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The ongoing demographic transition, entailing changes in population size, age structure, household composition, regional distribution, migration and so on, has become a worldwide issue affecting developed and developing countries alike[1,2].

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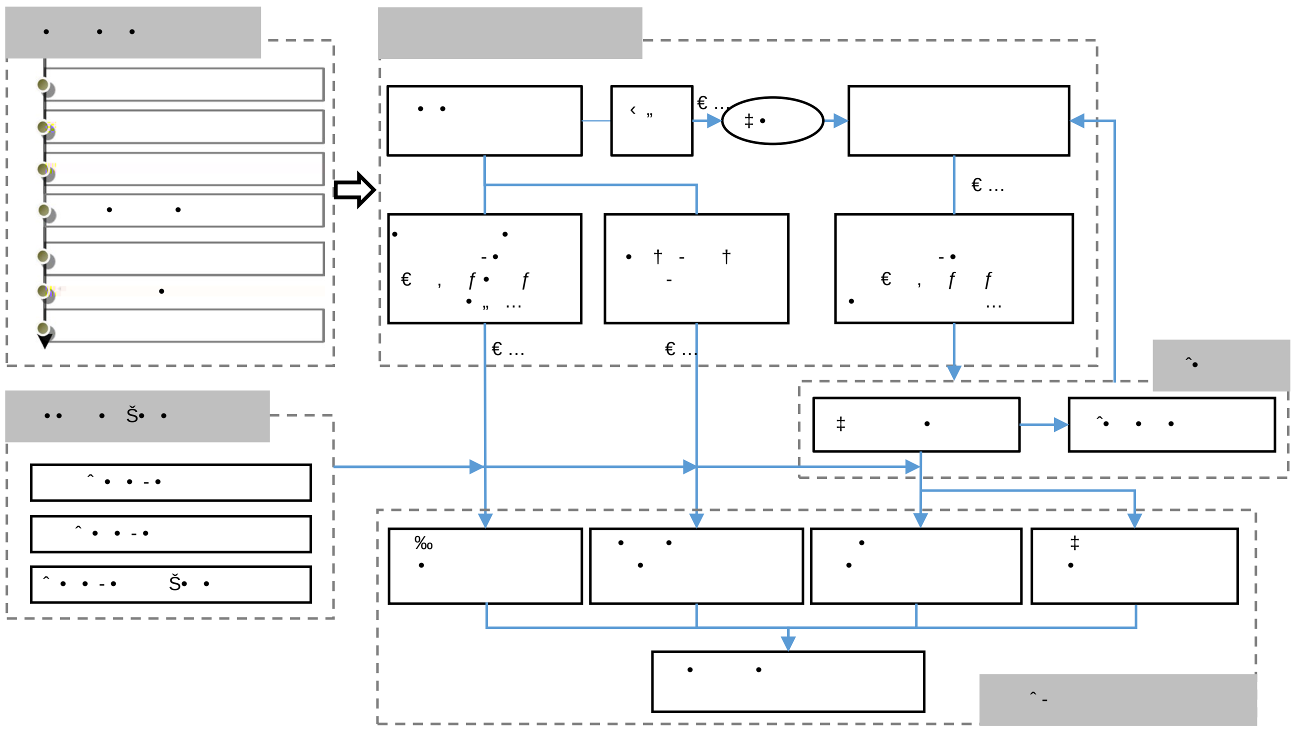


Fig. 1 | Analytical mechanism for demographic transition, lifestyle and environmental outputs. Households in different life stages have distinctive time-use and consumption patterns. Considering that people affect human society and the natural environment through both their consumptive and productive behaviour, which is specific across different life stages, three types of path from demographic transition (DT) to carbon emissions are considered in this study: (1) DT → Consumption pattern shift → Industrial production → Emissions, which considers the impact of consumption pattern shift triggered by demographic transition on industrial production and then emissions; (2) DT → Work time and labour force → Income → Consumption and value added → Industrial production → Emissions, which considers the impact of labour supply on consumption and industrial outputs by considering the labour-force change due to demographic transition, as well as a change in the number of working hours due to time-use pattern shift; and (3) DT → Non-work time → Energy services → Emissions, which considers the impact of time spent on in-home emission-related activities and travel activities. The final environmental outputs of energy consumption and emissions are derived by displaying the joint effects of population composition change, household time-use and consumption patterns (that is, lifestyle) shift, technological development and economic growth.

families will substantially change the overall use of time and money in society and thereby affect the carbon emissions.

To address the above concerns and limitations, here we conduct a comprehensive bottom-up analysis that couples population-composition change, household time-use and consumption pattern (that is, lifestyle) shifts, technological development, economic growth and environmental consequences all together in a systematic framework. Figure 1 depicts the analytical mechanisms at work for evaluating how demographic shifts to urbanization and small and ageing households impact energy consumption and carbon emissions, in which the behavioural evolution in the life cycle is emphasized. This analysis has been enabled by the recent release of the only large-scale time-use survey data in China[33]. Drawing on the rich individual time-use data and the inferred household expenditure information, special attention is paid to the inter-life-stage and intra-life-stage variations of household time-use and consumption patterns to deepen our understanding of the underlying link (that is, human behaviour) between demographic transition and the generation of carbon emissions.

Demographic composition and lifestyle in China

China is a country with substantial regional differences in economic development, technology, energy mix and demographic composition[34]. To better understand the patterns of working and living in the Chinese population, the National Bureau of Statistics of China conducted the first large-scale China Time Use Survey (CTUS)[33] in 2008, covering ten provinces with various economic levels and geographical locations (Fig. 2a). Valid answers were collected from 37,142 individuals with ages between 15 and 74 in 16,616 households.

