Wave transition in household energy use

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Abstract: The energy ladder model and energy stacking model have been proposed in the literature to describe the relations between income growth and transition of energy consumed by households. Both models are largely descriptive and provide limited guidelines for quantitative verification. By contrast, the logistic substitution model has been adopted much earlier to depict the long-run energy transition of a society over time. This model assumes that substitute technologies in energy sources are available in the energy market. In the present paper, we argue that household energy transition over income can follow the same pattern as energy dynamics over time in the logistic substation model. Hence, we construct a new model, energy wave transition model, by adapting the logistic substitution model to describe household energy transition both over time and over income. The new model not only captures the features presented in the energy ladder and stacking models, but also provides methods for quantitative verification. We illustrate the new model using the energy consumption pattern of Chinese households as an example.

Keywords: Life cycle curve of energy use; energy wave transition; energy ladder model; energy stacking model; energy-Environmental Kuznets Curve; logistic substitution model

1. Introduction

Energy used by households is extracted from various sources. Biomass was occasionally used for cooking and heating before the Neolithic Revolution, when food acquisition shifted from hunting and gathering to organized farming. Organized farming proved to be a reliable source of food supply, and biomass as a by-product of farming has been widely used to provide energy for households. Biomass was the dominant energy source used by households until the Industrial Revolution. Since then, fossil fuels gradually dominated the industry because of their much higher energy densities and greater flexibility compared with biomass. Today, a variety of non-fossil energy sources, such as nuclear, wind, solar and other renewable sources, have gradually become an integral part of the energy used by households, whereas traditional biomass has become obsolete [1] because of the process of technology diffusion and competition. To study the energy transition, i.e., the switching from one or a series of energy sources in the economy to another [2], the energy consumption share is commonly adopted to describes the structure of energy consumption to indicate the substitution of energy sources in the energy transition studies, although other indicators such as total energy consumption and energy penetration are also important to describe the role of energy consumption in an economy [3, 4]. As with the economy-wide energy transition [2], The competition among the energy and technology sources is a kind of pure competition [5] with the index of energy consumption share. In the present paper, we develop a framework with which to describe the transition of energy sources used by households as household consumption is one of the key drivers of the economic development.

To capture the features of household energy transition, the energy ladder model [6] emphasizes income as the main driving force of energy transition. As household income increases, the demand for energy increases in daily life. The demand for energy may decline when the household income is higher, such that the household may consider advanced energy sources or simply change its lifestyle. The energy stacking model [3] suggests that the driving force of energy transition varies, including household income and other household characteristics. However, both models do not mention that energy transition is heavily influenced by technology substitution in the production of energy sources used by households, as commonly described by the logistic substitution model [5, 7, 8] over time. In a given year, the available technologies to produce energy sources may not change dramatically. However, we emphasize that these available technologies in the energy market compete to satisfy the demands of households whose choices are restricted by their income levels. Hence, we also introduce the logistic substitution model widely adopted in the technology substitution studies to the study of household energy transition over income.

Our proposed model can be used for technological forecasting in the energy transition. In the context of global warming, renewable energy would become the next generation of dominant energy source in the long term although fossil fuels will continue to be the dominant energy source in the near future. If households reduce their fossil fuel consumption and increase their consumption of renewable energy motivated by energy and climate policies, then the renewable energy industry will be encouraged to provide and develop alternative sources of energy. As a result, the energy consumption structure will be changed to slow down the global warming.

The remainder of the paper is organized into sections. The next section briefly reviews the literature relevant to the household energy transition. Section 3 describes our proposed energy wave transition model, and Section 4 provides alternative fitting methods for the new model. Section 5 demonstrates the feasibility of the new model using energy consumption in Chinese households as an example. Section 6 demonstrates some limitations of the approach adopted in this paper. The last section concludes the paper.

2. Literature review

According to the energy ladder model proposed by Leach [6], energy used by households can be classified into three groups from the bottom to the top rung of a ladder, namely, traditional biomass including firewood, “transition fuels” including coal and liquefied petroleum gas (LPG), and clean energy including electricity and sometimes natural gas. The classification may vary across regions. For example, traditional biomass including cow dung, crop residues and wood are at the bottom rung of the ladder. In South Asia. kerosene and gas are the transition fuels, and electricity is the clean energy at the top [4]. In China, coal, LPG, diesel and gasoline are considered as the transition fuels and both electricity and natural gas are the clean energy at the top of the ladder. One of the key features of energy transition is the switch in household consumption from biomass to modern fuels. The energy ladder model emphasizes that the energy transition is like a ladder, such that the fuels at the bottom rung of the ladder should be replaced with fuels at the upper rung, and eventually abandoned by households, as shown in Fig. 1.a.

