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Time use and carbon dioxide emissions accounting: An empirical analysis from China

Biying Yu [a, b, c, d], Junjie Zhang [a, b, c], Yi-Ming Wei [a, b, c, d, *]

[a] Center for Energy and Environmental Policy Research, Beijing Institute of Technology, Beijing, 100081, China
[b] School of Management and Economics, Beijing Institute of Technology, Beijing, 100081, China
[c] Beijing Key Lab of Energy Economics and Environmental Management, Beijing, 100081, China
[d] Sustainable Development Research Institute for Economy and Society of Beijing, Beijing, 100081, China

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ABSTRACT

Time is an absolutely scarce resource for humans. Considering the fact that people consume goods and services to fulfill their daily activities in 24 hours a day, a new perspective based on time use might be more intuitive for understanding why and how people allocate their time and consumption to different activities, and what the energy demand and emissions will be in the future when time-use patterns shift. Accordingly, the policy implications for reducing carbon dioxide emissions could be extended to more fundamental dimensions related to people's activity structures, activity duration, and consumption patterns of activities. This study attempts to transform the energy and emissions problems into a finite time-use problem, by investigating the change of energy consumption and emissions building on a time-use-based approach. To that end, we take China as the empirical context, and investigate potential time-use patterns for Chinese residents. Scenario analyses assuming that Chinese residents may shift to time-use patterns in developed countries are further conducted to give a general picture of future carbon dioxide emissions and meanwhile to explore a low-carbon time-use pattern for Chinese residents. We find that, a potential Chinese residents' low-emissions route may involve shifting to the activity patterns of American residents and the hybrid consumption patterns of activities composed of patterns found in Finland, Japan and UK. And six main time-use activities, including *Travel*, *Personal care*, *Repairs, Gardening and Pet care*, *Sleep and Rest*, *Eating and Drinking*, and *Recreation and Leisure*, will make a greater contribution to increasing daily emissions from residents if they shift their time-use patterns in the future.

1. Introduction

Currently, residents' energy consumption, including direct household energy utilization and the energy consumption embedded in the process of goods manufacturing, account for a very large proportion of the total energy consumption (Dias et al., 2014; Liu et al., 2011; Zhang and Wang, 2017; Zhang et al., 2015b). Specifically, the proportions reach up to 80%, 36%–66%, 52%, and 69%–79% in the U.S., EU countries, South Korea, and China, respectively (Bin and Dowlatabadi, 2005; Park and Heo, 2007; Reinders et al., 2003; Wang and Shi, 2009). Therefore, reducing residents' emissions at the source has great significance for achieving global energy and carbon mitigation targets.

Traditional research studies that analyze residents' energy consumption and carbon dioxide emissions from the perspective of consumption have some shortcomings. Specifically, such an approach mainly focuses on consumption structures and consumption amounts, which cannot answer why consumers consume those goods and services and what for (i.e. the source of consumption). Moreover, existing studies consider consumption as a black box, and take little note of the fact that consumers consume goods and services to fulfill their daily activities. In other words, consumption is an input of people's everyday activities (Juster and Land, 1981; Røpke, 2009). Essentially, these activities—rather than consumption itself—finally result in consumers' energy consumption and carbon dioxide emissions. Given these limitations, some scholars (Jalas, 2002; Reisch, 2001; Yu et al., 2018) argue that research concerned with promoting sustainable energy consumption and protecting the environment should turn to understanding

* Corresponding author. BIT Center for Energy and Environmental Policy Research, No. 5 South Zhongguancun Street, Haidian District, Beijing, 100081, China.
E-mail address: wei@bit.edu.cn (Y.-M. Wei).

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what people will do and how they will do it as keys to what quantity of emissions will be generated and changed in the future, implying that the time-use pattern should be emphasized for the analysis of energy use and emissions.

Time, as an absolutely scarce resource for humans (24 hours a day), never differs by social environment, economic situation, age, household type, individual difference, or any other elements. In this sense, time offers a fair perspective from which to analyze how residents consume their daily goods and services, and consequently their energy consumption and emissions. More specifically, by utilizing the time-use approach, we can clearly find out what consumers actually allocate their consumption to, rather than the aggregate amount and structure of their consumption. Changing time-use patterns (e.g. what to do and how to do it) can essentially change people's demand for consumption from the start. Another important advantage of this approach is that it can help make concrete policies to guide consumers to sustainable lifestyles in their everyday life. For example, households could be encouraged to shift to less energy-consuming activities from energy-intensive activities so as to reduce the total household energy consumption (Isaksson and Ellegård, 2015). Although some realize the importance of conducting time-use-based environmental analysis (Druckman and Jackson, 2016), relevant studies are quite limited, especially for developing countries.

Consequently, different from previous literature, instead of targeting how people differ in how they spend their money, this paper transforms the energy and emission problems into a finite time-use problem, and goes further to explore the original sources that trigger people's demand for energy and the generation of emissions. We pay attention to how people allocate their time to different activities, what goods and services are required to support their activity time, and what the accompanying energy consumption and carbon dioxide emissions are.

As the most populous country in the world, China might have more potential to reduce carbon dioxide emissions by changing residents' time-use behaviors. This paper is the first to aim at answering the question of how much carbon dioxide Chinese residents will emit in the future by developing a time-use-based approach. Three dimensions of the time-use pattern are targeted in the proposed method: activity structure, activity duration, and activity consumption. The availability of the first large-scale national time-use survey data in China collected in 2008 offers the opportunity to fulfill this study. Valid information from 37,142 individuals from 16,616 households in 10 provinces was obtained in this survey. Based on these rich data, carbon dioxide emissions per unit of activity time for Chinese residents are for the first time calculated and compared with those of residents in six typical developed countries (Japan, Australia, Germany, Finland, the UK, and the U.S.). By assuming that Chinese residents may copy or follow the time-use patterns and relevant policies causing low-carbon time-use activities in these developed countries, we design several scenarios to evaluate carbon dioxide emissions that Chinese residents might emit under different time-use pattern changes. On the basis of this analysis, we finally aim to explore suitable time-use patterns for achieving a low-carbon society in China.

The remaining parts of the paper are as follows. Section 2 summarizes some literature on environmental analysis from the perspective of time use. Section 3 presents the time-use-based approach estimating the carbon intensities of time-use activities. Section 4 presents the data used in the paper. Section 5 shows current carbon intensities of different time-use activities in China. Section 6 compares the results between China and six developed countries, and discusses the results of scenario analyses. Conclusions and limitations are given in Section 7.

2. Literature review

Most of the existing literature focuses on analyzing residents' carbon footprints from the perspective of consumption (Wei and Liao, 2016; Wei et al., 2011; Zhang et al., 2015a). The approaches employed mainly include the input-output model (IOM) (Li et al., 2015; Long et al., 2017; Mi et al., 2016; Tian et al., 2016), life cycle assessment (LCA) (Jones and Kammen, 2011; Kawajiri et al., 2018; Morioka et al., 2010; Saner et al., 2013), emission coefficient method (ECM)[1] (Fan et al., 2013), and consumer lifestyle approach (CLA) (Wang and Yang, 2014; Wei et al., 2010). Meanwhile, some literature forecasts residents' energy consumption and carbon dioxide emissions by assuming aggregate changes in their consumption, such as Dai et al. (2012), Wood et al. (2017), Wakiyama and Kuramochi (2017), among others. However, these studies cannot further answer why those consumption occurred and what's the original source for causing the consumption as well as how to change them.

To explore the original sources for resulting in energy demand and emissions, different from the perspective of consumption, several scholars call for a shift in focus of analyzing environmental problems from the purchase of goods and services towards everyday activities (Jalas, 2005). For example, Røpke (2009) thought that people in their everyday life are engaged in activities, such as cooking, eating, sleeping, taking care of their children and working, etc., and that consumption is an important input for these activities; that is, the performance of such activities usually needs various material artefacts. In this sense, it is plausible that decomposing and projecting the energy demand and emissions from daily time-use patterns are more reasonable because they can clarify why the consumption is needed and where it comes from. Time-use data derived from time-use surveys offer a base for researching environmental issues from the perspective of time use, although a large field of existing time-use literature focuses on social rather than environmental problems. Cogoy (1995, 1999) pointed out that time use also has environmental implications. Nässén and Larsson (2015) proposed that time-use methods can extend the scope of analyzing the impact of residents' activities on the environment to all activities, rather than just to purchase activities.

To date, a limited number of studies have shed light on the ever-increasing energy consumption and carbon dioxide emissions from a time-use perspective. Schipper et al. (1989) may be one of the earliest researchers who estimated and compared energy consumption of different time-use activities in the U.S. in the mid-1980s. They analyzed the energy use and time use of activities and divided them into three items, i.e. at home, personal services and transport. Jalas (2002, 2005) measured energy intensities of different time-use activities for Finnish households. Druckman et al. (2012) calculated greenhouse gas (GHG) intensities of different activities in the form of GHG emissions per unit time of activities. Though these studies are mainly at a descriptive level, which compare different time-use activities through putting up some notions of commodity intensity, energy intensity, carbon intensity of activities, etc., they provide a new perspective to analyze environmental problems.

Furthermore, some scholars have further focused on the impact

[1] It is worth mentioning that, the ECM has similar concept with environmentally extended input-output analysis (EEIOA). These two methods calculate household carbon emissions via multiplying carbon emission coefficients (or carbon intensities) of consumption by consumption of energy and non-energy goods. The ECM is mainly used to calculate household emissions from fuels, while EEIOA is mainly used to calculate direct and indirect emissions.