The CTUS data identify that individuals in different age, household and income groups have unique time-use patterns. A shift over a life cycle will cause substantial trade-offs in the time allocated to work, home, leisure and transportation as people age (Fig. 2c–f), accompanied by increases in household production, leisure and in-home activity time; changes in paid-work time and travel time follow a bell-shape curve. The elderly spend less time outside the home, indicating that an ageing society is likely to have higher domestic energy consumption, ceteris paribus. However, this change may be offset by the increasing number of small-sized households, leading to an unknown aggregate time-use pattern in the future. Moreover, household income levels play a significant role in shaping the time-use and consumption pattern (Fig. 2b,f). For example, paid-work time is longer for high-income populations and the shares of expenditure on transportation; communication; and education, culture and recreation increase as the income grows. These are in line with the evidence found in other contexts (for example, the United Kingdom and the United States)[35]. Given the key impacts of activity types and the duration of each activity on energy use, and income as well as the impact of private consumption amounts and structure on industrial production, we can plausibly surmise that future carbon emissions will go through a period of substantial adjustment with economic development, urbanization and demographic transitions to smaller and ageing families. The direction of the switch

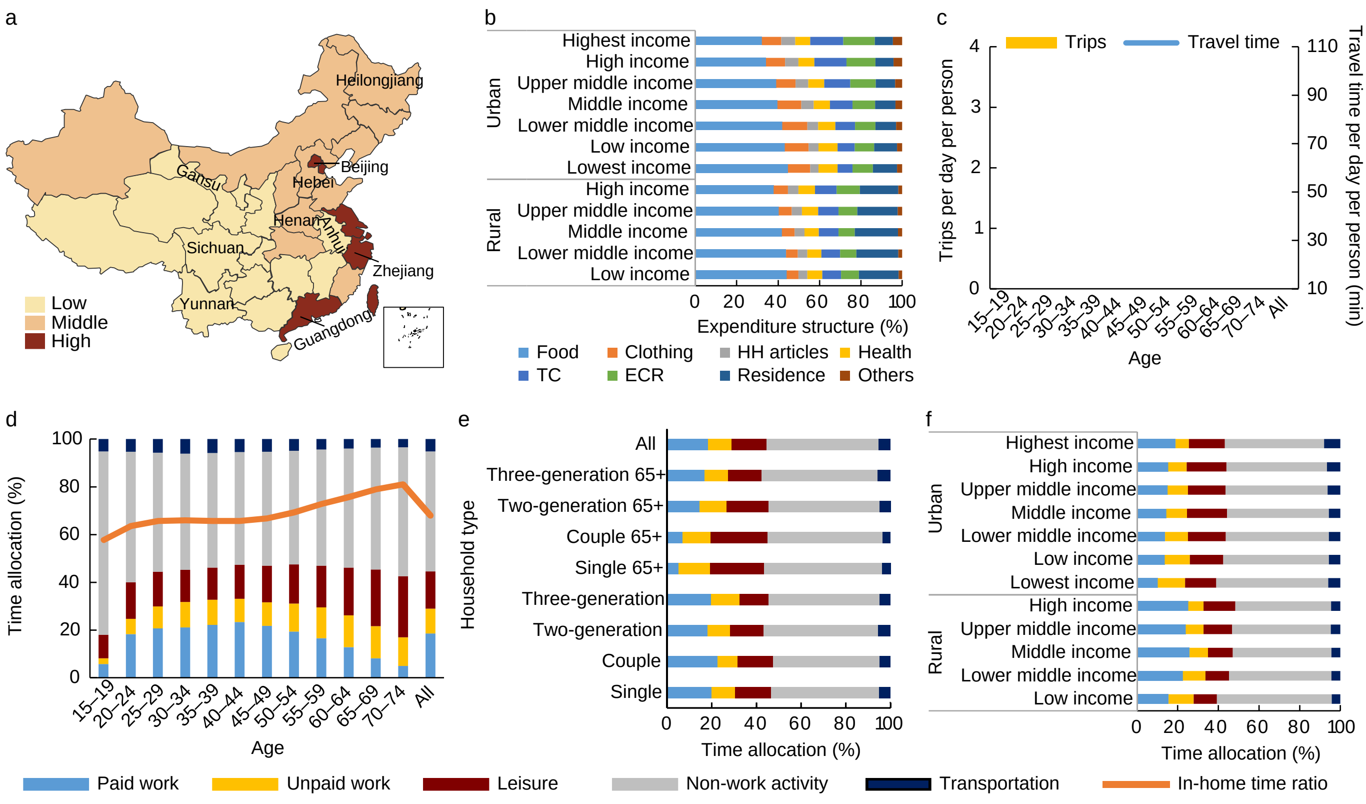


Fig. 2 | Chinese time-use pattern and consumption pattern. **a**, Provincial economic development level indicated by GDP per capita in 2008 (low: GDP per capita ≤ US$3,000; middle: US$3,000 < GDP per capita ≤ US$5,000; high: GDP per capita > US$5,000). The data show that approximately half of the provinces in China are much less developed as indicated by the GDP per capita values, which are lower than the national average (US$3,000). Ten of the provinces surveyed in the 2008 CTUS are labelled with their names. **b**–**f**, The consumption pattern by income level (**b**), and time-use pattern by age (**c**,**d**), by household type (**e**) and by income level (**f**). The consumption pattern in **b** is explained using the indices of household expenditure per capita, which includes expenditure on: food; clothing; household articles (HH articles); health; transport and communication (TC); education, culture and recreation (ECR); residence; and other goods and services (Others). See Supplementary Table 1 for the classification of paid work, unpaid work, leisure, non-work activity and transportation in **d**–**f**. The in-home time ratio in **d** represents the percentage of time spent at home in 24 h. Panel **a** is made based on the GDP per capita data for China[57]. Panels **b**–**f** are based on CTUS data[33].