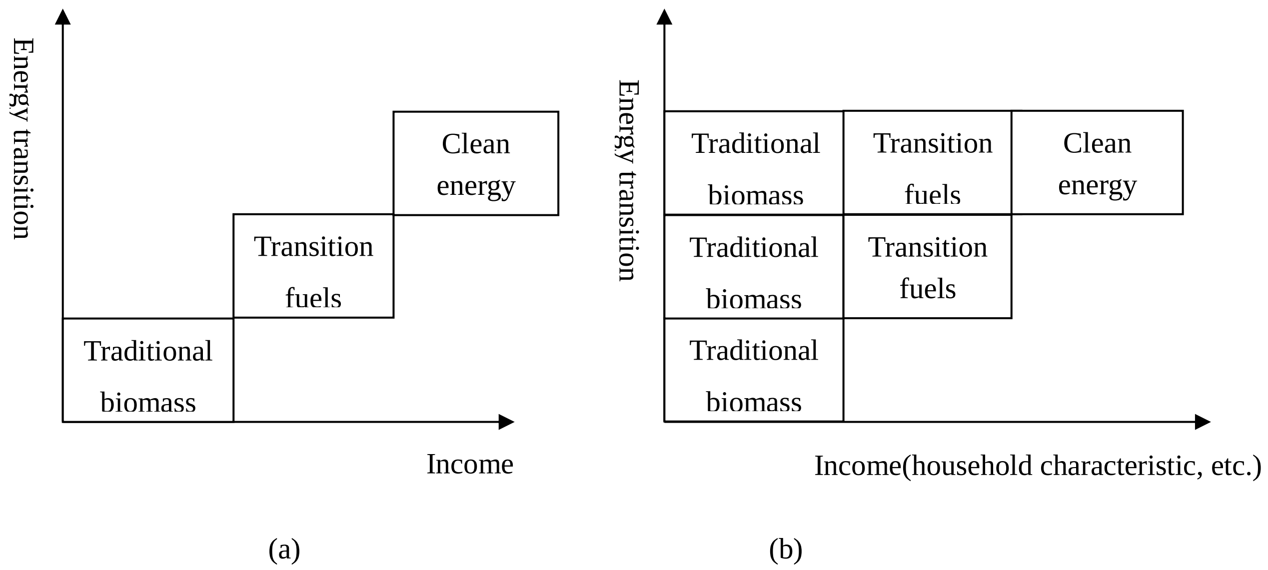

Fig. 1 The energy ladder (a) and energy stacking (b) models

However, some empirical studies show that energy transition is not a linear, unidirectional or “natural” process, and households always consume more than one energy sources [9]. Masera [3] argues that two opposite forces drive energy use with the development of economy and technology. One of the forces pushes households to use new, convenient and clean energy sources in the upper rung, whereas the other force pulls the households to maintain their lifestyles rather than abandon traditional energy sources at the bottom rung of the ladder. Thus, the energy sources used grow over time. The phenomenon is described by the other model, the energy stacking model, as shown in Fig. 1.b. Masera [3] also points out that the pushing and pulling forces include technical, socio-economic and cultural aspects, as well as health effects. Brouwer and Falcão [10] show strong correlations between fuel consumption and socio-economic factors, such as household size, area of residence, as well as household income. Similar to poor households, wealthy households tend to use charcoal in combination with non-wood fuels, which is in contradiction with the energy ladder model. The stacking model is a multi-energy model which is close to the reality, but the description of two forces is too vague to be meaningful. This paper establish the energy wave transition model based on the technology substitution theory, as both the forces are closely related to the technology substitution.

To some extent, both models are supported by recent empirical evidence. For example, Hiemstra-van Der Horst and Hovorka [11] confirm that multiple energy sources are used by households in Maun, Botswana, supporting the energy stacking model, although their evidence could not deny the energy ladder model. Nansaior [4] and Gundimeda [12] support the energy ladder model because biomass use declines as households become more urbanized. Their findings also support the energy stacking model because wealthy households continue to use biomass. Both models assume that the use of biomass for household energy purposes decreases as fossil fuels and clean energy are used more frequently. The debate between the two models is whether biomass, such as firewood, will finally be abandoned by households. Most developed countries have abandoned the use of firewood, but some rural areas in developing countries continue to use them as their main energy source. The questions to distinguish the two models are whether the biomass is an inferior good and whether wealthy households consume less biomass, given that households finally abandoning biomass are impossible to observe.

Using a cross-sectional survey data from households in Hubei Province of China, Peng [13] confirms that the energy stacking model is a more accurate description of household energy transition than the energy ladder model. At the same time, that study shows that less than 10% of households have abandoned the use of biomass, and biomass is used less in absolute terms only by the wealthiest households, supporting the energy ladder model [13]. Démurger and Fournier [14] strongly support the argument that economic wealth owned by a household is a significant and negative determinant of firewood consumption. Therefore, biomass can be considered as an inferior good although the household is at the top of the wealth distribution. Firewood consumption might decrease very slowly or remain almost the same. This finding is consistent with that of Masera [3], who insists that even wealthy households will not abandon the use of biomass as an energy source.

The debate on which of the two energy transition models are more suitable is associated with the fact that energy transition is not properly and quantitatively defined in both models [1]. In the energy ladder model, energy transition is roughly defined as switching from a traditional energy source to a new one without specifying whether the former is an inferior good or will finally be abandoned. In the energy stacking model, energy transition is studied empirically, and the definition of energy transition becomes more blurred. Does the energy transition imply that aside from traditional energy, a household adds a new energy for use? Or does energy transition mean that, as more energy sources are used, the energy consumption level of a household increases? Energy transition cannot be studied quantitatively without an explicit definition. In the present paper, we will propose a new model, energy wave transition, in which energy transition is explicitly defined and potential quantitative indicators are discussed. We argue that both energy ladder and energy stacking models can be considered as special cases of the new model. The energy transition of households in China will be used as an example to explain the new model.

The energy wave transition model uses logistic functions to discuss the energy transition. Using logistic functions is appropriate to describe the technology improvement. Logistic functions were generally used to study the technology improvement in the 1970s [15-17]. Modis [18] also discusses the strengths and weaknesses of the S-curves simulated by logistic functions. Kucharavy [5] divides models using logistic functions into three classes, namely, simple logistic model, component logistic model, and logistic substitution model. In general, as stated by Cesare Marcheetti in Modis [18], "*anything that begins and ends an existence will fit a logistic*." Unlike models using exponential functions, these logistic models have an upper stage approaching a limit to capture a main feature of the energy transition. These logistic models also have slow developing and vanishing stages. A simple logistic model is mainly used to measure one kind of energy technology, which can only describe the increasing and upper stage of a curve. Component logistic model focuses on the consumption of one energy source, and utilizes mathematical methods to decompose the technology influence on energy consumption. Bi-logistic model is a special kind of component logistic model, which uses two simple logistic curves to measure the entire life of the energy life curve from increasing to decreasing [19]. The current paper focuses on energy transition in households that use one energy source with one kind of energy technology. The new logistic model has a quadratic term of time or income.