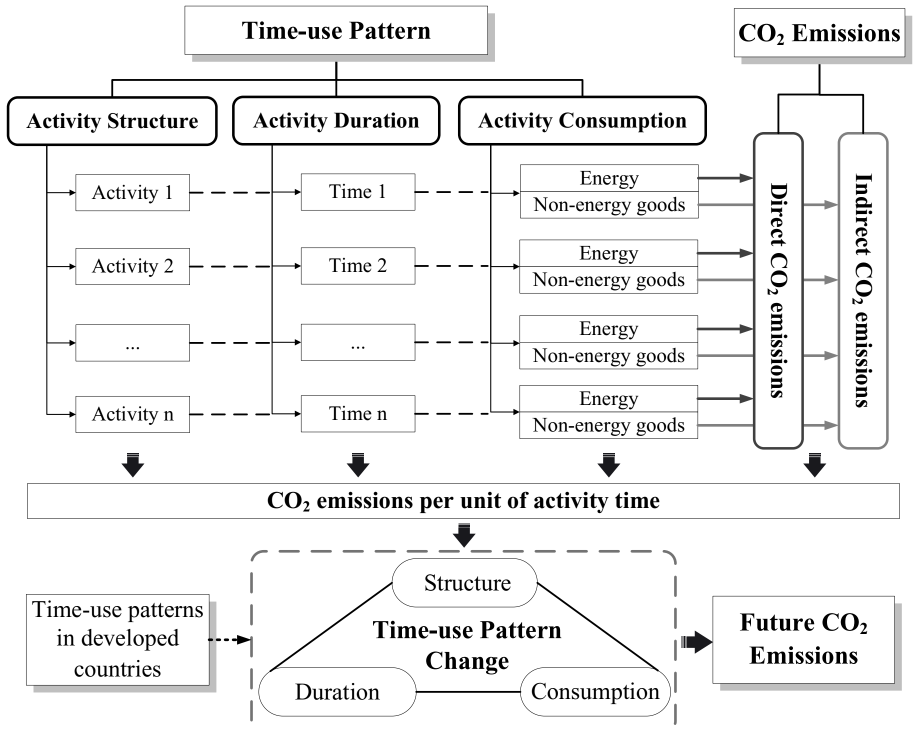

Fig. 1. Time-use-based approach framework for carbon dioxide emissions accounting.

of time-use pattern changes on energy consumption or carbon dioxide emissions. Binswanger (2004) used a household-production-function approach to analyze the impacts of time-saving innovations on households' time use and energy use. Brenčič and Young (2009) empirically analyzed impacts of time-saving innovations on households' time allocation and energy use with Canadian data. Yu et al. (2013) found that restructuring time allocation behaviors would substantially change household energy consumption in the context of Beijing. In this sense, policies that guide people to spend more time on less energy- and carbon-intensive activities could play an effective role in achieving more energy savings and emissions reductions. Therefore, residents can change their energy consumption and carbon emissions through changing their time use patterns.

Referring to the existing literature, this paper attempts to transform the energy and emissions problem into a finite time-use problem, by investigating the change of energy consumption and emissions based on a time-use-based approach. Meanwhile, it contributes to enriching the existing evidence in developing countries for projecting the impact of time-use pattern change on carbon dioxide emissions.

3. Time-use-based approach to carbon dioxide emissions accounting

3.1. Time-use-based approach framework

Fig. 1 illustrates the research framework of this paper from the time-use perspective. The time-use pattern includes three dimensions: activity structure (what to do), activity duration (how long to do it), and activity consumption (how to do it). As people are engaged in different activities in their everyday life, they need to allocate their daily time, materials, energy, and other inputs to fulfill those activities. The activity structure can affect the duration of activities and can to some extent affect material and energy inputs into activities. The duration of all activities is constrained by 24 hours per day, implying more time for one activity and less for others. Material inputs include people's everyday non-energy consumption (like food, clothing, home appliances, etc.), while energy inputs include energy for their daily energy services. Clearly, energy inputs into activities will result in direct carbon dioxide emissions when people engage in activities, while the consumption expenditures will lead to indirect emissions.[2] Combining the duration of activities with their direct and indirect emissions, carbon dioxide emissions per unit of time of a specific activity can be estimated. In the future, one or several dimensions of residents' time-use patterns may change, leading to different environmental outcomes. Regarding the direction of future changes, residents in less developed areas might follow their lifestyles or refer to the related policies that cause low-carbon time-use patterns in developed countries. Accordingly, with the pictures of residents' future time-use patterns including the dimensions of activity structure, activity duration, and activity consumption, the questions about how much carbon dioxide emissions residents will emit and what kind of time-use patterns may contribute to a low-carbon society can be answered.

3.2. Time-use-based approach for carbon dioxide emissions analysis

The principle of a time-use-based approach for carbon dioxide emissions analysis is to decompose the impact of activity structure, activity duration, and activity consumption on carbon dioxide emissions. And the core of this method is to calculate the carbon

[2] The indirect carbon emissions of residents are defined as the emissions resulting from the whole life cycle of products and services used by the residents, including those associated with their manufacturing and eventual transport, retail etc.

intensities of activities based on total carbon dioxide emissions and activity structure and duration. Carbon dioxide emissions caused by households include direct and indirect components (Zhang et al., 2015b).

Household direct carbon dioxide emissions: Household direct emissions are generated from household fuel combustion (e.g. coal, gas and oil). Note that emissions related to heat and electricity are excluded in the household direct carbon dioxide emissions.[3] Household direct carbon dioxide emissions can be expressed as

$$E_{k,i}^{D} = \alpha_{k,i} \times \sum_{n} \left(A_{n,t} \times h_n \times c_n \times O_n \times \frac{44}{12} \right) \quad (1)$$

where $E_{k,i}^{D}$ is direct carbon dioxide emissions resulted from the ith end-use energy services of residents' kth time-use activity; $A_{n,t}$ is the real consumption of the nth fuel[4] by residents at year t. h_n is the net calorific value of the nth fuel; c_n is the carbon content of the nth fuel; and O_n is the carbon oxidation rate of the nth fuel. A detailed description of the computing method is presented in Yu et al. (2016); $\frac{44}{12}$ is the relative atomic mass between carbon dioxide (44) and carbon (12); and $\alpha_{k,i}$ is the proportion of carbon dioxide emissions resulted from the ith end-use energy services of residents' kth time-use activity.

Household indirect dioxide emissions: Household indirect emissions are embedded in the production process of goods and services that households consume. The input-output analysis (IOA) is one of main methods[5] used to calculate indirect emissions from electricity and heating and other consumption expenditures (Turconi et al., 2013). Household indirect emissions are calculated by multiplying consumption expenditures on non-energy goods and services by carbon intensities of production sectors producing the corresponding non-energy goods and services, which carbon intensities are measured by sectoral carbon emissions per unit of sectoral total outputs derived from IO tables. Therefore, one specific activity's indirect carbon emissions can be expressed following as (Cohen et al., 2005; Jalas, 2002; Pachauri, 2004)

$$E_{k}^{In} = \sum_{j} c_{k,j} \times e_j \quad (2)$$

where, E_{k}^{In} is the indirect emissions of the activity$k$; $c_{k,j}$ is the jth household consumption expenditure related to the activity k; and e_j is the carbon intensity per unit of total output value of household expenditure$j$.

Carbon intensity of activities: Combining the activity structure, activity duration, and the above calculated carbon dioxide emissions (see Appendix A), the carbon intensity of activity k, namely carbon dioxide emissions per unit of activity time, can be estimated as

$$I_k = \frac{\sum_{i=1}^{6} E_{k,i}^{D} + E_{k}^{In}}{t_k} \quad (3)$$

where, I_k is the carbon intensity of the activity k; $E_{k,i}^{D}$ is the direct dioxide emissions of the end-use energy service i related to the time-use activity k. $i = 6$, namely six end-use energy services including space heating and cooling, lighting, cooking, water heating, home appliance and personal transportation; and t_k is the duration of the activity k.

It is worth mentioning that, though we mainly focus on carbon dioxide emissions from producing household consumption, some other greenhouse gas emissions rather carbon dioxide emissions are dominated in some consumption categories, for example major sources of emissions in food production include nitrous oxide (N_2O) from fertilizer application in crop production and manure treatment in livestock production, and methane (CH_4) from flooded rice paddies and ruminant enteric fermentation (Yue et al., 2017). However, to be in line with other consumption categories and compare with existing research, here we only consider carbon dioxide as main emissions of food and all other consumption.

4. Data

4.1. Data source

For the empirical analysis, we take China as the context. We further investigate potential time-use patterns for Chinese residents based on the comparisons of time allocation and activity carbon dioxide intensities in six typical developed countries: Japan, Australia, Germany, Finland, UK, and U.S. The data used here are given as follows.

(1) China

The benchmark year of this analysis for China is set as 2008 because the time-use survey in China was carried out in 2008. Time-use data are from the 2008 China Time Use Survey (CTUS) (National Bureau of Statistics of China, 2009), the first large-scale time-use survey in China. Note that though China has conducted the second time-use survey in 2018, the time-use data are not available yet. Details of the time-use survey and data are introduced in Appendix B.

Household direct energy consumption data. We calculate the direct carbon dioxide emissions using Eq. (1) by employing the final household energy consumption data in China Energy Statistic Yearbook (National Bureau of Statistics of China, 2010b). Note that the data for household energy consumption excludes those for electricity and heat. Based on Zheng et al. (2016), we distribute urban and rural residents' total emissions to the six end-use energy services: space heating and cooling, lighting, cooking, water heating, home appliance, and private transportation.

Household consumption expenditure data. The China Statistic Yearbook (2009) provides urban and rural household consumption expenditure data on eight aggregate categories (Zhang et al., 2017). To better match with time-use data, these eight categories are further divided into more detailed consumption categories based on the Household Consumption Expenditure Classification (2013), some provincial yearbooks (e.g. Bureau of statistics of Shandong (2009); Bureau of statistics of Gansu (2009)) and existing researches (e.g. He (2011); Zheng et al. (2016)) (see Appendix A).

Carbon intensities of household consumption expenditures. The China Statistic Yearbook (2009) provides direct energy

[3] It is worth noting that fossil fuels related carbon emissions for heating are included in household direct emissions, while electricity related emissions for heating are excluded.

[4] Household fuel consumption includes raw coal, cleaned coal, other washed coal, briquettes, coke, coke oven gas, other gas, other coking products, crude oil, gasoline, kerosene, diesel oil, fuel oil, liquefied petroleum gas, refinery gas, other petroleum products, and natural gas.

[5] Different from IOA, life cycle analysis (LCA) is also generally used to calculate household indirect emissions, and is a bottom-up approach that uses engineering data and process-specific information preferably obtained directly from the plants (Turconi et al., 2013). However, due to the unavailability of data, such as local power or heating plants' data across countries, we have to use the IOA in our paper to calculate the indirect emissions from electricity and heating and other consumption expenditures for consistency across countries.

Table 1
Data sources for developed countries.