(more sustainable or less sustainable), however, remains unknown, which is the main question we will answer in this study.

Lifestyle change may be more significant for less developed regions in the future, which may result in greater influences on the environment. On this basis, Sichuan province in China was selected for the empirical phase of this study; it is a typical province in a primary stage of development with a large gap between its rural and urban populations and wide-scale migration aggravating its demographic transition. The base year and target year here are set to 2009 and 2030, respectively.

Intuitively, individuals or households are likely to take one of four possible routes (or scenarios) in the future, which plot the trajectories of intra-life-stage and inter-life-stage variations (Fig. 3a), described as follows. In scenario S1, individuals/households retain the same household type (that is, no movement to the next life stage) and lifestyle up to the target year, with no change from the base year; neither intra-life-stage variation nor inter-life-stage variation occurs (lifestyle and demographic composition remains the same as in 2009). In scenario S2, individuals/households change their lifestyle due to the new economic and social environments (for example, telecommuting, using maid services or childcare services instead of performing the task themselves), but keep the same household structure; only intra-life-stage variation occurs (lifestyle shifts but demographic composition remains the same as in 2009). In scenario S3, individuals/households move to the next life stage (for example, get married or have children) and adopt the base-year lifestyle for that household type in the future; only inter-life-stage variation occurs (demographic composition transitions but lifestyle remains the same as in 2009). In scenario S4, individuals/households move to the next life stage and adopt a new lifestyle; both intra-life-stage variation and inter-life-stage variation occur (both lifestyle and demographic-composition change).

As future lifestyle is decided by future needs, preferences and socio-demographic and economic factors that are difficult to predict, we assume that those individuals and households who will undergo a change in lifestyle will follow the time-use patterns and consumption patterns manifested by households of the same structure and income level in developed provinces. It is surmised that future lifestyle change in less developed provinces (that is, with lower gross domestic product (GDP) per capita) will mimic the patterns observed in developed provinces (that is, with higher GDP per capita) and the trends shown in Fig. 2 and Supplementary Fig. 1 support this assumption. It is useful to consider what would happen if individuals/households in poor provinces turn to the lifestyle of people in the developed provinces. Consequently, the lifestyle in 2030 for Sichuan residents corresponding to the four scenarios presented above is portrayed in Fig. 3. If a time-use pattern shift occurs, the time-use pattern in Sichuan in 2030 is designed by referring to the patterns in three developed provinces in China; otherwise, it would maintain the pattern in the base year. The future consumption pattern is inferred on the basis of household income, consumption structure and labour supply in the future (see Fig. 3