3. Energy wave transition: model description

3.1 Life cycle curve of Energy use

Energy drives appliances to meet the consumption demand of households. The life-span energy consumed by an appliance from its establishment to its death has been studied extensively using the so-called life cycle assessment (LCA) approach [20, 21]. However, few studies have focused on the life cycle of the use of energy sources by households from its introduction to its abandonment. For example, the use of coal energy was gradually introduced to households since the Industry Revolution. The coal use has increased and still dominates the use of other energy sources by households in certain developing countries such as China although the coal use started to decrease in some developed European countries.

A life cycle of energy use may exhibit a variety of styles, as shown in Fig. 2. One style could be asymmetric. Firewood has been used for a long period, and its use has declined rapidly after the emergence of fossil fuels. By contrast, the fossil energy use has risen quickly since the Industrial Revolution. Until now, no signals have shown that the dominant position of fossil fuels would change in the short term, although the use of renewable energy is on the rise. Fig. 2.a illustrates this asymmetric life cycle curve of fossil fuels with solid line and the life cycle curve of firewood with a dotted line. This condition is a common state, but requires a long series time data to be fitted by a logistic function. Another style of life cycle peaks multi-times, as shown in Fig. 2.b. This type of life cycle may be caused by war or disease, which may disturb the on-going energy transition. Fig. 2.c shows that only one kind of energy, such as electricity, is used by a household in a given period. A multistage life cycle is shown in Fig. 2.d, and illustrates that the energy consumption share reaches stagnation and rapidly increases after a new technology of the energy use emerges in households several times. Figs. 2.b to 2.d show the special cases of energy-use life cycles, which only occur when fuel and energy are not distinguished from each other. The special cases can be fitted by component logistic model, but will seldom occur in the energy transition in households. Hence, the present paper will focus on the bell-shaped life cycle curve as shown in Fig. 3, which is considered to be the typical life cycle curves.

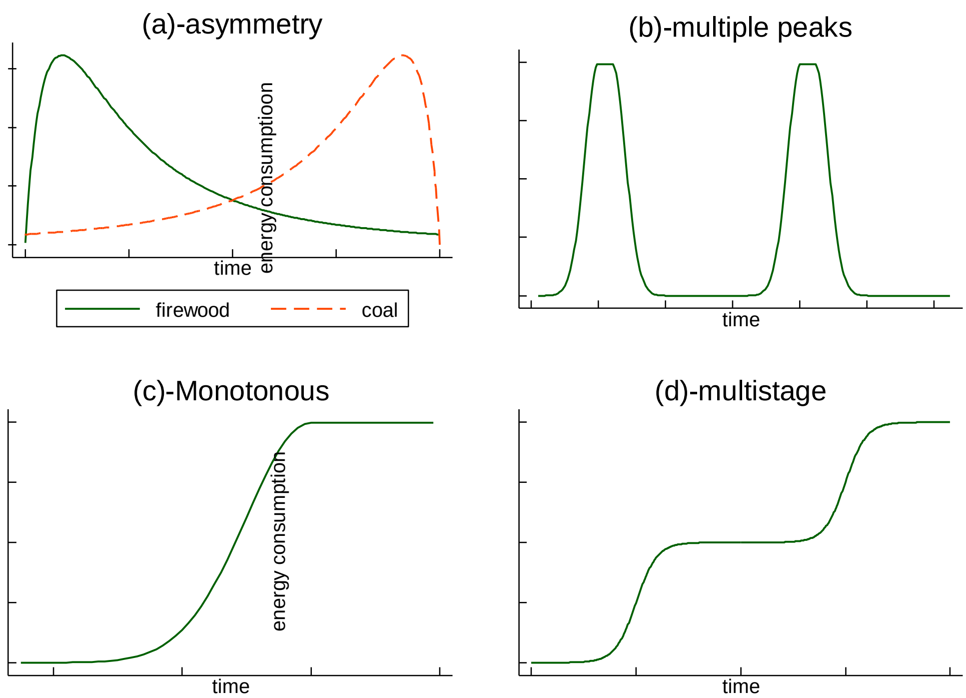

Fig. 2.
Life cycle curves of energy use.

A life cycle curve of energy use has five stages, namely, development, increasing, ceiling, decreasing and floor, as time and income increase. The life cycle of energy good *E1* is illustrated in Fig. 3. Initially, energy good *E1* (e.g., coal) is used by few households and accounts for a small share of total energy use. Gradually, the energy good *E1* is used by more households because of its lower price, more reliable supply, and suitability for appliances. Hence, its share in total energy use increases gradually and accelerates until a turning point when the share becomes stable for a certain period. When a new energy good *E2* (e.g., electricity) emerges and is used by households, the use of the energy good *E1* is discouraged, and its share in total energy use decreases until it reaches a certain low level or finally becomes zero, implying that *E1* is abandoned by households. The life cycle curve of energy use shown in Fig. 3 is bell-shaped. If both long tails are ignored, then the life cycle curve becomes an inverted U-shape.

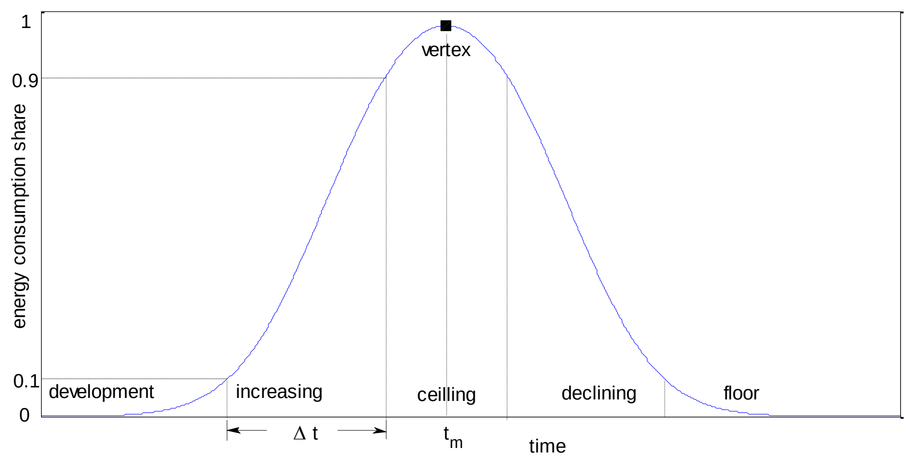

Fig. 3. Life cycle curve of energy use.

