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Future scenarios for energy consumption and carbon emissions due to demographic transitions in Chinese households

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Population dynamics has been acknowledged as a key concern for projecting future emissions, partly because of the huge uncertainties related to human behaviour. However, the heterogeneous shifts of human behaviour in the process of demographic transition are not well explored when scrutinizing the impacts of population dynamics on carbon emissions. Here, we expand the existing population–economy–environment analytical structure to address the above limitations by representing the trend of demographic transitions to small-family and ageing society. We specifically accommodate for inter- and intra-life-stage variations in time allocation and consumption in the population rather than assuming a representative household, and take a less developed province, Sichuan, in China as the empirical context. Our results show that the demographic shift to small and ageing households will boost energy consumption and carbon emissions, driven by the joint variations in time-use and consumption patterns. Furthermore, biased pictures of changing emissions will emerge if the time effect is disregarded.

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]. Establishing a clear link between demographic transition and carbon emissions is a complicated task. The human population influences the environment through the bulk effects of forces such as economic growth, technological development, urbanization, population dynamics and behavioural alteration[3–8]. Speaking broadly, we can intuit that a population shift can affect energy consumption and emissions via three main channels: first, the redesign of time-use patterns among work, leisure and home activities, which are elements that act directly on the demand for energy services (for example, time spent on appliances and travel) and indirectly on material requirements through changing income due to changes in working hours[9–11]; second, the dependence of productive activity on the household and age structure (that is, labour force in the household), which could pose constraints or stimulation on consumption activities[12,13]; and third, the potential influence of household-composition change on industrial production via altered demand patterns and needs[13,14]. To summarize, we can group these channels into two categories: time-use patterns and consumption patterns under the constraints of socioeconomic level and technology choice, or what we further define as 'lifestyle' in this study. As Becker[15] states, households combine their time and market goods to produce more basic commodities that directly enter their utility functions. From this standpoint, research concerned with assessing the influence of demographic transition on energy consumption and related carbon emissions should understand the allocation of time and money in the future; that is, what consumers will do over the 24 hours in a day and how they will do it, and what consumers will buy and how much they will spend. More specifically, it is not the number or composition of a population that will directly cause the change of emissions; instead, the lifestyle shift accompanying the demographic transition causes the change of aggregate time spent on productive and consumptive activities as well as the aggregate money spent on goods and services, which consequently drives the change of total emissions.

Many studies to date have evaluated the impacts of population change on energy consumption or carbon emissions[16–21], among which behavioural or lifestyle impacts are generally approached from the perspective of changing the basket of goods and services they purchase[3,22–27]. Most, however, have devoted little attention to describing the environmental implications of how people spend their time, another fundamental dimension of people's lifestyles[9,11,28]. A narrow body of research has built on the notions of commodity intensity, energy intensity or CO_2 intensity of activities, and has used time as a denominator to establish comparisons between the ways in which energy consumption and emissions are generated for different households through the activities of everyday life[9,28,29]. Although they are on a descriptive level, the integration of time use into environmental analysis opens a whole new array of possibilities for sustainability research.

Another obstacle blocking our view of the inherent changes when demographics shift is the widely adopted notion of the 'representative household/individual', which assumes that one productive and consumptive pattern is shared among all individuals and households. The occurrence of demographic transitions in the future implies that the distribution of population or households in each life stage will be reconstructed. Given the evident heterogeneity of lifestyles between people in different life stages (that is, inter-life-stage variation, or intergroup variation)[12,30–32] as well as between people in the same life stages (that is, intra-life-stage variation, or intragroup variation)[4,11,28], a population shift to, for example, smaller and ageing