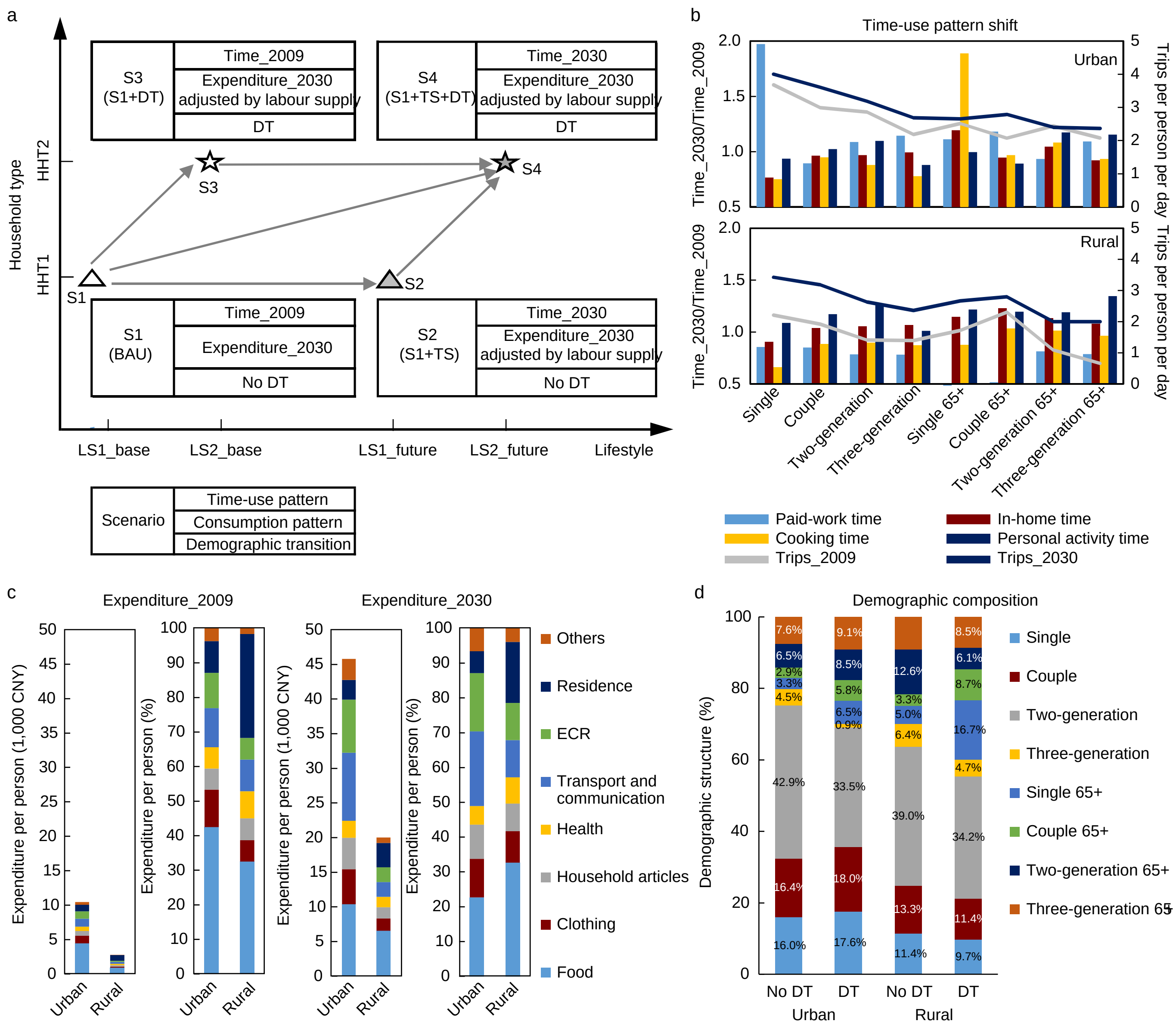
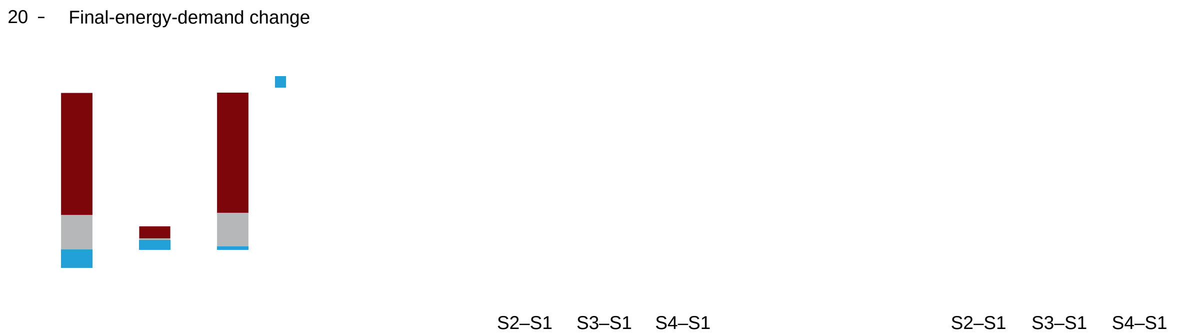


Fig. 3 | Four scenarios of future society in Sichuan. **a**, Four scenarios (routes) of the potential change of household type and lifestyle. DT, demographic transition; TS, time-use pattern shift; LS_base: lifestyle in the base year; LS_future: lifestyle in future; HHT: household type. **b**, Time-use pattern shift indicated by the ratio of Time_2030 and Time_2009, with 1 meaning no shift (Time_2009 is the annual household hours per person for specific activities in 2009, and similarly for Time_2030). **c**, Consumption patterns. **d**, Demographic composition. Time_2030 is quantified by averaging the activity time of residents in Beijing, Zhejiang and Guangdong provinces, as indicated in the CTUS data. Expenditure_2030 is estimated by future household income, the share of expenditure in income, and the share of sub-category expenditures in total expenditure for the relevant income group. The results are shown in Supplementary Fig. 1. Scenario S1 is set as the business-as-usual (BAU) case. The consumption patterns in S2–S4 are the results of adjusting Expenditure_2030 according to the changing labour force and working hours (see Supplementary Fig. 2 for the process). DT indicates that the proportion of the population in different life stages will change, indicating that some of the households will move to the next life stages and the demographic structure will change. No DT in **a** and **d** indicates the demographic composition remaining the same as that in 2009, and DT indicates that the proportion of small and ageing households will increase. 65 in **b** and **d** indicates households with elders aged 65 .

and the Household consumption patterns section in the Methods for details). The demographic composition in the future is assumed following the population projection and the situation in China if demographic transitions occur (see the Data and assumptions for demographic composition section in the Methods for details).

Regarding the lifestyle in S1 and S3, the future time-use pattern for each population group is designed to be unchanged from the base year (Time_2009). S2 and S4 describe the changes in activity pattern (Time_2030). Compared with S1 and S2, the shifts in the population composition by household type in S3 and S4 will produce shifts in the overall time and the aggregate mix of goods demanded attributable to the inter-life-stage variance of lifestyle. Figure 3b shows that the majority of rural households will reduce their paid-work time and cooking time, but increase their in-home personal-care time. Urban households without elders of 65 , especially singles, will work longer, and stay at home and cook at home less. Conversely, single elders will cook more and stay at home longer. The changing work time is likely to influence productive activities, which might lead to different household income and, subsequently, different consumption patterns. The increasing non-work activity time might cause extra energy demand for the corresponding energy services, but the extra demand might be neutralized by the decrease in energy demand due to the switchover to activities that require less time. The activity pattern shift increases the number of trips, especially for rural residents. More trips will be taken by single-person and couple households (Fig. 3b).