A bell-shaped life cycle curve of energy use has one vertex and four turning points (Fig. 3). The vertex indicates the maximum share in energy use. As long as more than two energy goods are in use, the maximum share must be less than 1. The vertex may exist because of the limited resources. The four turning points indicate the uneven development of energy and the gradual development of new technologies.

The life cycle curve of energy use is inspired by the logistic growth model because the natural growth of autonomous systems in competition might be described using a logistic model. A logistic model demonstrates that the rate of growth has a bell-shaped curve, but the model itself measures the increasing or decreasing part only. Bi-logistic model may have some features of the bell-shaped curve, but the growth rate of model may be multiple bell-shaped. [17-19]. The energy-use life cycle would have some features of the bell-shaped curve as technology substitution drives the use of energy sources by households. Hence, we propose a new energy transition model. The figure of the life cycle curve may have some features of the normal distribution like bi-logistic model, but we use quadratic time logistic model to fit the figure as described in section 4.

3.2 Energy wave transition over time

The life cycle curve of an energy use describes the energy consumption shares in total energy used by households over time. We develop the energy wave transition model to describe the life cycle curves of the use of all the energy sources by households. Households have experienced from only using biomass to a rapid decline in biomass use, a rapid rise (and in some cases, a slow decline) in fossil energy use, and a gradual rise in the use of new and clean energy (e.g., electricity). The life cycles of the three energy goods over time are illustrated in Fig. 4. The curves shown are similar to the oscillating waves of the ocean. For this characteristic, we refer to our model as “energy wave transition.” Grubler [22] reports this global phenomenon, and demonstrates that the use of three primary energy goods has been incorporated into one figure to show the energy transition worldwide from 1850–2008.

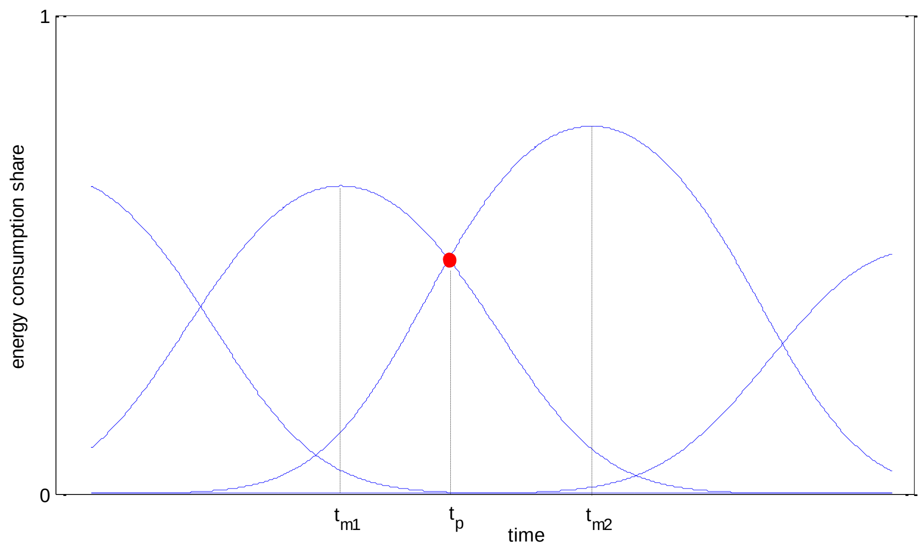

Fig. 4. An illustration of energy wave transition.

The energy wave transition model has three characteristics. First, several energy goods may be in use at any point in time, and the most utilized energy good is called “main energy good.” Second, energy goods at a given time may exhibit different stages in their life cycles. At least one energy good must remain in its declining stage if the main energy good exhibits its increasing stage. This characteristic indicates that energy consumption is transitioning to the main energy good. Third, when a new energy good is introduced, the new energy good will replace the prevailing main energy good over time. Furthermore, if all energy goods are assumed to exhibit their floor stages for a long period, we would observe that households use more energy sources over time, which is consistent with the energy stacking model. Hence, the energy wave transition model is more general and can be used to explain the cases in both the energy ladder and energy stacking models.

The energy wave transition model is also inspired by the logistic substitution model [5, 7, 8]. The logistic substitution model emphasizes some basic assumptions. First, new technology enters the market and matures at logistic growth. Second, only a single technology is in the saturation period at any time. Third, declining technologies fade away steadily at logistic rates [8, 23]. We think that the energy transition is also pure competition [5], such that energy wave transition over time is based on the logistic substitution. The difference is that each energy source will experience a “bell” shape process, which does not have to be a normal distribution.

3.3 Energy wave transition over income

The energy ladder model interprets the process of energy transition as advanced energy used by a household to replace traditional energy along with increasing income. However, the energy stacking model interprets the transition as the gradual accumulation of advanced energy while the existing energy remains in use by a household as income increases. Nevertheless, both models focus on the relationships between energy transition and economic growth, as represented by income. However, the logistic model and logistic substitution model are only based on time. Hence, we construct the energy wave transition model over income.

In Subsection 3.1, we assume a bell-shaped life cycle curve of a single energy good over time. Can we obtain a similar bell-shaped curve over income for households? The energy transition shows a life cycle over time under many factors. Previous studies show that household energy consumption is affected by various factors that can be grouped into three sources. One source is related to energy endowment, such as the existence of energy supply and stable energy supply [24]. Another source is related to economic conditions related to whether households have sufficient ability to pay for necessary energy use [24-26]. The last source is related to household characteristics, such as cultural background and traditions, household size, education, and gender of household head [21, 26]. As shown in the energy ladder and stacking models, income as an indicator of economic conditions is one of the main forces driving the energy transition.