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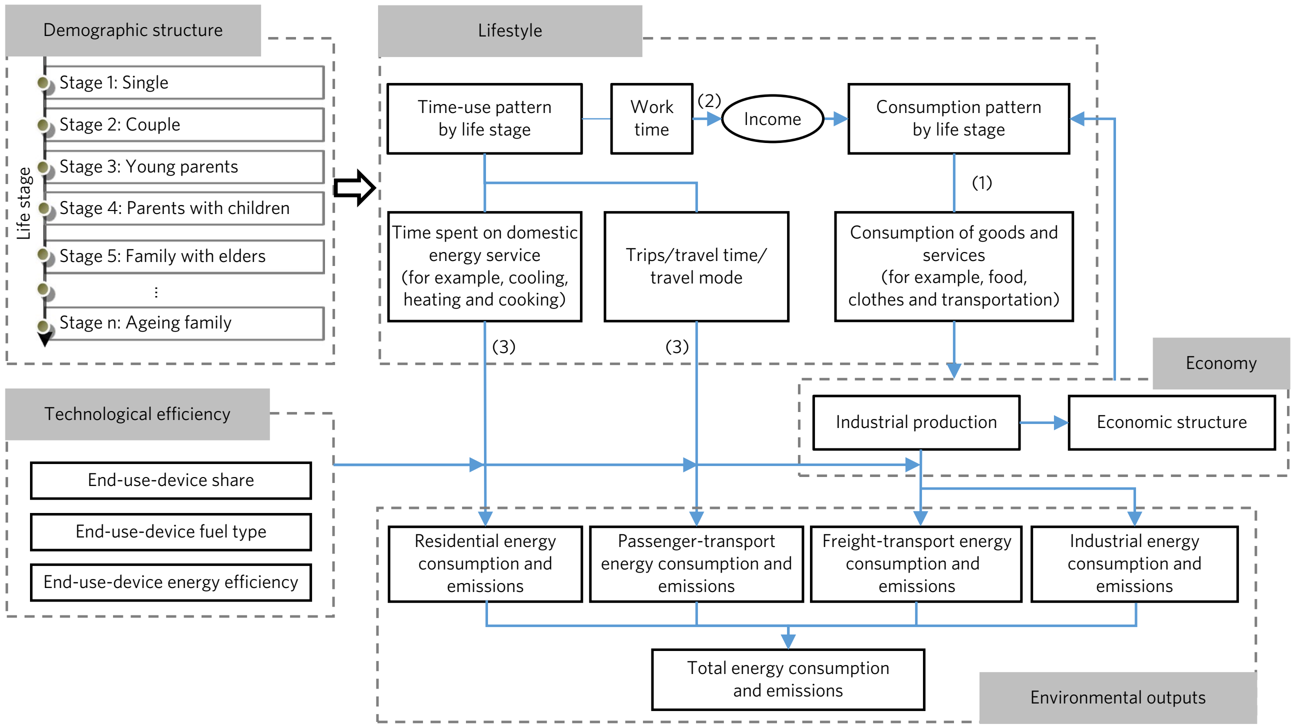

Fig. 1 | Analytical mechanism for demographic transition, lifestyle and environmental outputs. Households in different life stages have distinctive time-use and consumption patterns. Considering that people affect human society and the natural environment through both their consumptive and productive 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