As is demonstrated in developed countries and is the current trend in China, ageing households and small households (single-person or couple households) will increase rapidly in the future despite the implementation of the two-child policy in China[36]. In anticipation of this trend, the assumptions for the future demographic composition in the scenarios with demographic transition are proposed in Fig. 3d. The Data and assumptions for demographic composition section in the Methods and Supplementary Table 2 depict the process of demographic projection, as well as the populaa



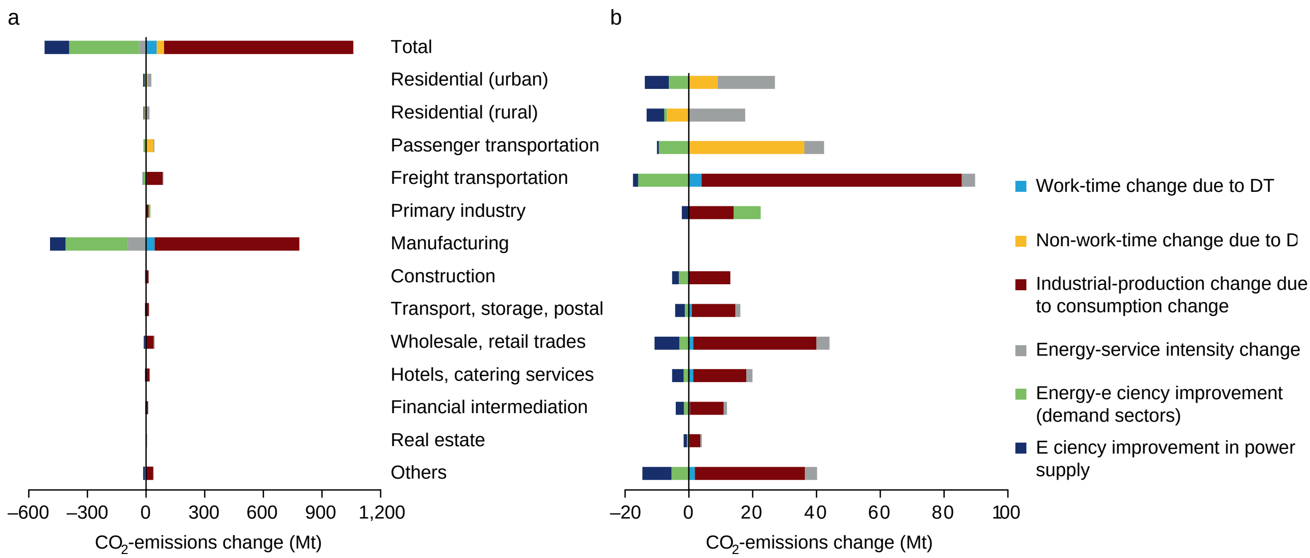


Fig. 5 | Decomposition of CO_2 emissions increase in scenario S4 in contrast to the base year 2009 for Sichuan. a,**b**, The decomposition results of all sectors (**a**) and a zoom-in of sectors without manufacturing industry (**b**). The contribution of factors to CO_2 emissions increase in S4 compared with the base year is shown here, including the time-use pattern shift accompanying the demographic transition (work-time change and non-work-time change due to DT), economic development (industrial-production change due to consumption change), energy-service intensity change, and technology improvement (energy efficiency improvement in energy demand sectors and efficiency improvement in power supply).

resulting from substantial variations in the patterns of time-use and consumption for households in different life stages and within the same stages. Given that Sichuan utilizes more hydropower than other regions of China, the future energy situation for the less-developed provinces that rely mainly on coal-fired power may be more critical.

Taking the lifestyle shifts that accompany the demographic transition into account (scenario S4), the population shift to small-family and ageing society in Sichuan is likely to increase primary energy demand by another 18 Mtce and CO_2 emissions by another 35 Mt, approximately 4.3% of the total energy demand and CO_2 emissions in 2030. The incremental carbon emissions increase mainly arises from the increasing service demand for heating, cooking, hot water and road passenger transport, as well as the increasing consumption of goods and services from the manufacturing industry, hotel and catering service industry, and other industries such as health care, culture, education and recreational service industries. This finding highlights a considerable opportunity to control the future emissions in the less-developed regions in China by focusing on a small number of sectors and services where more energy-efficiency technologies can be installed or supplementary policies can be initiated.

Expanding on the existing literature, our model explicitly emphasizes and incorporates the effect of time spent on productive and consumptive activities, as well as the monetary effect. Our empirical results indicate that in S4, between 2009 and 2030, another 97 Mt of CO_2 emissions (12% of total emissions in 2030) will be generated, which are attributed to the changing work time and non-work time with the demographic transition. In addition, among the impacts of population shift on emissions, 93% arises from changing time-use patterns. This suggests that time-use patterns have a non-negligible impact on carbon emissions, and that inaccurate pictures of emissions change will be drawn if the time effect is disregarded. This finding reminds us of the need to more deeply consider the implications of time use in environmental analysis.

The above results form a firm basis for discussing several factors. First, how population policies (for example, pro-natalist policy) can influence climate change mitigation and adaptation. Second, the type of supplementary policies required to limit the environmental consequences of a small and ageing household society (for example, promotion of efficient technology, car ownership restraint and efficiency standards for industrial production). Finally, how policies or businesses associated with people's time-use patterns (for example, the Internet era, telecommuting, e-shopping, measures to improve the work–life balance, increasing density of facilities in neighbourhoods, and prevalence of home services) and consumption patterns (for example, prices, taxes, information provision, and product ranking systems) shape the outline of energy demand and carbon emissions in a broader context.