In the logistic models, energy substitution is based on energy-production technology improvement as time elapses. We think that improvement in technology is one of the main driving forces for the energy transition. This idea echoes the assumption that technology is one of the main driving forces for economic development. Technology improves with time and substitute technologies exist simultaneously in a given period. High-quality energy produced by advanced technologies tends to be more expensive than energy produced by traditional technologies since advanced technologies require more investment on research and development activities. Generally, wealthy households are willing to consume more high-quality energy produced by advanced technologies although they have to pay more. Hence, we can assume similar life cycle curves of energy use over income to the curves over time as household income is highly correlated with technology.

In the literature, a relevant theme is the so-called energy-environmental Kuznets curve (Energy-EKC), which assumes an inverted U-shaped relationship between energy consumption and economic growth in a region. Energy-EKC refers to the increase in energy consumption to satisfy the demand resulting from economic growth. Energy-EKC declines as technology develops after a turning point [27, 28]. Empirical studies show that Energy-EKC can be observed in some countries, in which the total energy consumption (i.e., per capita energy consumption) is used as the indicator of energy consumption [28, 29]. If carbon dioxide emissions from fossil fuels are considered as one proxy of energy consumption, then Energy-EKC is also observed in some countries by some studies on EKC, focusing on carbon dioxide emissions [13, 30, 31]. Energy-EKC can be considered a bell-shaped curve without the tails on both sides. Similar to Energy-EKC, we can assume a bell-shaped life cycle curve of a single energy good over income for households. The analysis over time in Subsection 3.2 would be valid if time is replaced with income.

4. Energy wave transition: fitting methods and indicators

4.1 Fitting methods

To empirically verify the new energy wave transition model based on historical data, we adopt alternative logistic functions to estimate the parameters of the life cycle curve of an energy good, depending on an observed pattern of the energy consumption curve. The estimated energy consumption shares, which fall within the range of 0 to 1, can be expressed as a logistic function given by

$$\hat{P} = E(P \mid X) = \frac{1}{1 + \exp(XA)}, \tag{1}$$

where P refers to the expected energy consumption shares, X represents the explanatory variables, and vector A is the parameters to be estimated. Depending on the targeted independent variables, we have several specifications.

4.1.1 Linear time

If the independent variables include time t and a constant, then the logistic model can be expressed as

$$y = \frac{1}{1 + \exp(\alpha(t + \beta))}, \tag{2}$$

or an equivalent equation,

$$\ln\left(\frac{1-y}{y}\right) = \alpha t + \beta\,, \tag{3}$$

where α and β are parameters to be estimated and y is the energy share in total energy use. Similar to the logistic models [7], we obtain an equivalent equation given by

$$y = \frac{1}{1+\exp\left(-\frac{\ln(81)}{\Delta t}(t-t_m)\right)}, \tag{4}$$

where y is the value of the energy shares between 0 to 1, t_m is the midpoint at which the time y reaches 50% of the ceiling of y, and Δt is called characteristic duration. If $y_{\max}$ is the ceiling of y, characteristic duration (Δt) represents the time required to grow from 10% to 90% of $y_{\max}$.

Component logistic model shows that growth is the sum of some discrete "wavelets" given by

$$y(t) = \sum_{i=1}^{n} y_i(t), \tag{5}$$

where $y_i(t)$ is from (4). The component logistic model uses Fisher-Pry transform to normalize the model [7, 32-34].

The specification can be used to simulate or fit the first three stages of a life cycle curve of one energy source. The component logistic model can also fit the entire energy life curve cycle, but we do not think the model will fit very well, as discussed in the example of Chinese household energy consumption.

4.1.2 Quadratic time

If the independent variables include one additional term of time squared, then we obtain the specification of the logistic model given by

$$y = \frac{1}{1 + \exp(\alpha t^2 + \beta t + \gamma)}. \tag{6}$$

The curve of the equation is illustrated in Fig. 3. We can also transform this equation into an equation as expressed by

$$\ln\left(\frac{1 - y}{y}\right) = \alpha t^2 + \beta t + \gamma. \tag{7}$$

The growth rate parameter α can specify the “width” or “steepness” of the bell-shaped curve. Parameter α can be replaced with a variable that specifies the required time for the trajectory to increase from 10% to 90% of the ceiling of y. This period can also be referred to as characteristic duration (Δt), which is inspired by the characteristic duration of the linear time specification mentioned in Section 4.1.2. However, the characteristic duration in quadratic time not only pertains to the time of increase from 10% to 90% of the ceiling of y, but also to the time of decrease given that the quadratic time model is symmetric. Through simple algebra, the characteristic duration is related to α by $\Delta t = \frac{1.34}{\sqrt{\alpha}}$. The ceiling of y, or y_m, is related to α, β, γ by $y_m = \frac{1}{1 + \exp(-\frac{\beta^2}{4\alpha} + \gamma)}$, and the time for the trajectory to reach y_m is labeled t_m, which in turn, is related to α, β by $t_m = -\frac{\beta}{2\alpha}$. Here, t_m refers to the midpoint in the quadratic time model, and such midpoint is different from that in the linear time specification, which pertains to the time when the energy consumption share reaches 50% of the ceiling. By contrast, the midpoint in the quadratic time model pertains to the time when the energy consumption share reaches the maximum of y.

The three parameters, $\Delta t, y_m, t_m$ define the parameterization of the quadratic time logistic specification given by

$$y = \frac{1}{1 + \exp\left(\left(\frac{1.34}{\Delta t} \right)^2 (t - t_m)^2 + \ln\left(\frac{1 - y_m}{y_m} \right) \right)} . \qquad (8)$$

The quadratic time specification is useful, because the parameters are obtained by fitting the model to data that can be easily compared with many different systems. This specification is also more useful than the linear time specification as the former can model all the five stages of the energy-use life cycle trajectory in time-series data.

4.1.3 Linear logarithm of income

As discussed in Section 3, this paper aims to extend the logistic substitution model from time to income. Therefore, the logarithm of income replaces the time in the logistic specifications presented in the above Sections 4.1.1 and 4.1.2 to build specifications of the logarithm of income.