Country	Time use data	Household consumption data	Household direct emissions data	Input–Output data	Sectoral emissions data
Japan	Survey on Time Use and Leisure Activities (2011)	Japan Statistical Yearbook (2014), OECD.Stat*	Handbook of Japan's & World Energy and Economic Statistics (2015)	World Input–Output Database (WIOD)**	WIOD
Australia	How Australians Use Their Time (2006)	Household Expenditure Survey: Detailed Expenditure Items, OECD.Stat	WIOD, Energy Technology Perspectives (2017)	WIOD	WIOD
Germany	Zeitverwendungserhebung (2012/2013)	OECD.Stat	WIOD, Energy Consumption of Private Households (Temperature Adjusted) of Federal Statistical Office (Destatis)	WIOD	WIOD
Finland	Time Use Survey of Statistics Finland (2009–2010)	OECD.Stat	Emissions into Air by Industry in the Statistics Finland, Energy Consumption in Households of Statistics Finland	WIOD	WIOD
UK	United Kingdom Time Use Survey (2014–2015)	OECD.Stat	Greenhouse Gas Emissions in the United Kingdom (1990–2014), Energy Consumption in the United Kingdom	WIOD	Fuel Use by Economic Sectors in the United Kingdom (1990–2014)
U.S.	American Time Use Survey (2009)	OECD.Stat	Emissions of Greenhouse Gases in the United States (2009)	WIOD	WIOD

Note: * The database of OECD.Stat can be accessed at http://stats.oecd.org; ** The database of WIOD can be accessed at http://www.wiod.org/home. More detailed descriptions of WIOD can be found in Mi et al. (2016).

consumption data in 43 sectors, and we calculate their carbon dioxide emissions using Eq. (1). As for sectors without total output data for 2008, we use the industrial sectoral gross output value instead (National Bureau of Statistics of China, 2010a). Referring to Wei et al. (2007), we match eight expenditure categories with the related production sectors, and calculate carbon intensities for each expenditure category.

(2) Developed countries

The data used to calculate carbon intensities of time-use activities in other developed countries are given in Table 1. Especially, these data on carbon emissions from households and production sectors are from official and generally published source, and do not have the question of double counting.

It is worth mentioning that, for all countries including China and the target developed countries, the direct household carbon emissions are estimated based on household fuel consumption excluding electricity and heat.

4.2. Data matching

The activity categories in the time-use survey are common international lexical categories, including aggregate categorization (10 categories in the Chinese data), and detailed categorization (114 categories in the Chinese data). The activity categories in the paper are comparable to some previous literature (Druckman et al., 2012; Jalas, 2002, 2005). However, one difference is that the activity Travel is set as a separate category instead of regarding it as an integral part of other activities. This is because considering the duration of one specific activity with travel time cannot reflect the actual time people engage in that activity and the impacts of policies targeting only the travel activity or the associated activity cannot be evaluated if we put them together. Each activity category can be matched with specific consumption expenditures. For some activity categories, the allocation is relatively obvious, but some time-use categories are less-specifically defined by the objects that are being used. Besides, some expenditures play an infrastructure role in the everyday life of residents. For the case when the consumption expenditures can be allocated to multiple activities, we decompose the expenditures by the duration of related activities. It is worth mentioning that we exclude a part of expenditures that cannot be allocated to specific activities. Similarly, regarding the energy consumption and emissions for end-use energy services that can be allocated to multiple activities, we also adopt the proportions of activity duration to decompose the energy services.

Note that to make our analysis comparable between China and developed countries, we are using the same allocation of consumption expenditures and energy consumption to time-use activities for China and for other developed countries (Japan, Australia, Germany, Finland, UK, and U.S.), as expressed in Appendix A.

5. Results and analysis

5.1. Current situation of time-use patterns in China

Fig. 2 shows how an average Chinese resident allocates his or her daily time in a weighted day.[6] In a 24-hour day, an average Chinese resident spends the most time on *Sleep and Rest*, accounting for 37.5% of total daily available time (9.0 hours). *Paid work and Volunteer work* is the second-most time-consuming activity, with 4.5 hours. The activities of *Eating and Drinking*, and *Food preparation and Dish washing* consume 2.8 hours per day. Furthermore, the ten activities, including *Sleep and Rest*, *Paid work and Volunteer work*, *Watching TV and Videos/DVDs*, etc., account for 90% of the daily total available time. The other activities such as *Spending time with friends/family*, *Study*, *Repairs*, *Gardening and Pet care*, etc., only account for 10% of daily total available time.

We further analyze daily time-use patterns of urban and rural residents, as shown in Fig. 3. The time allocated to some activities has a notable difference between these two areas. In particular, urban residents spend less time on *Paid work and Volunteer work*, but more time on *Watching TV and Videos/DVDs*, *Listening to Radio and Music*, *Travel*, *Sport and Outdoor activities*. While this contrasts with how rural residents spend their time. One of the main reasons could be that the level of mechanization is very low in rural areas, and heavy farm work makes residents work long hours in the field

[6] The weighted day means that a weight of 5/7 is assigned to time spent on weekdays and 2/7 to time spent on weekend days.

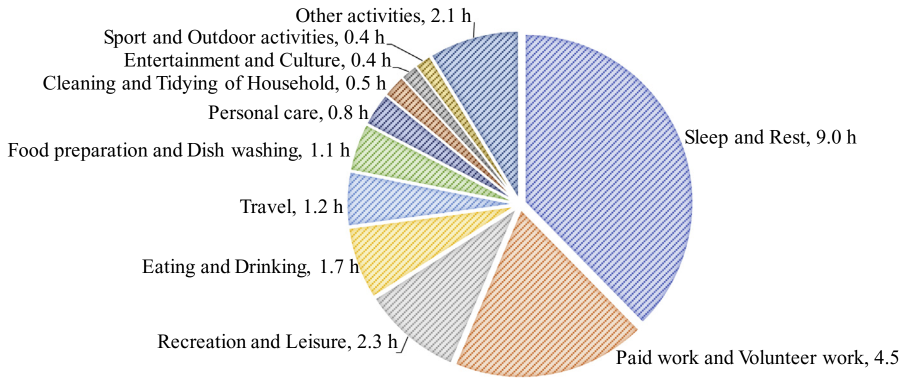

Fig. 2. Daily time use of an average Chinese resident (total time: 24 hours).

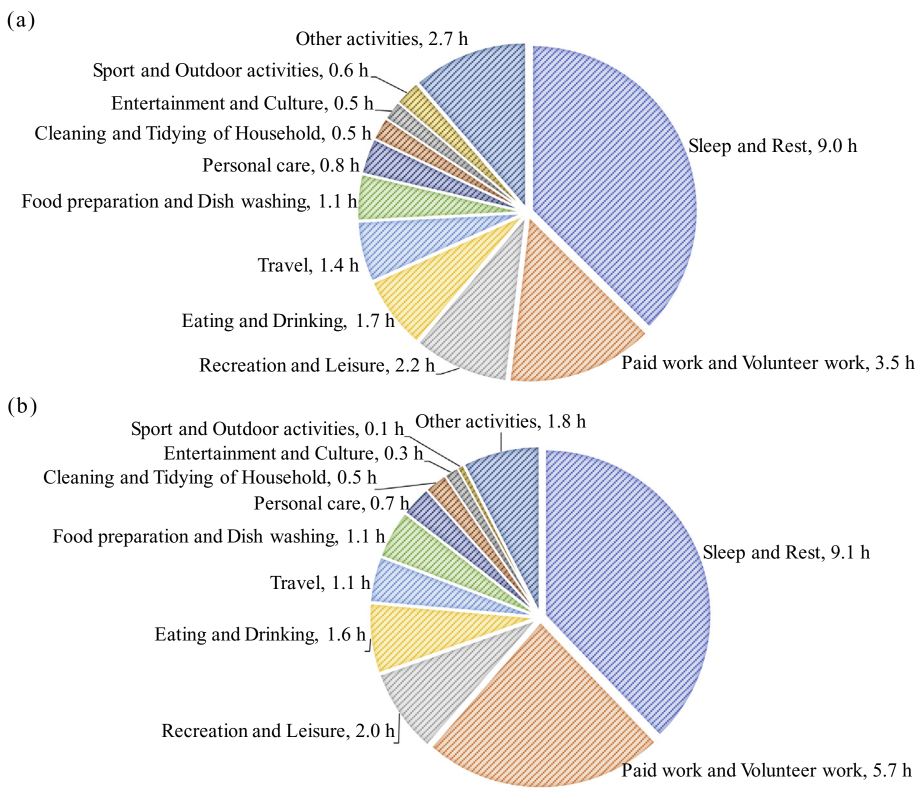

Fig. 3. Daily time allocation of an average Chinese resident in urban (a) and rural (b) areas (total time: 24 hours).

(Zhou, 2011). Another reason could be that rural residents always work for their self-owned business.

5.2. Carbon intensities of time-use activities in China

As there are notable differences in time-use patterns between urban and rural residents, we estimate respective carbon intensities of time-use activities in these two areas, and further analyze the relationship between daily activities and inputted materials. Fig. 4 illustrates the duration and carbon intensities of different activities, and the area below the broken line represents the carbon dioxide emissions of different activities. For example, the duration of the activity *Sleep and Rest* for urban residents is 9.0 hours/day, and its carbon intensity is 0.03 kg CO_2/hour. The area below, namely its carbon dioxide emissions, is 0.27 kg CO_2/day.