Our study adds to the description of heterogeneous lifestyles in the population when evaluating the environmental consequences of demographic transitions, but is limited in terms of describing the mechanisms behind the phenomenon. Specifically, factors shaping time-use and consumption patterns should be given more attention[37]. How these translate to 2030 and beyond is highly uncertain. For example, it remains unclear how people will choose and demand technology in the future, how technology will change their time allocation and consumption, and how households' response to policy affects emissions[38]. In addition, time-use patterns and consumption patterns mutually frame each other[39–43]. Here, we consider only the link between time and money through changing income. However, substitution always occurs between them as the value of time increases. In this sense, further efforts should be made to explore such behavioural mechanisms and incorporate them into the population–economy–environment analytical structure to instruct policymakers on the design and evaluation of a more comprehensive policy scheme. Developing alternative demographic scenarios may also assist readers in understanding the results.

Methods

Framework of the Extended Snapshot tool. We apply the methodological framework of the Extended Snapshot (ExSS) tool here to systematically account for the interactions between economic growth, technological changes, population dynamics and lifestyle (Supplementary Fig. 4). ExSS is a bottom-up engineering model covering all of the activities in the relevant energy-consuming sectors. ExSS accounts for the driving forces of each activity as inputs and provides the environmental consequences from those activities as outputs.

Building on the original ExSS[44], we replaced the 'representative household' assumption with a classification of households and population based on a set of household structures, each with its own consumption pattern and activity pattern. The impacts of demographic transition on carbon emissions through lifestyle are portrayed from three aspects in the improved ExSS: the impact of consumption pattern shift triggered by income growth on industrial production and then emissions; the impact of labour supply on consumption and industrial outputs by considering the labour-force change due to demographic transition, as well as a change in the number of working hours due to time-use pattern shift; and the impact of time spent on in-home emission-related activities and travel activities. These three aspects take into account that people affect human society and the natural environment through both their consumptive and productive behaviour that is specific across different life stages. See Supplementary Fig. 4 for a schematic of the improved ExSS tool. The mathematical equations can be grouped into four parts: demographic-composition estimation; link between demographic composition, time use and labour supply; link between labour supply and economic structure; and energy-demand estimation.

Demographic-composition estimation in ExSS. The number of households in different life stages is calculated on the basis of population and household shares, as shown in equations (1) and (2).

$$HHD_{hht} \quad Pop \quad Pop\ share_{hht} \quad HHsize_{hht} \tag{1}$$

$$Pop\ share_{hht} \quad (HHshare_{hht} \quad HHsize_{hht}) \quad \underset{hht}{} (HHshare_{hht} \quad HHsize_{hht}) \tag{2}$$

where HHD_{hht} is the number of households by household type hht; Pop is the total population, which is 81.9 million people in 2009, and 85 million people in 2030; $Pop\ share_{hht}$ is the share of population belonging to household type hht; $HHsize_{hht}$ is the average household size for household type hht obtained from the survey data; and $HHshare_{hht}$ is the share of household type hht, which denotes the demographic composition.

Link between demographic composition, time use and labour supply in ExSS. Labour supply is described by the number of the population in employment at different life stages and their specific working hours in equation (3). As populations at different life stages have diverse employment and working hours, demographic transition is likely to cause a labour-supply change in the whole society.

$$LS_{Urban,Rural} \quad \underset{Urban,Rural}{} \quad HHD_{hht} \quad HHwork_{hht} \quad AWH_{hht} \tag{3}$$

where $LS_{Urban,Rural}$ is the total number of hours labourers spend at work distinguished by urban and rural; $HHwork_{hht}$ is the average number of members in employment in the household by type hht; AWH_{hht} is annual working hours per worker belonging to household type hht.

Link between labour supply and economic structure in ExSS. Labour supply is further linked with the economic system by reflecting the total-wage change in input–output analysis.

$$Wage \quad \underset{Urban,Rural}{} \quad LS_{Urban,Rural} \quad WR_{Urban,Rural} \tag{4}$$

$$FDtot_{pc} \quad Wage \quad CR \tag{5}$$

$$FD_{pc,ids} \quad FDtot_{pc} \quad SPC_{ids} \tag{6}$$

(Here we omit the process of input–output analysis.)

$$Wage \quad \underset{ids}{} \quad IO_{wage,ids} \tag{7}$$

Here, Wage is defined as total annual wage for all of the labour force, which needs to be equivalent to the total wage of all industries in the input–output table; $WR_{Urban,Rural}$ is the wage rate per working hour distinguished by urban or rural; $FDtot_{pc}$ is the total private consumption (pc) in the final demand in the input–output table; CR is the proportion of consumption in the total wage; $FD_{pc,ids}$ is the amount of private consumption for the industrial sector (ids) in the final demand; SPC_{ids} is the share of private consumption for the industrial sector (ids); $IO_{wage,ids}$ is the wage of industry (ids) obtained from input–output analysis.

According to the input–output analysis, the industrial structure can be derived under the constraint that the total wage of all industries equals the wage obtained through the labour supply and wage rates.