The general specification of the linear logarithm of income is given by

$$\ln\left(\frac{1 - y}{y} \right) = \alpha \ln(I) + \beta , \qquad (9)$$

where I denotes income.

The parameters α, β can be normalized to R_I and I_m, respectively. R_I is the growth rate of income (I) when the energy consumption share increases from 10% to 90% of the upper energy consumption. For instance, if R_I is equal to 2, income must be doubled when the energy consumption share increases from 10% to 90% of the ceiling. The introduction of R_I is inspired by the characteristic duration (Δt) in the linear time specification. I_m is the income when the energy consumption share reaches 50% of the ceiling. The two parameters (R_I and I_m) can be used to define the specification of the linear logarithm of income given by

$$y = \frac{1}{1 + \exp\left(\frac{\ln 81}{\ln R_I} \ln I + \ln I_m \right)}. \tag{10}$$

4.1.4 Quadratic logarithm of income

Next, we extend the specification of logarithm of income from linear to quadratic. The general specification of the quadratic logarithm of income is expressed as

$$\ln\left(\frac{1\text{-}y}{y} \right) = \alpha[\ln(I)]^2 + \beta \ln(I) + \gamma. \tag{11}$$

The parameters α, β, γ can be normalized to be R_I, I_m and y_m, respectively, in which y_m is the ceiling of y, and $y_m = \frac{1}{1 + \exp(-\frac{\beta^2}{4\alpha} + \gamma)}$. Therefore, regardless of the increase in income, the energy consumption will not exceed y_m. Meanwhile, I_m is the income when the energy consumption share reaches y_m, that is, $I_m = e^{-\frac{\beta}{2\alpha}}$. In other words, the energy consumption share will reach y_m when the income reaches I_m. $R_I = e^{\frac{1.34}{\sqrt{\alpha}}}$ is the growth rate of income when the energy consumption share increases from 10% to 90% of the upper energy consumption. The specification of this logistic function is given by

$$y = \frac{1}{1 + \exp\left(\left(\frac{1.34 \ln {}^{I}\!/\!{}_{I_m}}{\ln R_I} \right)^2 + \ln\left(\frac{1 - y_m}{y_m} \right) \right)}. \tag{12}$$

4.2 Indicators of the energy wave transition model

Energy transition is the process of changes from one energy source to another. In the model, Δt refers to the speed of energy transition according to time, whereas R_I refers to the speed of energy transition according to income. Generally, we can construct two new energy transition indices, namely, Energy Vertex Interval and Energy Transition Point, when two energy sources are present in the energy wave transition model (Fig. 4).

When two energy sources, $y_1(t)$ and $y_2(t)$, are present, we assume that

$$y(t) = y_1(t) + y_2(t), \tag{13}$$

and according the quadratic time specification in Section 4.1.2, we have

$$y_1(t) = \frac{1}{1+\exp(\alpha_1 t^2 + \beta_1 t + \gamma_1)} = \frac{1}{1+\exp\left(\left(\frac{1.34}{\Delta t_1}\right)^2 (t-t_{m1})^2 + \ln\left(\frac{1-y_{m1}}{y_{m1}}\right)\right)},$$

$$y_2(t) = \frac{1}{1+\exp(\alpha_2 t^2 + \beta_2 t + \gamma_2)} = \frac{1}{1+\exp\left(\left(\frac{1.34}{\Delta t_2}\right)^2 (t-t_{m2})^2 + \ln\left(\frac{1-y_{m2}}{y_{m2}}\right)\right)}. \tag{14}$$

Energy Vertex Interval refers to the time interval between the vertices of two ife cycle curves of energy use, i.e., $t_{m2} - t_{m1}$. This interval measures the speed of energy transition from one energy good to another. Energy Transition Point (t_p) is a time point that indicates when the shares of two energy goods in use are the same. This point marks the intersection of the life cycle curves of two energy goods and serves as the starting point at which one of the two energy goods is used more than the other is. Through simple algebra, we obtain t_p given by

$$t_p = -\frac{\gamma_1 - \gamma_2}{\beta_1 - \beta_2}. \tag{15}$$

The new energy source begins to dominate the Energy Transition Point until the next Energy Transition Point appears. This energy source becomes the main energy during these two Energy Transition Points.

More than two energy sources usually exist in the real energy market. We can measure energy transition by simply examining the level of substitution between the dominant energy sources, which accounts for the largest market share, and its challenger or potential successor. If the challenger is a group of various energy sources, then we can aggregate these energy sources into one energy source.

5. An example: energy transition of Chinese households

We illustrate our new model using 1991 to 2011 energy time-series data collected from the China Energy Statistical Yearbook. The energy sources being used by Chinese households include coal, oil, gas, heat, electricity, and coke. Coal is mainly used for cooking and heating. Oil includes gasoline, diesel, kerosene, and LPG. Gasoline and diesel are mainly used for transportation, whereas kerosene is used for traditional lighting. LPG and gas are both used for cooking and heating. Heat is used only in northern cities and is provided by the government-led central heating system from the beginning of October to the end of March the following year. Electricity is commonly used in a variety of applications. Coke is a traditional energy source also used for cooking and heating.

For simplicity, we divide these energy sources into three categories, namely, solid energy, liquid energy, and clean energy. Solid energy, which includes coal and coke, is the most traditional, inefficient, and highly polluting energy source. Liquid energy includes gasoline, diesel, and kerosene. Clean energy includes gas, electricity, and heat.

Notice that we did not include biomass in this section as official firewood and biogas data are not available. In China, rural households have consumed almost all biomass as one of the main energy sources and urban households have almost abandoned biomass use since 1991. According to a survey conducted in the provinces of Shanxi, Zhejiang, and Guizhou from 2010 to 2011, nearly 40 percent of rural households use biomass for heating and cooking and that biomass accounts for 18 percent of their total energy consumption [35]. Rural households may consume more biomass before the survey since they have reduced their biomass use since 1990s [25]. Hence, the life cycle curves presented in this section may change to some extent if biomass use is included although these curves would probably remain bell-shaped.