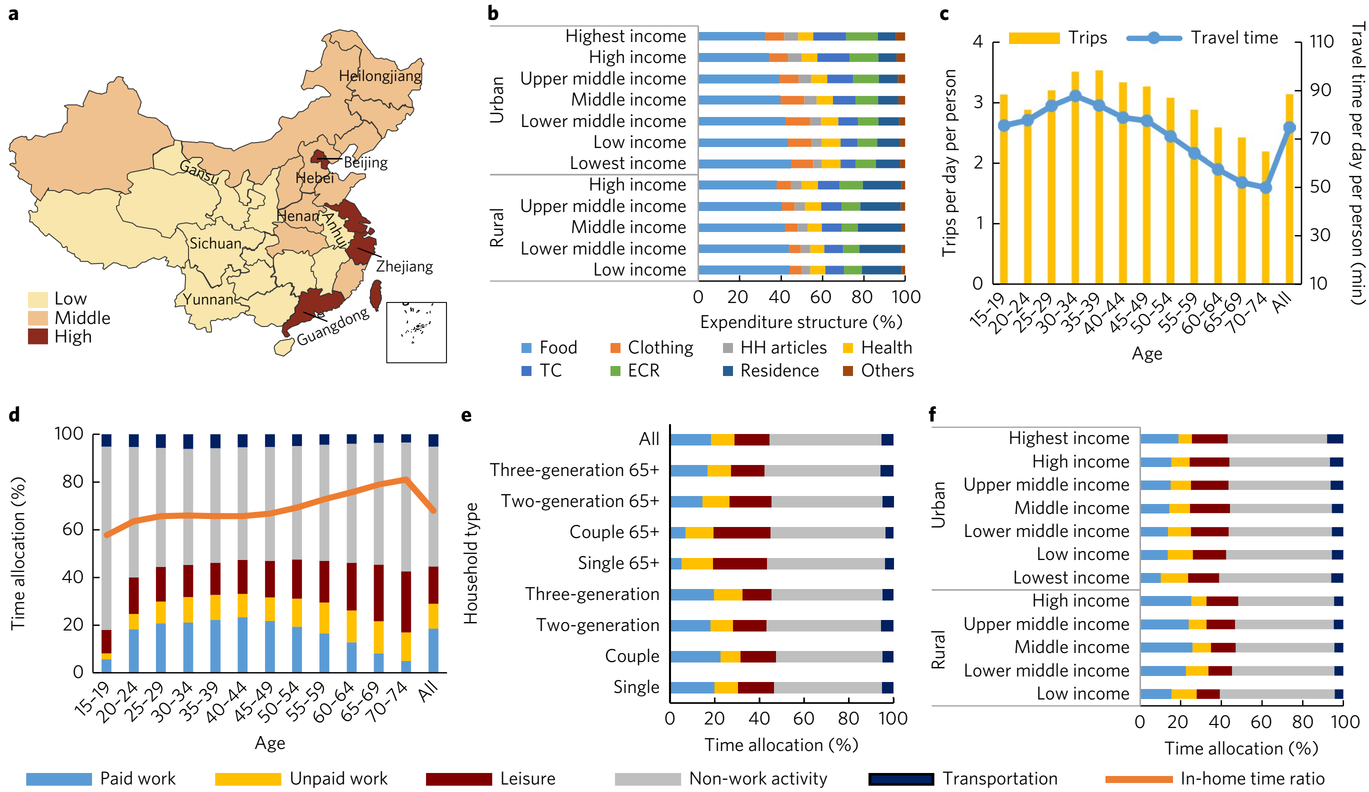

Fig. 2 | Chinese time-use pattern and consumption pattern. **a**, Provincial economic development level indicated by GDP per capita in 2008 (low: GDP per capita < US$3,000; middle: US$3,000 ≤ GDP per capita < US$5,000; high: GDP per capita ≥ US$5,000). The data show that approximately half of the provinces 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