Urban residents have higher carbon-intensive activities than rural residents. There are substantial differences in the distribution of carbon intensities of activities. Although the categories of the highest carbon-intensive activities are similar for urban and rural areas, their carbon intensities are notably different. In urban areas, some activities, such as *Sleep and Rest*, *Recreation and Leisure*, *Eating and Drinking*, and *Travel*, have longer duration and lower carbon intensities than other activities. The activity of *Repairs, Gardening and Pet care* has higher carbon intensity and shorter duration. Activities, such as *Entertainment and Culture*, *Sport and Outdoor activities*, etc., belong to the third group, which has lower carbon intensities and shorter duration. Some activities, such as *Food preparation and Dish washing*, *Personal care*, etc., have higher intensities and longer duration compared with other activities. Similar phenomena can be found for rural residents in rural areas,

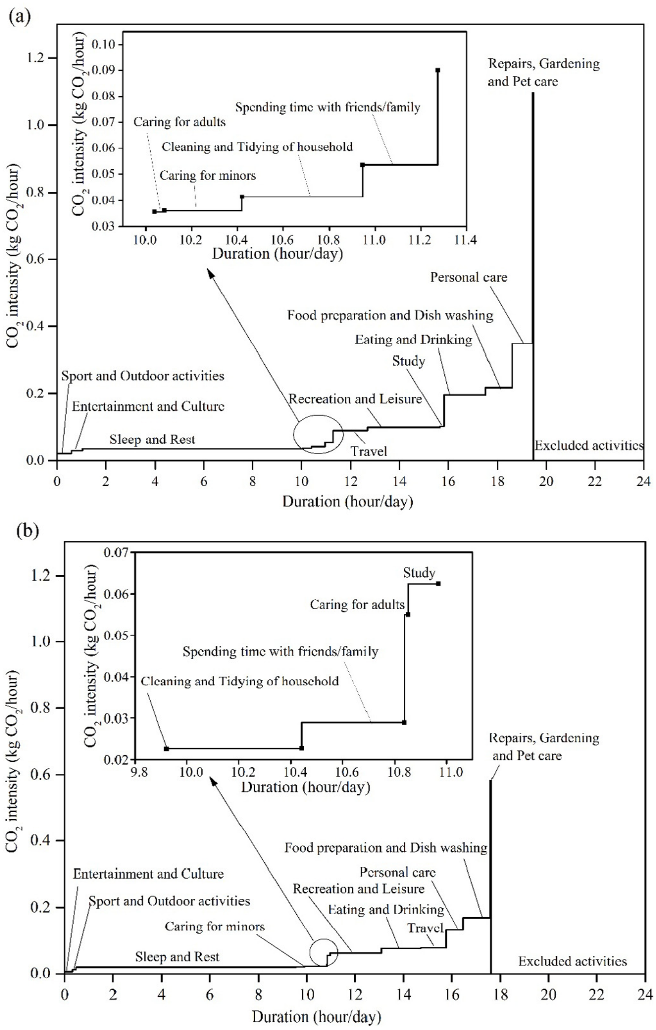

Fig. 4. Carbon intensities of time-use categories in urban (a) and rural (b) areas.

but the carbon intensities of activities are quite a bit lower compared with residents in urban areas. For example, the three lowest carbon intensive time-use activities in urban area are *Sport and Outdoor activities*, *Sleep and Rest*, *Entertainment and Culture*, while the three highest carbon intensive activities are *Food preparation and Dish washing*, *Personal care*, *Repairs, Gardening and Pet care*. Though rural residents have same lowest and highest carbon intensive activities as those of urban residents, their carbon intensities are dramatically lower than the latter.

To understand the composition of CO_2 intensities of time-use activities, we further decompose carbon dioxide emissions of different activities into two sources, i.e. direct emissions related to fuel consumption and indirect emissions embedded in the consuming goods and services, and estimate direct and indirect carbon intensities of activities, as shown in Fig. 5. We can observe that, the distribution of direct and indirect carbon intensities to the same category of time-use activity is similar between urban and rural areas. In urban areas, for most of time-use activities, such as *Food preparation and Dish washing*, *Travel*, *Relaxing and leisure* etc., majority of carbon dioxide emissions directly come from the energy services. While indirect emissions dominated for activities including *Eating and Drink*, *Repairs, Gardening and Pet care*, *Personal care* etc. The performance of carbon intensities of time-use activities for rural residents presents similar features, but with evident differences in the size of the intensity for all activities.

6. Discussions of low-carbon routes for changing time-use patterns in China

Given the significant differences of structure, duration and carbon intensities of different activities among Chinese people, it implies that changing individual time-use patterns might substantially affect the composition and aggregate amount of residents' energy consumption and corresponding carbon dioxide emissions. Consequently, we turn our concern of leading sustainable society to exploring low-carbon time-use patterns. Although shifts in residents' time-use patterns have been identified based on the evidence in developed countries (Gershuny, 1987; Höjer et al., 2011; Juster et al., 2003), how Chinese time-use patterns will evolve is unclear. To find a possible low-emission route for guiding Chinese time-use patterns in the future, we regard some typical developed countries in Asia (Japan), Oceania (Australia), Europe (Germany, Finland, UK), and America (U.S.) as potential changing directions for Chinese people, and analyze their time-use patterns and carbon intensities of activities.

6.1. Time-use patterns and activity carbon intensities for residents across different countries

The time-use patterns of residents from seven typical countries are shown in Fig. 6. It is observed that there are outstanding characteristics in the time-use patterns between China and developed countries. Compared with China, residents in developed countries usually spend more time on activities such as *Recreation and Leisure*, *Personal care*, *Sport and Outdoor activities*, *Cleaning and Tidying of household*, but spend less time on activities of *Sleep and Rest*, *Paid work and Volunteer work*, *Travel*, and *Food preparation and Dish washing*. Such differences might lead to substantial gaps of CO_2 emissions from residents.

We also calculate the CO_2 intensities of time-use activities across different countries, as depicted in Fig. 7. This shows that activities including *Personal care*, *Repairs, Gardening and Pet care*, *Food preparation and Dish washing*, and *Travel* have relatively higher CO_2 intensities compared with other activities in all developed countries. To understand the reason behind this, a detailed decomposition of the energy and emission carriers is given in Appendix C. Regarding the performance of different countries, most time-use activities show the lowest intensities in Finland, while most activities show the highest intensities in the U.S. An important reason is that, compared with other countries, American residents allocate significantly more energy and non-energy consumption to engage in time-use activities (Du, 2015). To identify the reasons for the lowest emissions, we select six activities with the highest carbon intensities and further examine the carbon intensities of activities among different countries.

It is worth mentioning that, carbon emissions of these activities in total account for 81%, 91%, 82%, 81%, 82%, 88%, 72%, and 80% of total (direct and indirect) emissions in Japan, Australia, Germany, Finland, UK, U.S., urban China, and rural China, respectively.

6.1.1. Travel

While *Travel* time, for which the average value is about 1.0 hours/day, only shows slight differences in selected countries, CO_2 intensities of *Travel* are significantly different across these countries. Specifically, Americans have the highest intensity for *Travel* (9.4 kg CO_2/hour), followed by Australians (5.5 kg CO_2/hour). Europeans rank third, and Japanese have the lowest CO_2 intensities from their *Travel*, as depicted in Fig. 8.

Higher mode share of public transport and shorter commuting

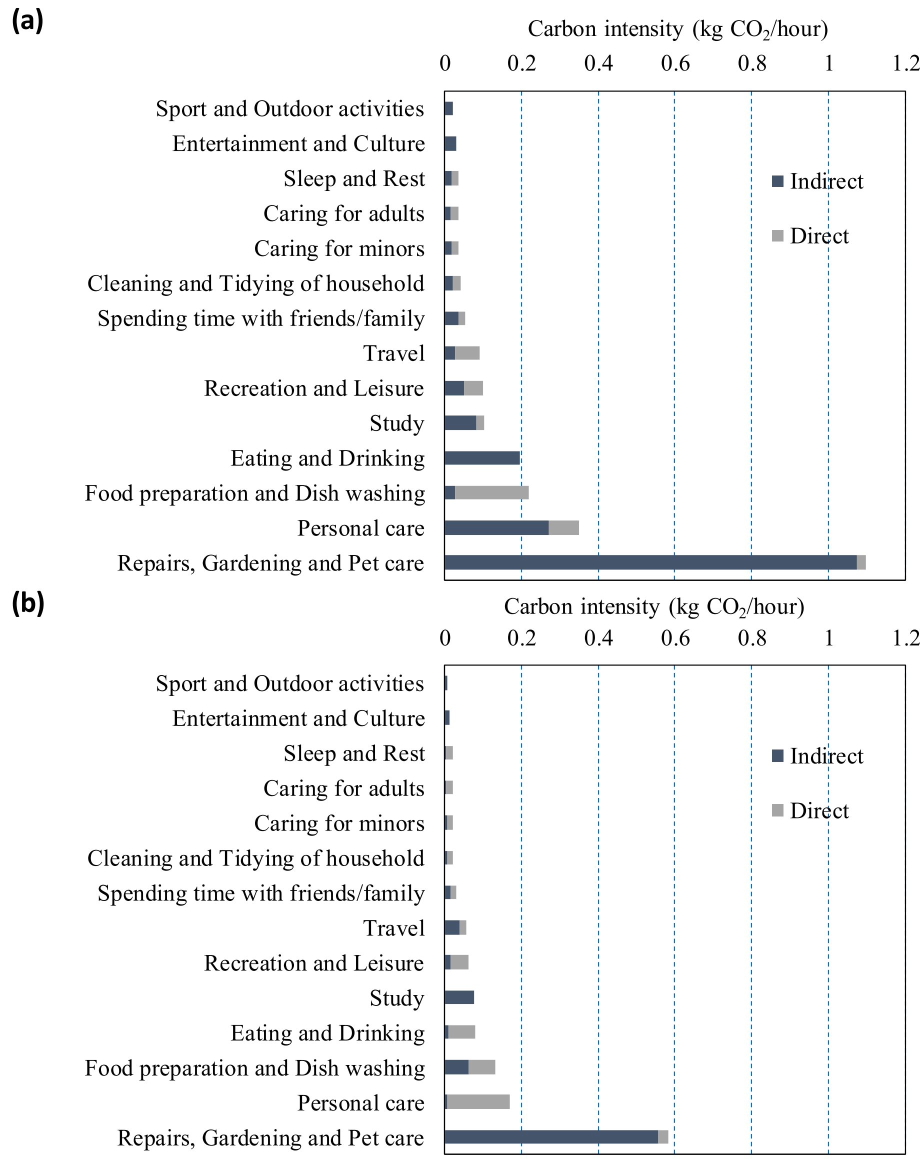

Fig. 5. Indirect and direct carbon intensities of time use categories in urban (a) and rural (b) areas
Note: The CO_2 emissions from electricity and heat are only included in indirect part.

distance to work are two important factors causing Japan to have the lowest CO_2 intensity of *Travel* (Kempton and Kubo, 2000). On the one hand, U.S. and European countries are more car dependent than Japan. On the other hand, the typical commuting distance in Japan is only about 67% of the average U.S. daily commuting distance (30 km), and the average daily commuting distance in European countries is between 5 and 30 km (Silva et al., 2009). Some additional policies also make Japan have a less intensive *Travel*, for example, the Action Plan on Promoting Low Pollution Vehicles, Kei-car Program, Eco-car Tax Breaks and Subsidies (Geller et al., 2006; Lipscy and Schipper, 2013), etc.

6.1.2. *Food preparation and dish washing*

The time-use activity of *Food preparation and Dish washing* is the second highest carbon-intensive activity in most countries. Significant differences in CO_2 intensities and duration of *Food preparation and Dish washing* exist among countries. We can observe that, the activity of *Food preparation and Dish washing* is less carbon intensive and less time consuming in European countries, such as UK, Germany and Finland. Contrarily, Australians spend more time on *Food preparation and Dish washing* with much more CO_2 embedded than other countries, as depicted in Fig. 9.