To fit the life cycle curve of one energy source, we draw a scatter graph to observe the likely shape of the curve. This graph helps us determine the specification of the logistic function for the life cycle curves of the energy source. Hence, the linear time specification is used for the fitting of life cycle curves of coal, electricity, solid energy, liquid energy, and clean energy. The estimated results are shown in Table 1. For the curves of coke and LPG, the quadratic time specification is used to obtain the estimated results in Table 2. The linear logarithm of income specification is adopted for the life cycle curves of solid, liquid, and clean energy over income (represented by GDP), while the quadratic logarithm of income specification is adopted for the curves of coke and LPG, which are commonly used by rural households. The estimated results for the curves over income are shown in Table 3.

Table 1.
Estimated results of energy used by households in China over time.

	Coal	Electricity	Solid	Liquid	Clean
Time	0.135***	-0.0914***	0.137***	-0.122***	-0.114***
	(17.09)	(-15.40)	(17.92)	(-11.17)	(-14.24)
Constant	-269.5***	184.7***	-274.3***	246.6***	229.3***
	(-17.10)	(15.55)	(-17.93)	(11.30)	(14.26)
N	21	21	21	21	21
Figure	5-1	5-2	6-1	6-1	6-1
Δt	-33	48	-32	36	38
t_m	1996	2021	2002	2025	2005

Data source: energy time-series data from 1991 to 2011 collected from the China Energy Statistical Yearbook.

Note: The dependent variable is the energy share in total energy use. All parameters are estimated by the linear time specification as described in Subsection 4.1.1. Standard deviations are reported in parentheses.

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 2.
Estimated results of coke and LPG used by households in China over time.

	Coke	LPG	Coke rural	LPG rural
Time	-62.73***	-46.64***	-61.67***	-89.73***
	(-7.49)	(-11.98)	(-7.12)	(-7.14)
Time squared	0.0157***	0.0116***	0.0154***	0.0224***
	(7.50)	(11.96)	(7.13)	(7.12)
Constant	62694.9***	46727.7***	61630.7***	89992.8***
	(7.48)	(11.99)	(7.11)	(7.15)
N	21	21	21	21
Figure	5-3	5-4	6-2	6-2
Δt	10	12	11	9
t_m	1999	2004	1998	2006
y_m	0.011	0.15	0.013	0.077

Data source: energy time-series data from 1991 to 2011 collected from the China Energy Statistical Yearbook.

Note: The dependent variable is the energy share in total energy use. All parameters are estimated by the quadratic time specification as described in Subsection 4.1.2. Standard deviations are reported in parentheses.

* p < 0.05, ** p < 0.01, *** p < 0.001

Table 3.
Estimated results of energy used by households in China over income.

	Solid	Liquid	Clean	LPG rural	Coke rural
GDP	1.467***	-1.296***	-1.246***	-76.66***	-39.38***
	(17.71)	(-10.33)	(-14.68)	(-9.09)	(-4.92)
GDP squared				5.09***	2.82***
				(8.69)	(5.08)
Constant	-2.65***	5.15***	2.53***	290.83***	141.79***
	(-18.11)	(23.38)	(16.93)	(9.60)	(4.93)
N	21	21	21	21	21
Figure	9-1	9-1	9-1	9-2	9-2
R_I	0.05	29.68	33.98	1.81	2.22
I_m	6.07	53.28	7.64	1853.97	1069.11
y_m				0.083	0.011

Data source: energy time-series data from 1991 to 2011 collected from the China Energy Statistical Yearbook.

Note: The dependent variable is the energy share in total energy use. All parameters are estimated by the specifications as described in Subsections 4.1.3 and 4.1.4. Standard deviations are reported in parentheses.

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

5.1 Energy wave transition over time

Based on the estimated logistic functions presented above, we can predict the life cycle curves of an energy source. As shown in Figure 5, the bell-shaped life cycle curves are not observed for coal and electricity because of their long life cycles over time. Over the last two decades, coal (a traditional energy source used by households) may be at the declining stage, whereas electricity (a form of clean energy) may be at the increasing stage. The characteristic duration of coal is -33, indicating that coal will decrease from 90% to 10% of the ceiling of the coal use shares after 33 years. The curves predict that coal use share reached 50% of its ceiling in 1996, and the electricity use share will reach 50% of its ceiling until 2021. By contrast, LPG and coke may have short life cycles and have experienced the majority of the bell-shaped life cycle curves. We observe the vertex and two turning points of LPG. LPG is at its increasing stage between 1991 and 1997, at its ceiling stage between 1998 and 2007, and at its declining stage between 2008 and 2011. Coke also shows a bell-shaped curve with a vertex and turning points. Coke has fallen into its declining stage after reaching the vertex in 1999. The coke consumption share has declined from 1.22% in 1999 to 0.46% in 2005 with an annual decrease of 0.56%. Meanwhile, in the following six years, the share has declined to 0.15% in 2011 with an annual decrease of 0.31%, which is only about half of the annual decrease between 1999 and 2005. In the near future, coke may continue to be used and its consumption share may decline gradually, which may indicate its transition to the floor stage. The characteristic duration of coke consumption is 10 years, and the ceiling of coke consumption is 1.1% of the total energy consumption. In other words, coke has reached the ceiling of 1.1% energy consumption in 1999 and can either increase or decrease from 0.11% to 0.99% of the energy consumption share in 10 years. In comparison, LPG has reached the ceiling of 15% energy consumption share in 2004.