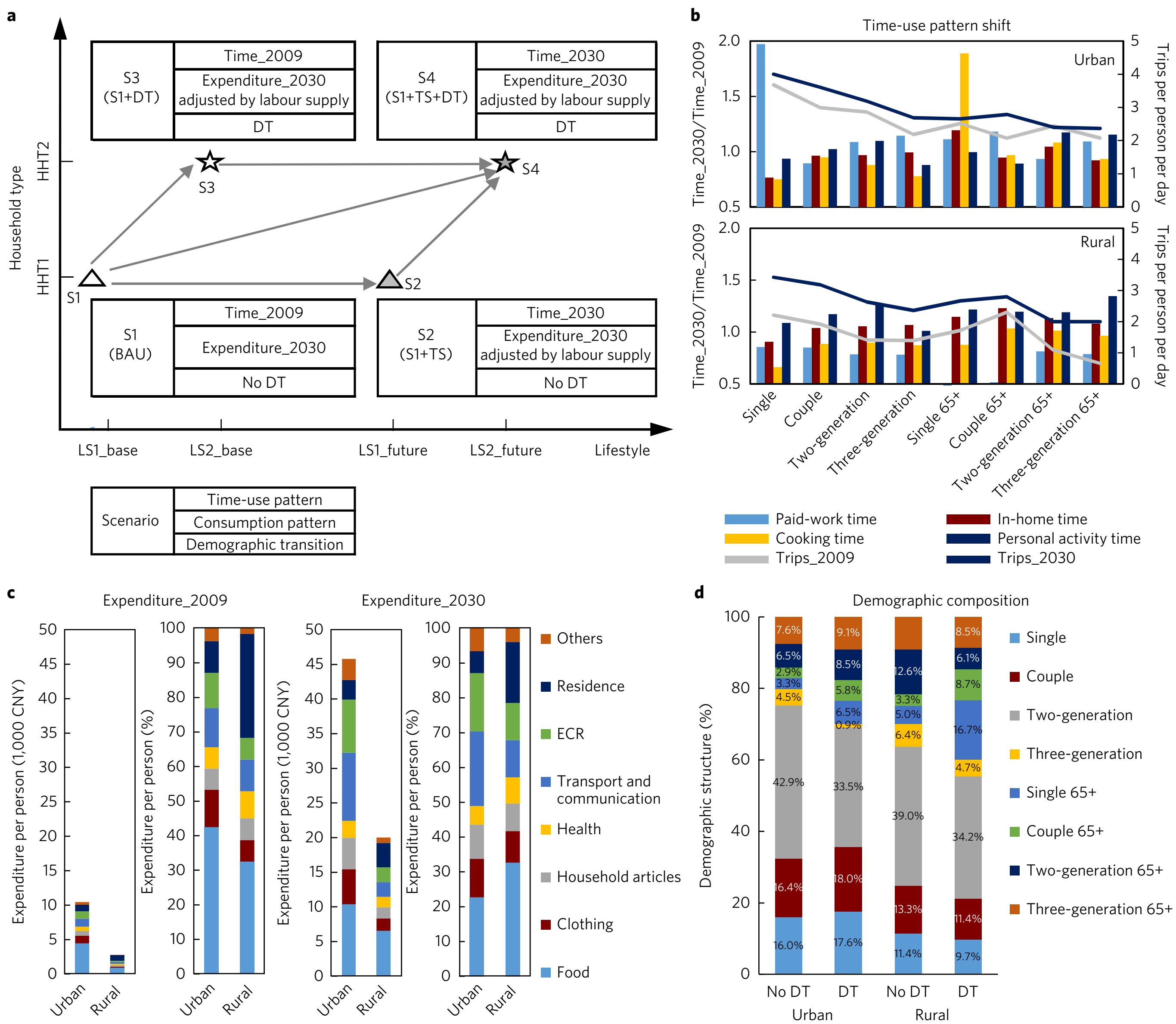

Fig. 3 | Four scenarios of future society in Sichuan. a, Four scenarios (routes) of the potential change of household type and lifestyle. DT, demographic transition; TS, time-use pattern shift; LS_base: lifestyle in the base year; LS_future: lifestyle in future; HHT: household type. **b**, Time-use pattern 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 population indicators.

Environmental impacts of a small-family and ageing society

Driven by the income growth, demographic transition and the accompanying lifestyle shifts depicted by S4, the total primary energy demand in 2030 may reach approximately 433 million tonnes of standard coal equivalent (Mtce), and approximately 808 million tonnes (Mt) of CO_2 are likely to be emitted from energy-consuming activities in Sichuan in 2030, which is three times the CO_2 emitted in 2009 (Supplementary Table 3).

Next, we explore the differences between the environmental consequences caused by the lifestyle shifts and demographic transitions among the four scenarios. The energy consumption and emissions in different sectors as well as the contributions of each household group are researched by employing the improved Extended Snapshot method (see Methods). Figure 4 shows the energy demand and CO_2 emissions change in S2, S3 and S4 compared with S1. As seen in Fig. 4a,c, compared with scenario S1 without demographic transition and lifestyle shift, the shift of the time-use pattern within each population group in S2 results in an evident increase of final energy demand (15.2 Mtce) and CO_2 emissions (33.1 Mt) in the industrial, commercial and freight transportation sectors due to the changing work time and the corresponding consumption. Meanwhile, there are higher final energy consumption (1.2 Mtce) and CO_2 emissions (2.2 Mt) in the passenger transportation sector, but smaller energy consumption and emissions in the residential sector due to the changing non-work time. This indicates that the time-use pattern acts on energy demand and carbon emissions mainly through productive activities (that is, work-time change). In scenario S3, final energy demand and CO_2 emissions are only 2.2 Mtce and 4.2 Mt greater than that of S1, respectively, implying that the inter-life-stage variations of time-use and consumption patterns triggered only by the demographic transition have limited impacts on energy-demand and emissions change.

The demographic transition to small and ageing households as well as the accompanying lifestyle change within and between life stages in S4 leads to an additional 18 Mtce of primary energy consumed in contrast to S1, to which coal, oil, gas and biomass are the main contributors (Fig. 4b). This further leads to another 35 Mt of CO_2 emissions generated, which is equivalent to 4.3% of total emissions in 2030. This is because overall allocation of time and money for the whole population varies, resulting from the joint change of demographic composition and the inter- and intra-life-stage variations of consumption pattern and time spent on productive and consumptive activities. Specifically, the impacts on increasing emissions through the change of consumption pattern due to demographic transition, and the change of work time and non-work time accounts for 7.2%, 86.1% and 6.7%, respectively, suggesting a dominant role of time-use pattern shift (93%). It is important to mention that, although the total changes in CO_2 emissions in S2–S1 and S4–S1 are quite similar (33 Mt and 35 Mt, respectively), it does not mean that it is not the demographic change but rather the changes in lifestyle that matter. Decomposition results (Supplementary Fig. 3) further show that the exact impacts and contributions on emissions for each group of households are very different in these two cases. The evident differences in the amount and the structure of the energy-demand change and CO_2-emissions change among the four scenarios depicted in Fig. 4a–c indicate the necessity of considering the inter-life-stage and intra-life-stage variations in the time-use and consumption patterns when evaluating the impacts of demographic transitions on the environment.