The activity of *Food preparation and Dish washing* mainly consumes energy services including home appliances, water heating, cooking, and non-energy consumption of refrigerators, freezers, dishwashers, etc. In terms of home appliances for storing food, some policies have been implemented in Europe to promote enhanced appliance efficiency, such as Energy Label Programs on durable household appliances. As a result, almost 90% of refrigerators reach efficiency level A (Lapillonne et al., 2015). Regarding preparing meals during cooking, most cooking appliances use electricity instead of gas in Europe (Hager and Morawicki, 2013). European regulations require typical gas stove conversion efficiencies of at least 52% (European Commission, 2010). Concerning work done after the meal, one good measure to reduce its energy is that European countries encourage new energy-efficient

Fig. 6. Time-use patterns of different countries.[7].

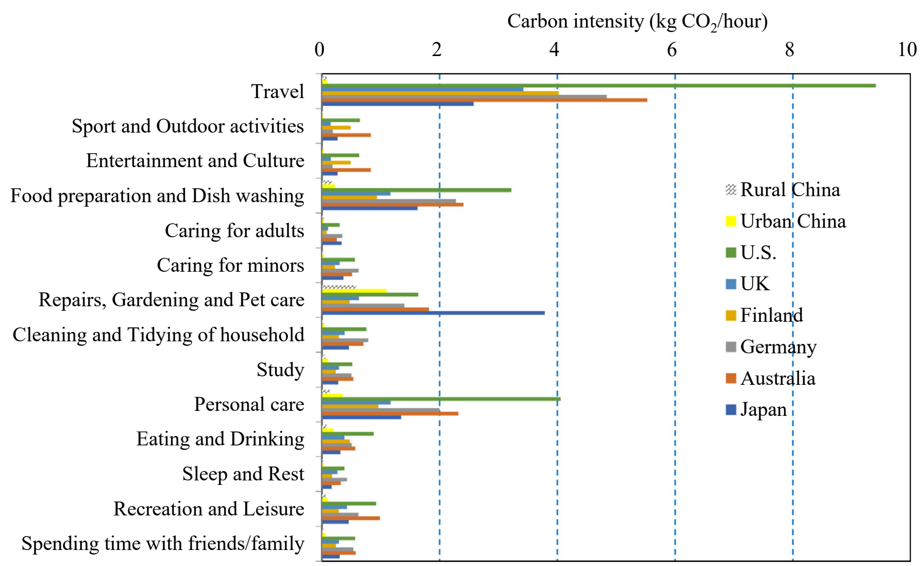

Fig. 7. CO_2 intensities of time-use activities across different countries.

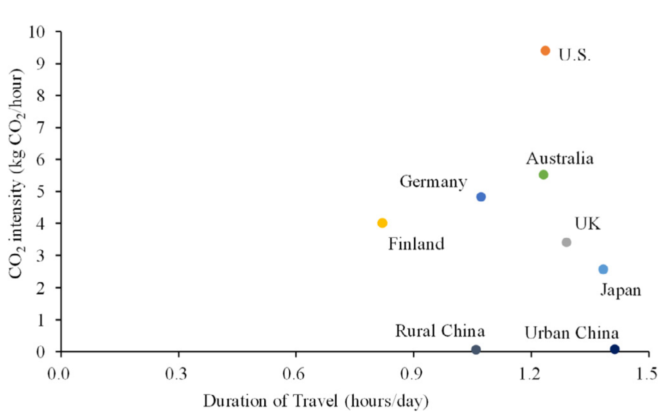

Fig. 8. CO_2 intensities and duration of Travel in different countries.

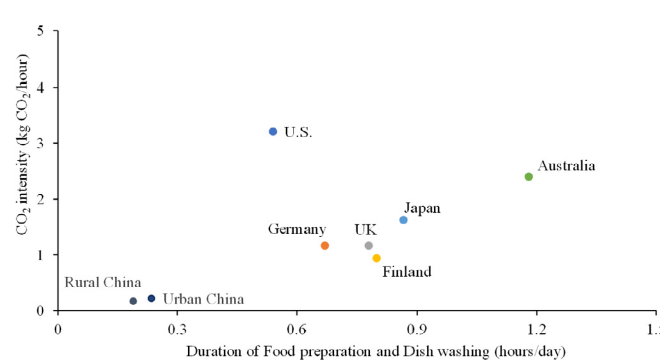

Fig. 9. CO_2 intensities and duration of Food preparation and Dish washing in different countries.

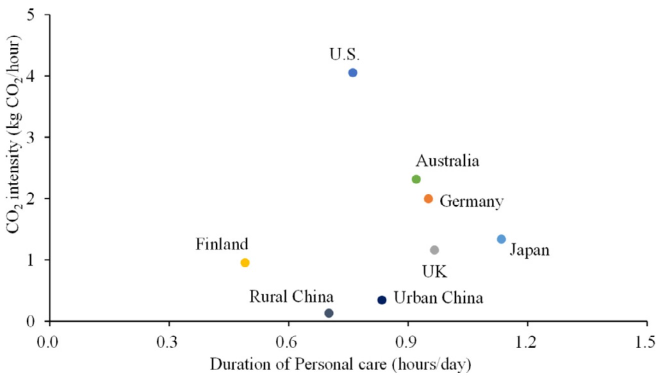

Fig. 10. CO_2 intensities and duration of Personal care in different countries.

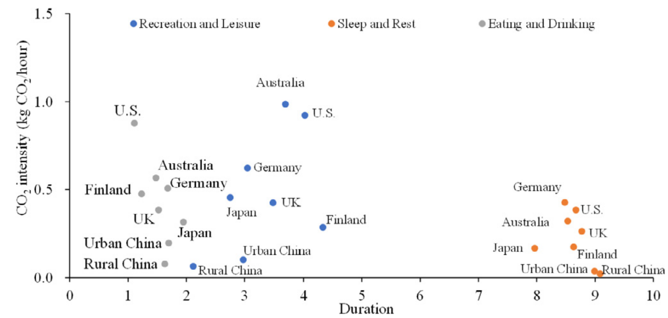

Fig. 11. CO_2 intensities and duration of three activities in different countries.

dishwashers and also educate resource saving during manual washing of dishes by applying the "Best Practice Tips[8]" (Fuss et al., 2011).

6.1.3. Personal care

Except for Finland and U.S., households in the remaining countries are revealed to allocate similar amounts of time to the activity of *Personal care*, for which the duration is about 1.0 hour/day. However, the CO_2 intensities of *Personal care* show an obvious gap across different countries. The activity of *Personal care* shows the highest intensity for Americans, while the lowest intensity is for Finnish, Japanese and British people also have relatively less intensive *Personal care*, as depicted in Fig. 10.

Bathing or showering is one of the main components in the activity of *Personal care*, and hot water is mainly used for personal hygiene. To increase the energy efficiency of dwellings, European governments have enacted policies like Energy Performance of Buildings Directive (EPBD)[9] (Santin et al., 2009). Furthermore, the European Directive of Cogeneration (2004/8/CE) promotes cogeneration (i.e. combined heat and electric power production, CHP), and in some northern European countries such as Finland, more than 70% of the district heat and constant domestic hot water is already produced in CHP plants (Rinne and Syri, 2013; Salomón et al., 2011). In Japan, in addition to the high energy-efficiency standard, people generally bathe in a bathtub, and the bath water in the tub is often reheated and reused (Murakami et al., 2007; Wilhite et al., 1996).

6.1.4. Recreation and Leisure, Sleep and Rest, and Eating and Drinking

Recreation and Leisure, *Sleep and Rest*, and *Eating and Drinking* are three time-consuming activities that are less CO_2 intensive. They are less carbon intensive in Japan, UK and Finland, but more carbon intensive in the U.S. and Australia, as depicted in Fig. 11.

Space heating and cooling and lighting are important energy services input into these three activities. The lifestyle pattern is an important reason why there is less intensive space heating, cooling and lighting in Japan. In terms of space heating in Japan, household space heating behavior is personal heating, compared with the central heating used in other developed countries. In terms of lighting, ceiling fixtures and fluorescent lights are common in Japanese households. Meanwhile, lights are normally used in the room when they are in (Wilhite et al., 1996). On the other hand, some implemented policies also promote the less energy consumption for space heating and cooling, for example, Housing Efficiency Assessment and Labeling Systems, Comprehensive Assessment System for Building Environmental Efficiency, Low-interest Loans for Residential Buildings, and Japanese Dress Code (Murakami et al., 2007).

6.2. Daily CO_2 emissions per capita for Chinese residents

Although the current CO_2 intensities of time-use activities in China are found to be much lower than those in the selected developed countries, a shift of Chinese time-use patterns could be foreseen following the evidence from other countries if no intervention is implemented. In light of the abovementioned significant differences of activity patterns and consumption patterns of activities, shifting to new time-use patterns for Chinese people might cause substantial changes of environmental outputs. To quantify these changes, we further evaluate future carbon dioxide emissions produced by an average Chinese resident by considering the potential shift of activity patterns and consumption patterns referring to the evidence of developed countries. We observe that Japanese and European people have lower carbon-intensive activities while Americans have activities with the highest intensity. Consequently, we sketch five scenarios to investigate the impacts of likely changes of Chinese time-use patterns on carbon dioxide emissions (Tables 2 and 3), including a business-as-usual (BAU) scenario, low-emission scenario (LES), high-emission scenario (HES), and two hybrid scenarios (HS1 and HS2). Detailed descriptions of the five scenarios are interpreted in Appendix D, and the consumption structures in different countries and under the hybrid scenario are presented in Appendix E. Differences of carbon dioxide emissions among the five scenarios indicate an evident impact of time-use pattern shifts on emissions.

6.2.1. Amount of change of daily CO_2 emissions per capita by considering time-use pattern changes

Chinese residents will have the lowest daily emissions per capita of 10.1 kg CO_2 if they shift to the duration of activities in the U.S. and the intensities of hybrid activities (HS2), as depicted in Fig. 12. Conversely, China's residents will have the highest daily emissions per capita of 26.7 kg CO_2 if they shift to both the duration and intensities of activities in the U.S. (HES). If they shift to the duration of

[7] Due to data availability, the survey years for the U.S., UK, Germany, Finland, Australia, Japan and China are 2009, 2014, 2012, 2009, 2006, 2009 and 2008, respectively. Considering that the lifestyle in developed countries remains relatively constant, therefore, we think that data surveyed in different years may not unduly influence this study. The total time of nine activities, except the category of Others in this figure, accounts for more than 82% in 24 h.