Energy-demand estimation in ExSS. In general, energy demand $ED_{eds,esv,f}$ in ExSS is calculated following equation (8)[45], but with extensive calculation for each index (equation (9)):

$$ED_{eds,esv,f} \quad ESVD_{eds,esv} \quad FS_{eds,esv,f} \quad EI_{eds,esv,f} \tag{8}$$

where eds is energy-demand sector, esv is energy-service type and f is fuel type. Energy service demand $ESVD_{eds,esv}$ is a function of driving force $DF_{eds,esv}$, which is distinguished by energy service esv and energy sector eds (see equation (9)). In the residential and road passenger transport sectors, time spent on energy-consuming activities or travel trips are thought to be another crucial factor for determining the energy service and energy demand in addition to the number of households. Consequently, the composite variable of total household activity time or trips is regarded as the driving force in the household sector. $FS_{eds,esv,f}$ indicates fuel share and $EI_{eds,esv,f}$ denotes energy intensity that is calculated according to the information on the available technologies[44].

$$DF_{eds,esv} \quad \begin{cases} \underset{hht}{} Pop_{hht} \quad T_{inhome,hht} & \text{(for heating, cooling, lighting and electric appliances in the household)} \\ \underset{hht}{} Pop_{hht} \quad (T_{cooking,hht} \quad T_{pactivity,hht}) & \text{(for hot water in the household)} \\ \underset{hht}{} Pop_{hht} \quad T_{cooking,hht} & \text{(for cooking in the household)} \\ PD_{ids} & \text{(for industrial sectors)} \\ \underset{td \quad hht}{} Pop_{hht} \quad Ptg_{hht,td} \quad Pts_{td,ptm} & \text{(for passenger transportation)} \\ \underset{ids \quad td}{} PD_{ids} \quad Ftg_{ids,td} \quad Fts_{td,ftm} & \text{(for freight transportation)} \end{cases} \tag{9}$$

Here, Pop_{hht} is the population by household type hht; $T_{inhome,hht}$ is the annual in-home time (excluding sleeping time) per person by household type hht; $T_{cooking,hht}$ is the annual in-home cooking time per person by household type hht; $T_{pactivity,hht}$ is the annual in-home personal activity time per person by household type hht; PD_{ids} is the gross output of industry ids, which is obtained through the input–output analysis; $Ptg_{hht,td}$ is the trip per person per day by household type and transportation destination td; $Pts_{td,ptm}$ is the modal share of passenger transportation; $Ftg_{ids,td}$ is the freight generation per industrial output by industrial sector ids and transportation destination td; $Fts_{td,ftm}$ is the modal share of freight transportation; ptm is the passenger transportation mode; and ftm is the freight transportation mode.

On the basis of the calculated final energy demand, we further estimate the primary energy for generating secondary energy (that is, electricity and heat) by balancing the power and heat supply with the final demand. The electricity and heat for own use, transmission loss and exchange with areas outside the target borders are explicitly considered in ExSS. Finally, we calculate the total primary-energy supply by summing up the primary energy consumption on the demand side and the primary energy for power and heat generation. The carbon emissions are derived by multiplying the primary energy consumption with the corresponding emissions factors[46]. The validity of the proposed ExSS model is discussed in Supplementary Note 1, Supplementary Table 5 and Supplementary Fig. 5.

Household consumption patterns. The consumption pattern for each household is explained using the indices of household expenditure per capita, which includes expenditure on food; clothing; household articles; health; transport and communication; education, culture and recreation; residence; and other goods and services. To reflect the heterogeneity of expenditure among populations, the current and future expenditures for each household (exp_{ihk}) are estimated by the exact household income ($Income_h$), the share of expenditure in income for that income group, and the shares of sub-category expenditures in the total expenditure for the relevant income group:

$$exp_{ihk} \quad Income_h \quad \frac{\underset{k}{} SY\ exp_{ik}}{SY\ Income_i} \% \quad \frac{SY\ exp_{ik}}{\underset{k}{} SY\ exp_{ik}} \% \tag{10}$$

where i is the income level used in the statistical yearbook (SY); h is a household; k is a sub-category of expenditure; $SY\ exp_{ik}$ is the expenditure on category k for income level i in the statistical yearbook; and $SY\ Income_i$ is the median income value for level i in the statistical yearbook.

For future expenditure in each household, we consider the following change in the parameters: the shares of expenditure in income and consumption structure refer to the experience in the developed provinces (that is, Beijing and Jiangsu), with similar income classifications reported in the latest statistical yearbook compared to the estimated future income in China; the future household income is projected on the basis of the future average income growth (an approximate growth of eight times for the GDP per capita), the shrunken income gap between urban and rural households in Sichuan (referring to the national case, the urban/rural income ratio falls from 3.1 in 2009 to 2.3 in 2030[47]), the uneven growth margins for different income groups (referring to Jiangsu province, whose urban/rural income ratio was around 2.3 in 2013) and the current exact household income. The results of household consumption patterns in S1 are shown in Supplementary Fig. 1. The consumption pattern in S2, S3 and S4 is further adjusted by considering the impacts of changes in labour force and working hours described in Supplementary Fig. 2.

Data and assumptions for economy. According to Sichuan's master plans[48], the population will increase to 85 million people and the urbanization rate will be 59% in 2030. The annual GDP growth target is set at 12% from 2011 to 2015, 11% from 2016 to 2020, and 10% from 2021 to 2030, on average, and the share of tertiary industry is expected to increase as a result of the economic transition in China (Supplementary Table 2). As shown in Supplementary Fig. 2, economic structure in 2030 (2030 input–output table) is first projected following the above assumptions and criteria based on the derived 2009 Sichuan input–output table. However, given that different productive and consumptive behaviours will result in distinctive industrial outputs that will further induce the economy change, the obtained 2030 input–output tables are then adjusted by representing the changing labour productivity and consumption patterns.