To further investigate where the above differences between S4 and S1 originate, we decompose the CO_2-emissions change by household type and by the roles of time and money (Fig. 4d). Although total CO_2 emissions are projected to increase by 35 Mt compared with S1 (Fig. 4c), the performance of each household type is quite diverse. In total, the groups of small and ageing households will emit 54 Mt of CO_2 (7% of total CO_2 emissions) more than S1, in which single and couple households without elders 65+ in urban areas will contribute 21 Mt and the remaining 33 Mt of CO_2 increase is from ageing households in both urban and rural areas. Examining the reasons for the aggregate emission change, it is revealed that the drivers vary by household type (Supplementary Table 4). Sometimes, the change of lifestyle is partially or fully neutralized by the change of number of households due to demographic transition (Supplementary Table 4).

Furthermore, because the demographic shift influences the environment via the variations in time-use and consumption patterns within and between household groups, we further distinguish between the effects of time and money (Fig. 4d). Our results show that, on average, 93% of the incremental CO_2 emissions is explained by increasing consumption resulting from the change of work time and consumption pattern shift, and 7% is explained by the increasing demand for energy services derived from the change in non-work time. By comparing the emissions under S3 in which the time effect is not included and emissions under S4 in which both the time and money effect are included, we find that the majority of the money effect (about 92%) is attributed to the changing work time. Regarding how time and money act on the environment, Fig. 4e reveals that small and ageing households generate substantial CO_2 emissions from the services of heating, cooking, hot water and road passenger transport due to their time-use pattern shift; these households also spend more money on the goods or services produced from the manufacturing industry, the hotel and catering service industry, and other industries such as health care, culture, education and recreational industries, which result in more emissions from those sectors (Fig. 4f). All of these findings will be very instructive for designing future supplementary policies to lessen the impact of demographic transition on the environment.

Compared with CO_2 emissions in the base year for Sichuan, the changes of consumption pattern due to income growth and demographic transition in S4 are the main drivers of CO_2 emissions increase, leading to an additional 966 Mt of CO_2 emissions emitted from the process of industrial production (Fig. 5). In addition, another 97 Mt of CO_2 emissions (12% of total emissions in 2030) will be generated, attributed to the changing time-use pattern with demographic shifts. These numbers suggest that lifestyle change in combination with demographic transition to small and ageing households has a substantial effect on the environment. The improving energy efficiencies of devices and power supply efficiencies will contribute to neutralize approximately 46% of the increasing CO_2 emissions, while 540 Mt of emissions will still remain.

Discussion

Our findings suggest that the demographic transition to small and ageing households in the future will boost energy consumption and carbon emissions in the less developed province of Sichuan,