[8] Best Practice Tips are transferred from experimental knowledge of how to optimize the use of resources in manual dishwashing, and combined with the experience of everyday life in manual dishwashing.

[9] EPBD is obliged by all European member states from 2003 to implement performance-based energy regulations aimed at decreasing energy consumption in buildings in relation to heating, cooling, ventilation, lighting and domestic hot water (Santin et al., 2009).

Table 2
Descriptions of five scenarios.

Scenario		Activity pattern	Carbon intensities of activities
Both activity pattern and consumption pattern keep the same			
BAU	Urban China	China in 2008	China in 2008
	Rural China	China in 2008	China in 2008
Both activity pattern and consumption pattern shift to Japan			
Low-emission scenario	Urban China	Japan	Japan
	Rural China	Japan	Japan
Both activity pattern and consumption pattern shift to U.S.			
High-emission scenario	Urban China	U.S.	U.S.
	Rural China	U.S.	U.S.
Activity pattern shift to Japan and consumption pattern shift to hybrid			
HS1	Urban China	Japan	Hybrid scenario
	Rural China	Japan	Hybrid scenario
Activity pattern shift to U.S. and consumption pattern shift to hybrid			
HS2	Urban China	U.S.	Hybrid scenario
	Rural China	U.S.	Hybrid scenario

Table 3
Potential future trends of time-use patterns designed in the hybrid scenario.

Activity	Hybrid scenario
Spending time with friends/family	Finland
Recreation and Leisure	Finland
Sleep and Rest	Japan
Eating and Drinking	Japan
Personal care	Japan
Study	Finland
Cleaning and Tidying of household	Finland
Repairs, Gardening and Pet care	Japan
Caring for minors	Japan
Caring for adults	Finland
Food preparation and Dish washing	Finland
Entertainment and Culture	UK
Sport and Outdoor activities	UK
Travel	Japan

activities in Japan and the intensities of hybrid activities (HS1), the daily emissions per capita will be slightly higher than emissions from residents under the scenario of HS2. The daily emissions per capita will be 11.5 kg of CO_2 if they shift to both the duration and intensities of activities in Japan (LES). Although the daily emissions per capita in Finland are the lowest, there are too many differences of geolocation and physical conditions between Finland and China.

6.2.2. Structure change of daily CO_2 emissions by considering time-use pattern changes

When Chinese residents change their time-use patterns, both the duration and CO_2 intensities of their time-use activities will affect their daily emissions per capita (see Fig. 13). For both urban and rural residents, activities such as *Travel*, *Personal care*, *Repairs, Gardening and Pet care*, *Sleep and Rest*, and *Recreation and Leisure* have an obvious increase in their CO_2 emissions, compared with the daily emissions per capita from residents whose activity patterns and carbon intensities of activities are in 2008 (hereafter called the emissions under the BAU scenario). In other words, these activities make considerable contributions to the increasing emissions from residents. For example, when investigating the increasing emissions under the HS2 compared with emissions under the BAU scenario, for urban residents, *Travel*, *Personal care*, *Repairs, Gardening and Pet care*, *Sleep and Rest*, and *Recreation and Leisure* contribute to 37%, 9%, 22%, 13% and 10% of their total emissions increment, respectively. For rural residents, the contribution ratios of the above five activities are 34%, 10%, 20%, 14%, and 11%, respectively.

6.2.3. Consumption composition of time-use activities

To give a deep insight into where the emissions come from for those carbon-intensive time-use activities, we further analyze the consumption needed to carry out those time-use activities[10] (Fig. 14). Results show that different activities require diverse consumption inputs, with clothing and medical products as the main inputs for fulfilling the daily activity of *Personal care*; maintenance and repair consumption as the main inputs for *Repairs, Gardening and Pet care*; water, electricity, gas and other fuels as the main inputs for *Sleep and Rest*; food as the main input for *Eating and Drinking*; and newspapers, books and stationery, and audio-visual, photographic and information processing equipment as the main inputs for main inputs for *Recreation and Leisure*. These findings aid our understanding of how to reduce carbon dioxide emissions from these activities.

Based on the above results, we can clearly answer the future increasing energy consumption and emissions are induced by what kind of consumptions and these consumptions are triggered by what kind of activities. By doing this, the policy implications for

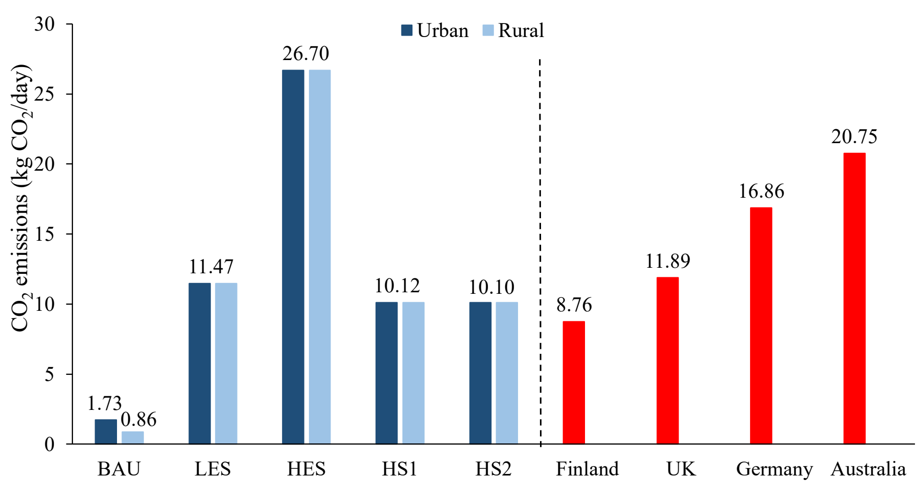

Fig. 12. Daily CO_2 emissions per capita for different scenarios and countries.

[10] The corresponding relationships between the household consumption and time-use activities are based on Appendix A.

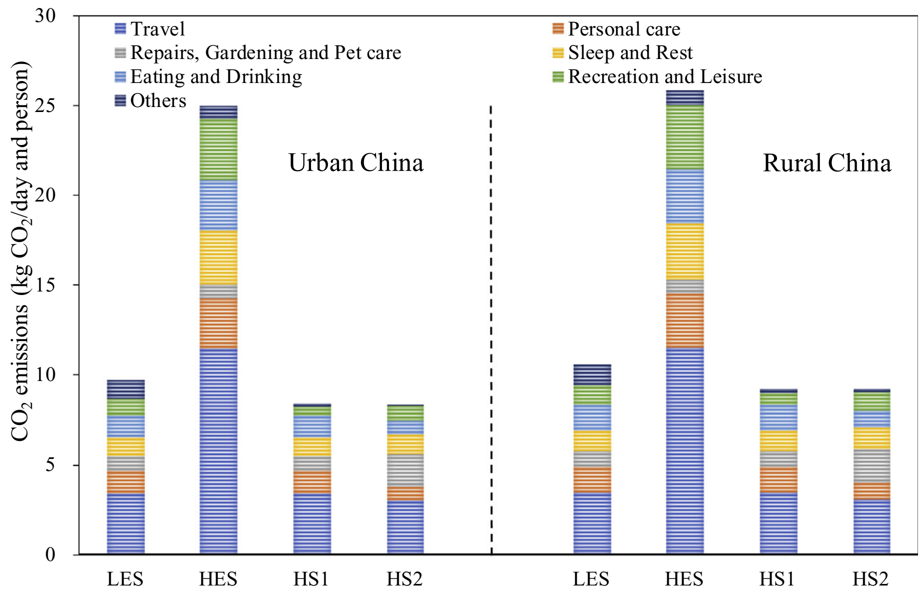

Fig. 13. Increments of CO_2 emissions for activities under different scenarios compared with BAU.

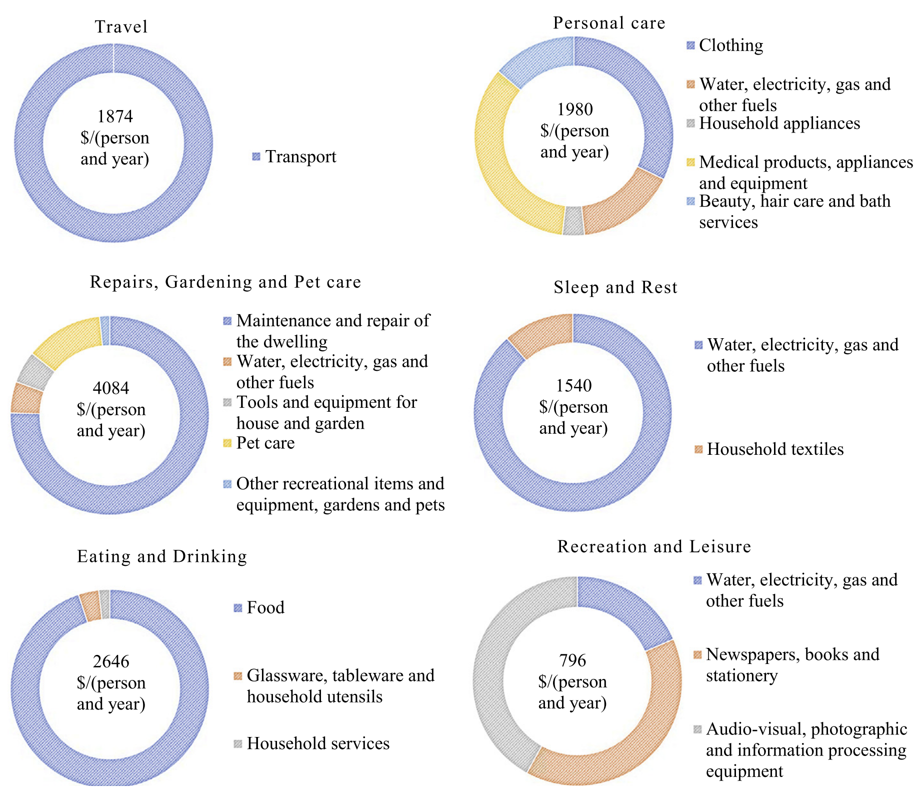

Fig. 14. Consumption composition of time-use activities under scenario HS2.

reducing carbon dioxide emissions could be extended to more fundamental dimensions related to people's time-use patterns, such as activity structure, activity duration and activity consumption.

