \frac{N_{a,t} - N_{a,2015}}{N_{a,2015}} + \frac{\beta_{a,t} - \beta_{a,2015}}{\beta_{a,2015}} \right) \times E_{a,2015}, \quad [13]$$

where ΔE_t denotes changes in total energy consumption compared to 2015, $\Delta E_{a,t}$ denotes changes in energy consumption for age group a in year t compared to the base year, $(Pop_{a,t} - Pop_{a,2015})/Pop_{a,2015}$ and $(N_{a,t} - N_{a,2015})/N_{a,2015}$ are the rates of change in the total population and household size for age group a in year t, respectively, and $(\beta_{a,t} - \beta_{a,2015})/\beta_{a,2015}$ denotes the rate changes of the impact of generational effects on energy consumption.

Data, Materials, and Software Availability. All study data are included in the article and/or *SI Appendix*. The CUHS is collected and managed by the National Bureau of Statistics of China. For academic purposes, researchers can apply for access to the data at http://www.tcdc.sem.tsinghua.edu.cn (59). The data statement, data for figure/table, and code for APCD model analysis have been deposited and are available at https://github.com/hxhjhy/Aging-generational-shifts-and-energy-consumption-in-urban-China (60).

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