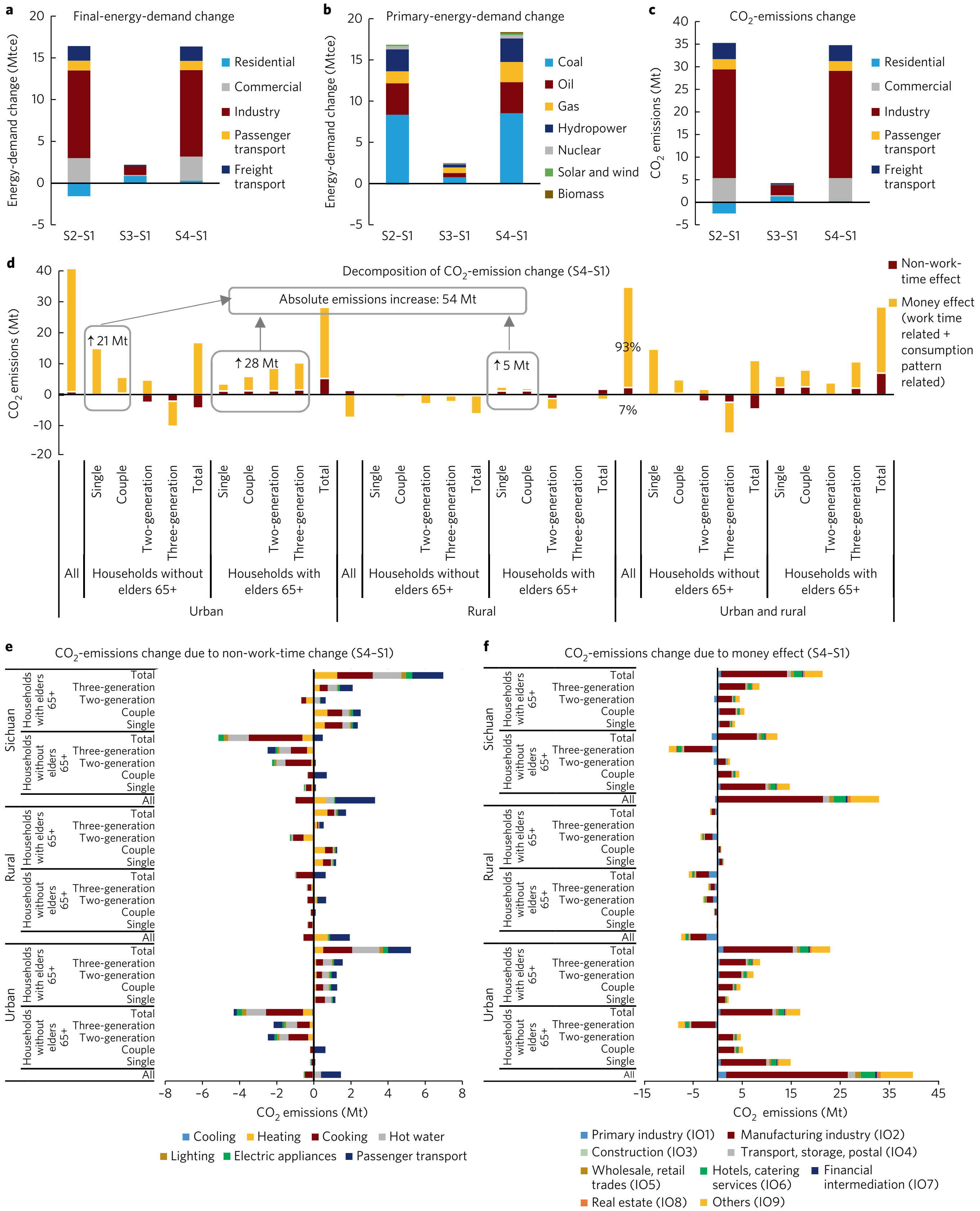

Fig. 4 | Structure of energy-demand and CO_2-emissions change compared with S1 for Sichuan. a, Final-energy-demand change in S2, S3 and S4 compared with S1. **b**, Primary-energy-demand change in S2, S3 and S4 compared with S1. **c**, CO_2-emissions change in S2, S3 and S4 compared with S1. **d**, Decomposition of CO_2-emissions change between S4 and S1. **e**, CO_2-emissions change between S4 and S1 due to non-work-time change. (**f**,) CO_2-emissions change between S4 and S1 due to the money effect related to the change in work time and the consumption pattern shift. As S4 is thought to be more realistic with the consideration of inter-life-stage and intra-life-stage variations, the decomposition analysis shown in **d**–**f** is performed only for S4.