7. Conclusions and policy implications

7.1. Conclusions

This study enriches the existing analyses which mainly investigate the impact of consumption on environmental outcomes from a time-use perspective. Time use offers a comprehensive perspective from which to consider the fundamental dimensions (i.e. why consumers consume goods and services and for what purpose) that may be influential for residents' emissions. Here, we take China as the empirical context and provide answers for the first time about how much carbon dioxide emissions will be emitted by Chinese residents after potential time-use pattern shifts. Several conclusions can be drawn.

For Chinese residents, a potential low-emissions route that guides people's time-use patterns may involve shifting to the activity patterns (incl. activity structure and activity duration) of American residents and the hybrid consumption patterns of activities composed of patterns found in Finland, Japan and UK. Specifically, as an average for the whole society, a combination of 8.7 hours/day for *Sleep and Rest*, 3.5 hours/day for *Paid work and Volunteer work*, 4.0 hours/day for *Recreation and Leisure*, etc., would constitute a low-carbon activity pattern. Regarding consumption patterns of activities, the Chinese Government could learn from and refer to the experience of developed countries, and encourage residents to shift to the consumption pattern found in: 1) Finland for activities such as *Spending time with friends/family*, *Recreation and Leisure*, and *Cleaning and Tidying of household*, etc.; 2) Japan for activities such as *Sleep and Rest*, *Eating and Drinking*, *Personal care*, etc.; 3) UK for activities such as *Entertainment and Culture*, and *Sport and Outdoor activities*. In this way, daily carbon dioxide emissions per capita in China would be approximately 10.1 kg CO_2.

Six main time-use activities will make a greater contribution to increasing daily emissions from residents if they shift their time-use patterns in the future. These six activities are *Travel*, *Personal care*, *Repairs, Gardening and Pet care*, *Sleep and Rest*, *Eating and Drinking*, and *Recreation and Leisure*. Therefore, reducing carbon emissions form household consumption that is input to engage in these activities will contribute considerably to reducing the emissions increment from carbon-intensive activities. For example, clothing, medical products, maintenance and repair consumption, water, electricity, gas and other fuels, food, newspapers, books and stationery, and audio-visual, photographic and information processing equipment are the main inputs for fulfilling the above six activities, and improving the energy efficiency of the production sectors related to these consumption categories might be a useful measurement.

7.2. Policy implications

We proposed some policy implications aiming at reducing carbon dioxide emissions by shifting residents' time-use patterns, based on the abovementioned findings:

(1) Activity structure shift: It is necessary to guide the urban and rural residents to reallocate time from carbon-intensive activities to low carbon-intensive activities, such as *Entertainment and Culture*, *Sport and Outdoor activities*, *Spending time with friends/family*, etc. Specially, to tackle some barriers for promoting low carbon-intensive activities, more infrastructures for, for example entertainment, culture, sports, outside activities etc., should be planned for residents.

(2) Activity duration change: The government could encourage and educate urban and rural residents to change the duration of carbon-intensive activities, such as *Food preparation and Dish washing*, *Personal care*, *Travel*, etc., such as choosing long duration but low carbon-intensive travel modes when time allows (the construction and promotion of railway transport), shortening the duration of *Personal care* (bathing or showering), and improving efficiency and shortening the time used to wash dishes.

(3) Consumption pattern change: The government and market could promote the consumption of green and environmentally friendly materials and goods relating to residents' daily activities, especially those related to carbon-intensive activities (e.g., *Food preparation and Dish washing*, *Personal care* etc.). On the other hand, policies or standards for improving the technology efficiency during material production processes are also necessary, especially in the sectors for producing the goods input to those carbon-intensive activities.

7.3. Limitations

This study can be further improved in the following aspects. First, the relationship between time use and consumption for different activities should be further investigated. Second, our results may be an underestimate compared with the overall carbon emissions related to residents as we mainly focus on non-work time. In addition, we made some assumptions when allocating the energy or expenditure to specific activities because of data limitations. To solve these problems, more detailed expenditure data and high-resolution energy consumption data are needed. Meanwhile, it is necessary to recommend the Chinese Government to conduct regular and ongoing time use survey as many developed countries have done. This study is relying on the only available national time use survey data collected in 2008. More recent data would be favorable for investigating the accurate change of time-use patterns. However, for this study, though current time-use patterns of Chinese residents may have been changed compared with that in 2008, we here mainly aim to explore a potential low-carbon time-use pattern for Chinese and the corresponding carbon emissions change. Therefore, using the 2008 time-use data for China may have impacts on the time-use pattern, but will not change our main conclusions related to the future society.

Acknowledgements

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Appendix A. Data matching

Table A.1
Activity categories, time use categories, related consumption expenditures and energy consumption by end-use categories

Activity category	Sub-activity category[a]	Consumption category[b]	Energy use by end-use category
Spending time with friends/family	• Talking and conversing (851) [c]	• Other recreational and cultural items (060202) • Recreational and cultural services (060203) • Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting
Recreation and Leisure	• Smoking (050) • Reading books, periodicals, other specified materials (811–813)	• Tobacco (010301) • Durables for recreation and culture (060201)	• Space heating and cooling

Table A.1 (*continued*)

Activity category	Sub-activity category[a]	Consumption category[b]	Energy use by end-use category
	• Watching/listening to TV, radio, audio devices (814–817) • Using computer technology for reading, video/audio, surfing the Internet (818–819) • Computer games (832) • Reading and writing mail (852)	• Other recreational and cultural items (060202) • Recreational and cultural services (060203) • communication (0502) • Water, electricity, gas and other fuels (0303)	• Lighting • Home appliances
Sleep and Rest	• Sleep and related activities (011–013)	• Household textiles (0403) • Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting
Eating and Drinking	• Eating and drinking (021–023)	• All food (0101), non-alcoholic beverages (0102), and alcoholic beverages (010302) • Catering services (0104) • Glassware, tableware and household utensils (040402) • Household services (040601)	
Personal care	• Personal hygiene and care (031–034)	• Clothing and footwear (02) • Large household appliances (040201) • Washing and sanitary items (040401), other items for routine household maintenance (040404) • Items for personal care (0405) • Repair of household appliances (040602) • Medical products, appliances and equipment (0701) • Beauty and hair care, bath services (080202) • Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting • Home appliances • Water heating
Study	• Homework, course review, research and activities related to general education (721) • Additional study, non-formal education and courses during free time (730) • Career/professional development training and studies (740)	• Education (only incl. textbooks, relevant articles, etc.) (0601) • Other recreational and cultural items (060202) • Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting
Cleaning and Tidying of household	• Cleaning and upkeep of dwelling and surroundings (521–522) • Care of textiles and footwear (531–533)	• Washing and sanitary items (040401), other items for routine household maintenance (040404) • Items for personal care (0405) • Water, electricity, gas and other fuels (0303)	• Home appliances • Space heating and cooling • Lighting
Repairs, Gardening and Pet care	• Planting flowers and grass (553) • Decoration, maintenance and small repairs (by yourself) (561–563) • Pet care (551–552)	• Maintenance and repair of the dwelling (excl. decoration) (0302) • Electronic tools and equipment for house (040203) • Household hand tools (040403) • Repair of household appliances (040602) • Other recreational and cultural items (060202) • Water, electricity, gas and other fuels (0303)	• Home appliances • Space heating and cooling • Lighting
Caring for minors	• Child care (611–614)	• Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting
Caring for adults	• Adult care (621–623)	• Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting
Food preparation and Dish washing	• Food management (511–512)	• Large household appliances (040201) • Small household appliances (040202) • Washing and sanitary items (040401) • Glassware, tableware and household utensils (040402) • Repair of household appliances (040602) • Water, electricity, gas and other fuels (0303)	• Space heating and cooling • Lighting • Home appliances • Water heating • Cooking
Entertainment and Culture	• Religious activities (040) • Hobbies, games and other pastime activities (831, 833–835) • Visiting/attending cinema, cultural, entertainment and sports events (841–844)	• Durables for recreation and culture (060201) • Other recreational and cultural items (060202) • Recreational and cultural services (060203)	
Sport and Outdoor activities	• Sports participation and related courses (821–826)	• Durables for recreation and culture (060201) • Other recreational and cultural items (060202)	
Travel	• Travel related to relevant activities (090, 199, 299, 399, 499, 599, 699, 799, 899)	• Transport (05)	• Personal transportation
Shopping outside[d]	• Shopping (541–542, 544)		
Formal education	• General education (711–713)		
Paid and Volunteer work	• Work for corporations/quasi-corporations, non-profit institutions and government (111–117, 120) • Work for household in primary production activities (210, 220, 230, 240, 250) • Work for household in non-primary production and construction activities (310, 320, 330, 340, 350, 360, 370, 380) • Work for household providing services for income (410, 420, 430, 440, 450, 460, 470) • Caring for and Helping non-household members (non-paid) (630)		

(*continued on next page*)

Table A.1 (*continued*)

Activity category	Sub-activity category[a]	Consumption category[b]	Energy use by end-use category
Others	Other specified/unspecified activities (060, 543, 570, 580, 640, 650, 750, 853, 860, 900)		

Note: a: The numbers in ( ) correspond to activity code in China Time Use Survey.
b: The numbers in ( ) correspond to the code in Classification of Individual Consumption (2013).
c: Talking and conversing in Time Use Survey includes face-to-face conversing, talking via telephone, SMS, internet, but socializing and communicating in American Time Use Survey only includes face-to-face conversing.
d: The carbon dioxide emissions of "shopping outside" are mainly from travel, and shopping-related travel time and carbon dioxide emissions are included in the activity of travel, so carbon dioxide emissions allocated to "shopping outside" will be zero.

Appendix B. Detailed description of time-use data of China

To understand Chinese work and life, a large-scale time use questionnaire survey was designed and first conducted in China in May 2008, administered by National Bureau of Statistics of China. This survey is the only large-scale time use survey in China so far, named 2008 China Time Use Survey (CTUS) (National Bureau of Statistics of China, 2009). It covered 10 provinces with varied economic levels, including Heilongjiang located in the northeastern region, and Hebei, Henan, Anhui, Zhejiang, Beijing located in the eastern region, as well as Gansu, Sichuan, Yunnan located in the western region. The survey contents include detailed respondents' time use diary and household/personal socio-demographic information. As a result, valid answers from 37,142 individuals aged between 15 and 74 in 16,616 households were collected. Table B1 is the statistics of the socio-demographic, and economic indicators for the survey sample. It can be seen that, the selected sample covered the whole population in terms of gender, marital status, education level, age, monthly income level, region, and occupation.