Data and assumptions for demographic composition. Demographic composition in the base year is derived from both Sichuan's 2010 Census data and time-use survey data. Specifically, the percentages of households with and without 65 elders, and the percentages of single and couple households in groups with and without 65 elders, are obtained from the census data. The percentages of two-generation and three-generation households are inferred on the basis of the time-use survey data. On the basis of the composition in the base year, the demographic composition in 2030 is assumed by setting the rates of change in the percentage of households in each group, in part following the results in Zeng et al.[49], and considering the situation in China. As Zeng et al.[49] include only the projection result for the whole of China in 2030, we adjust the percentage of households without elders 65 and households with elders 65 obtained from Zeng et al. by distinguishing the population composition in urban and rural areas in Sichuan, on the basis of the difference between Sichuan and China in the base year. The rate of change in the percentage for each subgroup of households (single, couple, two-generation, three-generation) in 2030 refers to the trend in Zeng's results of population composition in 2000 and in 2030. The following unique situations in China are taken into account to get the final demographic composition. Specifically, for urban households, the percentages of single and couple households without elders 65 , as well as households with elders 65 , are assumed to increase following the trends observed in developed countries. For rural households, the percentage of households without elders 65 is assumed to decrease given the large number of migrant workers in rural areas. The percentages of single and couple households with elders 65 are projected to increase in rural areas because most of the young generation work outside and the Chinese government has published a supporting policy to protect migrant workers' children that are 'left behind'[50]. This means that two-generation and three-generation households will decrease. See Fig. 3d for the demographic composition.

Data and assumptions for technology. Hydropower accounted for approximately 65% of the total power generation in 2009 in Sichuan[47] and is projected to grow further in the near future. By the year 2030, the planned share of hydropower is set

38. Hamza, N. & Gilroy, R. The challenge to UK energy policy: An ageing population perspective on energy saving measures and consumption. *Energy Policy* **39**, 782–789 (2011).
39. Baral, R., Davis, G. C. & You, W. Consumption time in household production: Implications for the goods-time elasticity of substitution. *Econ. Lett.* **112**, 138–140 (2011).
40. Brenčič, V. & Young, D. Time-saving innovations, time allocation, and energy use: Evidence from Canadian households. *Ecol. Econ.* **68**, 2859–2867 (2009).
41. Hamermesh, D. S. Time to eat: household production under increasing income inequality. *Am. J. Agric. Econ.* **89**, 852–863 (2007).
42. Jalas, M. A time use perspective on the materials intensity of consumption. *Ecol. Econ.* **41**, 109–123 (2002).
43. Cogoy, M. Dematerialisation, time allocation, and the service economy. *Struct. Change Econ. Dyn.* **15**, 165–181 (2004).
44. Gomi, K., Shimada, K. & Matsuoka, Y. A low-carbon scenario creation method for a local-scale economy and its application in Kyoto city. *Energy Policy* **38**, 4783–4796 (2010).
45. Shimada, K., Tanaka, Y., Gomi, K. & Matsuoka, Y. Developing a long-term local society design methodology towards a low-carbon economy: An application to Shiga Prefecture in Japan. *Energy Policy* **35**, 4688–4703 (2007).
46. Liu, Z. et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. *Nature* **524**, 335–338 (2015).
47. National Bureau of Statistics China *China Energy Statistical Yearbook 2010* (China Statistics Press, Beijing, 2010).
48. *Sichuan 12th Five-Year Population Development Plan* (The People's Government of Sichuan Province, 2012); http://www.sc.gov.cn/10462/10883/11066/2012/3/19/10203598.shtml
49. Zeng, Y., Land, K. C., Gu, D. & Wang, Z. *Household and Living Arrangement Projections: The Extended Cohort-Component Method and Applications to the US and China* (Springer, 2013).
50. China to Protect Migrant Workers' 'Left-Behind' Children *BBC News Asia* (15 February 2016); http://www.bbc.com/news/world-asia-35581716
51. Fridley D. et al. *China Energy and Emissions Paths to 2030* Report No. LBNL-4866E (Ernest Orlando Lawrence Berkeley National Laboratory, 2012); https://china.lbl.gov/sites/all/files/lbl-4866e-rite-modelaugust2012.pdf
52. *China Electric Power Industry Satistics Analysis 2011* (China Electricity Council, 2011)
53. Zhang, L., Li, H. & Gudmundsson, O. Comparison of district heating systems used in China and Denmark. *Euroheat Power (Engl. edn)* **10**, 12–19 (2013).
54. Dai, Y. & Hu, X. *Potential and Cost Study on China's Carbon Mitigation Technologies* (China Environment Press, Beijing, 2013).
55. Kainuma, M., Matsuoka, Y. & Morita, T. *Climate Policy Assessment: Asia-Pacific Integrated Modeling* (Springer Japan, 2011).
56. SAC/TC20, CECA, CSP. *Standards Collection of Energy Consumption per Unit Product* (China Standard Press, Beijing, 2014).
57. National Bureau of Statistics China *China Statistical Yearbook 2009* (China Statistics Press, Beijing, 2009).

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Author contributions

B.Y. designed the research and performed the analysis. Y.M. conceived the paper. Y.-M.W. and G.K. contributed to the methodology improvement and scenario design. All authors contributed to writing the paper.

Competing interests

The authors declare no competing financial interests.

Additional information

Supplementary information is available for this paper.

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