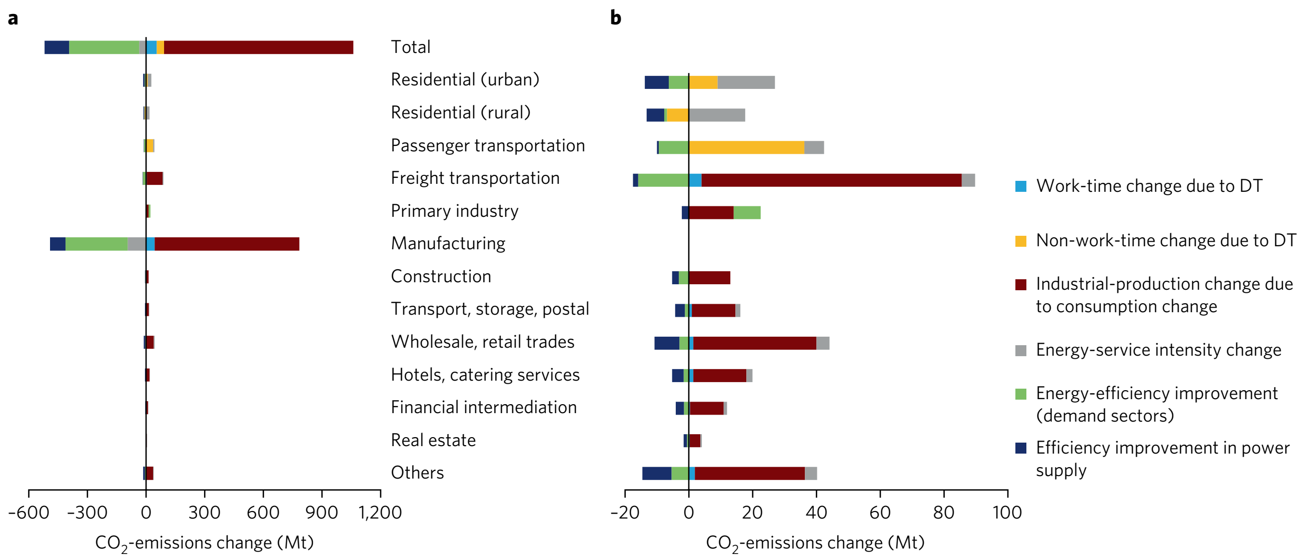

Fig. 5 | Decomposition of CO_2 emissions increase in scenario S4 in contrast to the base year 2009 for Sichuan. a,**b**, The decomposition results of all sectors (**a**) and a zoom-in of sectors without manufacturing industry (**b**). The contribution of factors to CO_2 emissions increase in S4 compared 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).

$$\mathrm{HHD}_{\mathrm{hht}} = \mathrm{Pop} \times \mathrm{Pop\_share}_{\mathrm{hht}} / \mathrm{HHsize}_{\mathrm{hht}} \tag{1}$$

$$\mathrm{Pop\_share}_{\mathrm{hht}} = (\mathrm{HHshare}_{\mathrm{hht}} \times \mathrm{HHsize}_{\mathrm{hht}}) / \sum_{\mathrm{hht}} (\mathrm{HHshare}_{\mathrm{hht}} \times \mathrm{HHsize}_{\mathrm{hht}}) \tag{2}$$

where $\mathrm{HHD}_{\mathrm{hht}}$ 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; $\mathrm{Pop\_share}_{\mathrm{hht}}$ is the share of population belonging to household type hht; $\mathrm{HHsize}_{\mathrm{hht}}$ is the average household size for household type hht obtained from the survey data; and $\mathrm{HHshare}_{\mathrm{hht}}$ 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.

$$\mathrm{LS}_{\mathrm{Urban,Rural}} = \sum_{\mathrm{Urban,Rural}} \mathrm{HHD}_{\mathrm{hht}} \times \mathrm{HHwork}_{\mathrm{hht}} \times \mathrm{AWH}_{\mathrm{hht}} \tag{3}$$

where $\mathrm{LS}_{\mathrm{Urban,Rural}}$ is the total number of hours labourers spend at work distinguished by urban and rural; $\mathrm{HHwork}_{\mathrm{hht}}$ is the average number of members in employment in the household by type hht; $\mathrm{AWH}_{\mathrm{hht}}$ 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.

$$\mathrm{Wage} = \sum_{\mathrm{Urban,Rural}} \mathrm{LS}_{\mathrm{Urban,Rural}} \times \mathrm{WR}_{\mathrm{Urban,Rural}} \tag{4}$$

$$\mathrm{FDtot}_{\mathrm{pc}} = \mathrm{Wage} \times \mathrm{CR} \tag{5}$$

$$\mathrm{FD}_{\mathrm{pc,ids}} = \mathrm{FDtot}_{\mathrm{pc}} \times \mathrm{SPC}_{\mathrm{ids}} \tag{6}$$

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

$$\mathrm{Wage} = \sum_{\mathrm{ids}} \mathrm{IO}_{\mathrm{wage,ids}} \tag{7}$$

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; $\mathrm{WR}_{\mathrm{Urban,Rural}}$ is the wage rate per working hour distinguished by urban or rural; $\mathrm{FDtot}_{\mathrm{pc}}$ 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; $\mathrm{FD}_{\mathrm{pc,ids}}$ is the amount of private consumption for the industrial sector (ids) in the final demand; $\mathrm{SPC}_{\mathrm{ids}}$ is the share of private consumption for the industrial sector (*ids*); $\mathrm{IO}_{\mathrm{wage,ids}}$ 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 $\mathrm{ED}_{\mathrm{eds,esv,f}}$ in ExSS is calculated following equation (8)[45], but with extensive calculation for each index (equation (9)):

$$\mathrm{ED}_{\mathrm{eds,esv,f}} = \mathrm{ESVD}_{\mathrm{eds,esv}} \times \mathrm{FS}_{\mathrm{eds,esv,f}} \times \mathrm{EI}_{\mathrm{eds,esv,f}} \tag{8}$$

where eds is energy-demand sector, esv is energy-service type and f is fuel type. Energy service demand $\mathrm{ESVD}_{\mathrm{eds,esv}}$ is a function of driving force $\mathrm{DF}_{\mathrm{eds,esv}}$, 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. $\mathrm{FS}_{\mathrm{eds,esv,f}}$ indicates fuel share and $\mathrm{EI}_{\mathrm{eds,esv,f}}$ denotes energy intensity that is calculated according to the information on the available technologies[44].