Table B.1
Descriptive statistics of the survey respondents

Variable	Survey data		National	Variable	Survey data		National
	Frequency	Percentage (%)	Percentage (%)		Frequency	Percentage (%)	Percentage (%)
Gender				Region			
Male	18,215	49.0	51.5	Urban	19,621	52.8	45.7
Female	18,927	51.0	48.5	Rural	17,521	47.2	54.3
Marital status				Household distribution across provinces			
Never married	4260	11.5	18.9	Anhui	2288	13.8	11.1
Married	31,502	84.8	74.0	Beijing	1500	9.0	3.4
Divorced	959	2.6	1.1	Gansu	1271	7.6	4.0
Widowed	421	1.1	5.9	Guangdong	1478	8.9	15.3
Education level				Hebei	2098	12.6	11.5
No schooling	1625	4.4	7.5	Heilongjiang	1650	9.9	7.4
Primary school	6250	16.8	31.2	Henan	2398	14.4	15.3
Junior secondary school	12,898	34.7	40.9	Sichuan	900	5.4	15.2
Senior secondary school	9422	25.4	13.7	Yunnan	1544	9.3	6.9
College and higher level	6947	18.7	6.7	Zhejiang	1489	9.0	9.9
Age (years old)				Total	16,616	100.0	100.0
15–19	2029	5.5	9.9	Employment			
20–24	1700	4.6	8.7	Average number of employed persons per household	1.6 person		1.5 person
25–29	2383	6.4	8.2				
30–34	3219	8.7	8.8	Occupation			
35–39	4977	13.4	11.7	1. Workers	3206	8.6	
40–44	5331	14.4	12.2	2. Employees	3476	9.4	
45–49	4478	12.1	9.1	3. Farmers	10,735	28.9	
50–54	4744	12.8	9.8	4. Migrant workers	2449	6.6	
55–59	3641	9.8	8.3	5. Business farmers	398	1.1	
60–64	2334	6.3	5.6	6. Salesmen	554	1.5	
65–69	1476	4.0	4.2	7. Service personal	1659	4.5	
70–74	830	2.2	3.6	8. Cadres	2081	5.6	
Monthly Income per person (US dollars)				9. EMS staff	1461	3.9	
(1 US dollar = 6.9 CNY in 2008)							
0	5524	14.9		10. Self-employed people	969	2.6	
(0, 72]	7219	19.4		11. Private business people	264	0.7	
(72, 144]	9869	26.6		12. Unemployed people	993	2.7	
(144, 288]	9569	25.8		13. Retirees	3882	10.5	
(288, 720]	4531	12.2		14. Full-time students	1957	5.3	
(720, 1440]	373	1.0		15. Home-makers	1642	4.4	
>1440	57	0.2		16. Others	1416	3.8	
Average income per person (US dollars)	Urban US $225.6 Rural US $65.7		Urban $206.1 Rural $57.5	Employment rate (people% with occupation of category 1–11)	27,252	73.4	

Source: Descriptive statistics for the survey sample is obtained from 2008 China TUS; and national statistics is obtained from China Statistical Yearbook (2009).

Appendix C. Carbon dioxide emissions from energy carriers of activities across countries

Fig. C.1 exhibits direct and indirect carbon dioxide emissions of the four highest carbon-intensive activities across different countries.

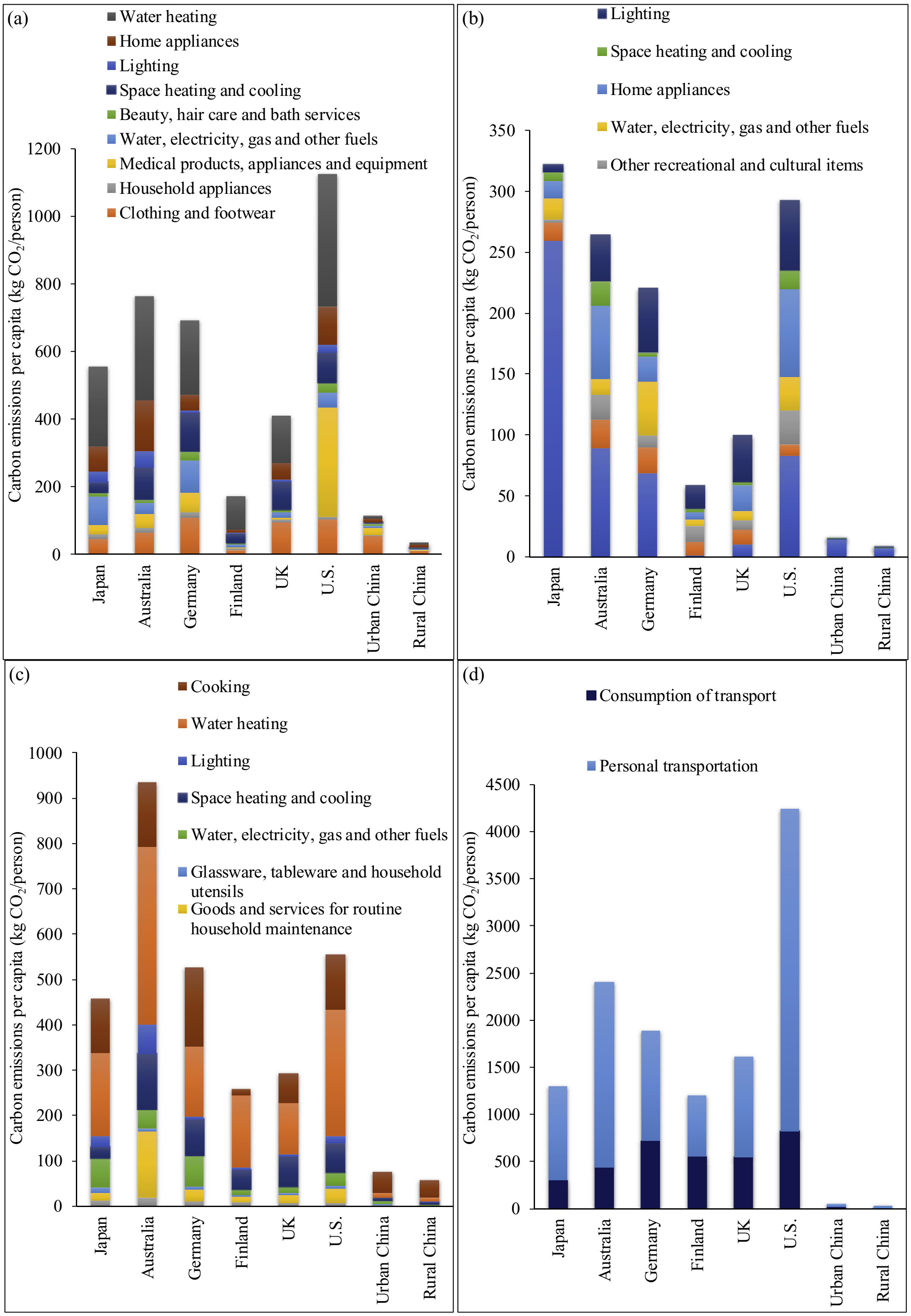

Fig. C.1. Carbon dioxide emissions from energy carriers of Personal care (a), Repairs, Gardening and Pet care (b), Food preparation and Dish washing (c) and Travel (d) across developed countries

Appendix D. Descriptions of five scenarios in detail

Business-as-usual (BAU) scenario: we set both the CO_2 intensities and duration of activities of China's residents in 2008 as the BAU scenario.

Low-emission scenario (LES): Japan has a relatively low-carbon time-use pattern. In addition, Japan is closer to the lifestyle and culture environment of China. Hence, residents in China have more potential to shift to the time-use pattern of Japan. In other words, in this scenario, we assume residents in China will shift to both the intensities and duration of activities of Japan.

High-emission scenario (HES): As almost all activities have the highest intensities in the U.S., CO_2 emissions from China's residents will become greatest if they shift to both the intensities and duration of activities in the U.S. Therefore, in this scenario, we assume that residents in China will shift to both the CO_2 intensities and duration of activities of the U.S.

Hybrid scenario (HS): Considering the future developments in China may not follow time-use patterns of a single country but rather a novel combination of the patterns outlined above. On the basis of lower carbon intensities in different countries, we specifically design the hybrid scenario here. Although some countries have the lowest intensities for some activities, the lifestyle, culture and climate environment causing the lowest intensities of activities in these countries cannot be copied by China. Thus, residents may shift to activities with lower intensities in those countries whose lifestyle, culture and climate environment are closer to those of China. The potential future trends of time-use patterns designed in the hybrid scenario are given in Table 3.

Hybrid scenario 1 (HS1): In this scenario, when residents shift to the duration of time-use activities in Japan, their intensities of activities will shift to those in the hybrid scenario.

Hybrid scenario 2 (HS2): In this scenario, when residents shift to the duration of time-use activities in the U.S., their intensities of activities will shift to those in the hybrid scenario.

Appendix E. Consumption structures for different countries under the hybrid scenario

Fig. E.1 shows consumption structure for different countries under the hybrid scenario. We divide household consumption expenditure into eight aggregate categories, namely Food, Clothing, Residence, Household facilities and articles, Transport and communications, Education, culture and recreation, Health care and medical services, and Miscellaneous goods and services. It is worth mentioning that we have excluded some expenditures as mentioned in Section 4.2; thus, the consumption structures shown in Fig. E1 are not exactly the same as the actual consumption structures in different countries. It can be seen that the consumption structure in the hybrid scenario is more similar to the case for Japan.

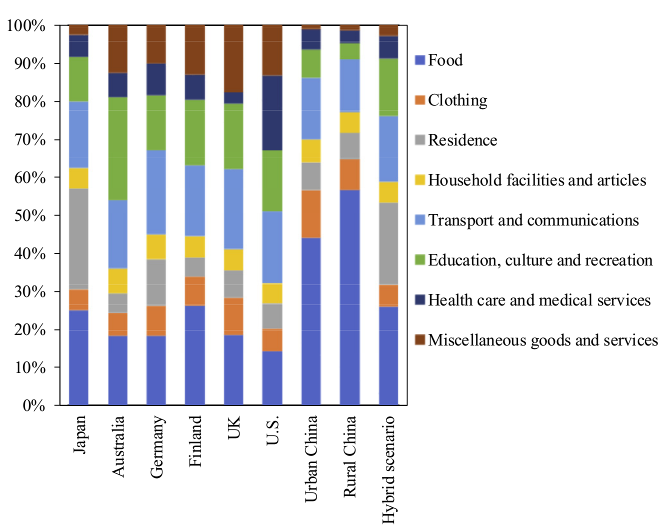

Fig. E.1. Consumption structures for different countries under the hybrid scenario

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