$$\mathrm{DF}_{\mathrm{eds,esv}} = \begin{cases} \sum_{\mathrm{hht}} \mathrm{Pop}_{\mathrm{hht}} \times \mathrm{T}_{\mathrm{inhome,hht}} & \text{(for heating, cooling, lighting and electric appliances in the household)} \\ \sum_{\mathrm{hht}} \mathrm{Pop}_{\mathrm{hht}} \times \left(\mathrm{T}_{\mathrm{cooking,hht}} + \mathrm{T}_{\mathrm{pactivity,hht}}\right) & \text{(for hot water in the household)} \\ \sum_{\mathrm{hht}} \mathrm{Pop}_{\mathrm{hht}} \times \mathrm{T}_{\mathrm{cooking,hht}} & \text{(for cooking in the household)} \\ \mathrm{PD}_{\mathrm{ids}} & \text{(for industrial sectors)} \\ \sum_{\mathrm{td}} \sum_{\mathrm{hht}} \mathrm{Pop}_{\mathrm{hht}} \times \mathrm{Ptg}_{\mathrm{hht,td}} \times \mathrm{Pts}_{\mathrm{td,ptm}} & \text{(for passenger transportation)} \\ \sum_{\mathrm{ids}} \sum_{\mathrm{td}} \mathrm{PD}_{\mathrm{ids}} \times \mathrm{Ftg}_{\mathrm{ids,td}} \times \mathrm{Fts}_{\mathrm{td,ftm}} & \text{(for freight transportation)} \end{cases} \tag{9}$$

Here, $\mathrm{Pop}_{\mathrm{hht}}$ is the population by household type hht; $\mathrm{T}_{\mathrm{inhome,hht}}$ is the annual in-home time (excluding sleeping time) per person by household type hht; $\mathrm{T}_{\mathrm{cooking,hht}}$ is the annual in-home cooking time per person by household type hht; $\mathrm{T}_{\mathrm{pactivity,hht}}$ is the annual in-home personal activity time per person by household type hht; $\mathrm{PD}_{\mathrm{ids}}$ is the gross output of industry ids, which is obtained through the input–output analysis; $\mathrm{Ptg}_{\mathrm{hht,td}}$ is the trip per person per day by household type and transportation destination td; $\mathrm{Pts}_{\mathrm{td,ptm}}$ is the modal share of passenger transportation; $\mathrm{Ftg}_{\mathrm{ids,td}}$ is the freight generation per industrial output by industrial sector ids and transportation destination td; $\mathrm{Fts}_{\mathrm{td,ftm}}$ 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 ($\mathrm{exp}_{\mathrm{ihk}}$) are estimated by the exact household income ($\mathrm{Income}_{\mathrm{h}}$), 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:

$$\mathrm{exp}_{\mathrm{ihk}} = \mathrm{Income}_{\mathrm{h}} \times \frac{\sum_{\mathrm{k}} \mathrm{SY}\_exp_{\mathrm{ik}}}{\mathrm{SY\_Income}_{\mathrm{i}}}\% \times \frac{\mathrm{SY}\_exp_{\mathrm{ik}}}{\sum_{\mathrm{k}} \mathrm{SY}\_exp_{\mathrm{ik}}}\% \tag{10}$$

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 $\mathrm{SY\_Income}_{\mathrm{i}}$ 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 as 77.6%, versus 7.4% for wind, solar and nuclear, and 15% for coal. Transmission loss is assumed to be reduced considerably from 7.7% to 6%[51,52].

According to the plan in developed provinces in China and the experience in developed countries[53], the fuel for heat supply is assumed to be converted from coal to natural gas and renewable energy in the future. The indices of energy efficiency and technology share in 2030 are adjusted on the basis of refs [51,54] and AIM (Asia–Pacific Integrated Model)/End-use model results[55]. Indicators for calculating the energy-service demand in nine industrial sectors come from ref. [54], and the standards for industrial products[56].

Data availability. The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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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
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