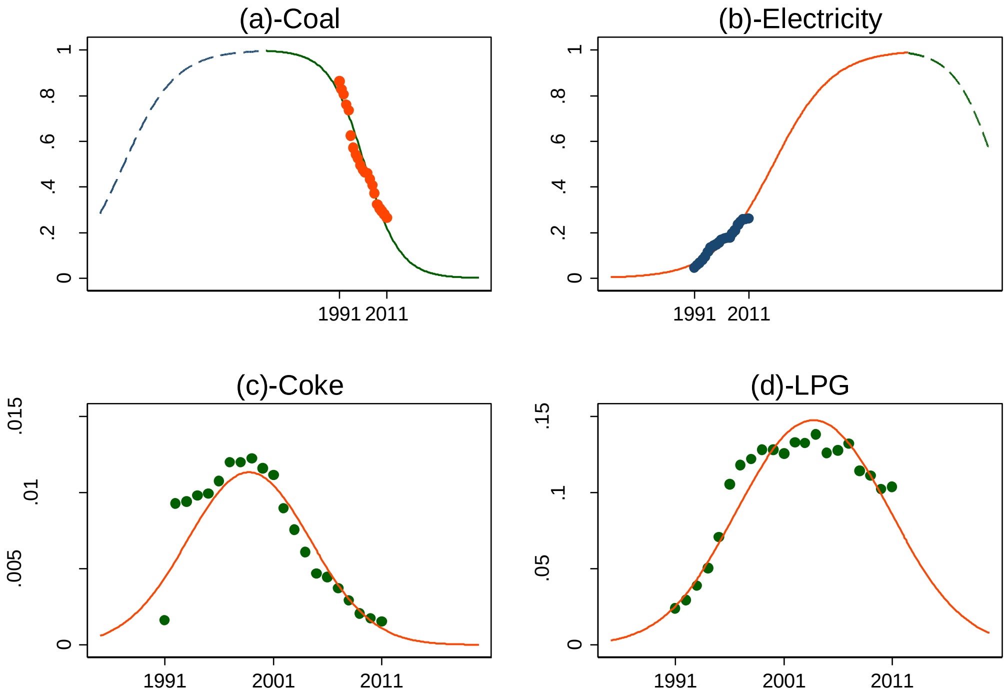

Fig. 5.

Life cycle curves of energy use over time of Chinese households.

The horizontal and vertical axes represent time and the energy consumption shares, respectively. The solid points represent the observed data, and the solid lines represent the estimated life cycles. The dashed lines are virtually drawn to illustrate the unobserved part of the life cycles.

We now discuss the Energy Transition Point and Energy Vertex Interval in the energy transition of households in China. As mentioned earlier, Energy Transition Point refers to the period when the shares of two energy goods in use are similar. In other words, this point is an intersection of the predicted life cycle curves of two energy goods, and serves as the starting point when one of the two energy goods is used more than the other. The new energy begins to dominate from the Energy Transition Point until the next Energy Transition Point appears. This new energy becomes the main energy during these two Energy Transition Points. Fig. 6.a shows the energy wave transition curves of the three energy goods being used by Chinese households. First, over the last 20 years, solid energy has been at its declining stage, whereas clean energy and liquid energy have been at their increasing stages, indicating that the energy being used by Chinese households has been under transition from solid energy to liquid and clean energy. Second, the fitted curves indicate that the Energy Transition Point or t_p from solid energy to liquid energy is estimated to be around 2013. We also examine the life cycle curves of LPG and coke used by Chinese rural households (Fig. 6.b). The Energy Transition Point or t_p from coke to LPG is estimated to be around 1996, whereas the actual data show that more LPG is being used than coke since 1996, indicating that an event in 1996 has significantly affected the energy consumption of households.

Energy Vertex Interval refers to the time interval between the vertices of two life cycle curves. As illustrated in Fig. 6.b, the predicted Energy Vertex Interval is seven years from coke to LPG used by rural households in China.

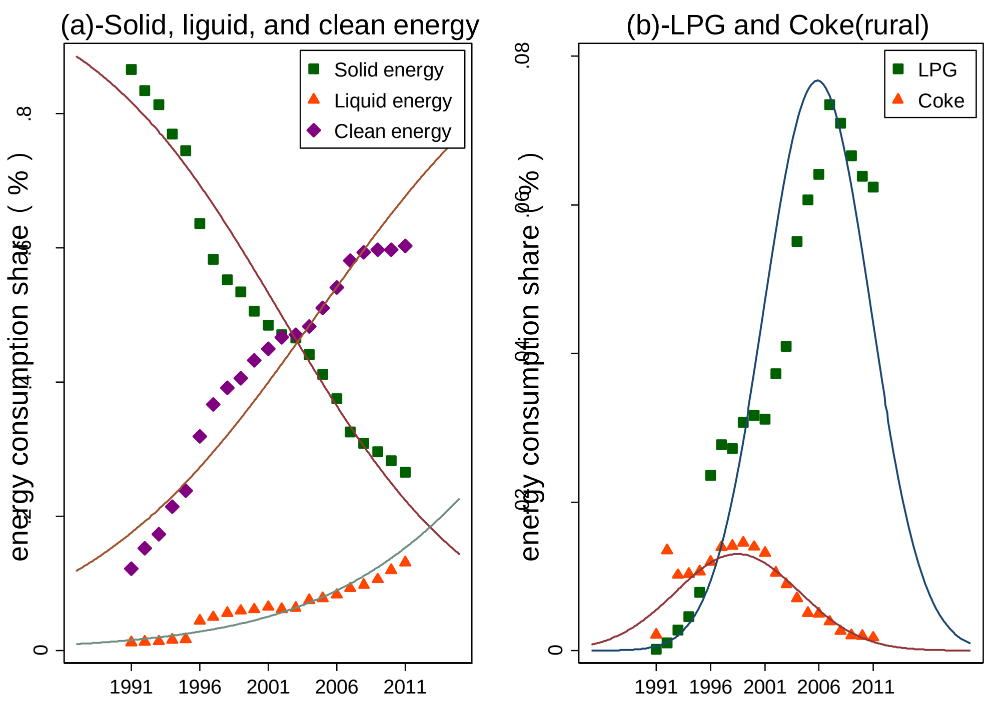

Fig. 6.
Energy wave transition over time in Chinese households.
The horizontal and vertical axes represent time and the energy consumption shares, respectively. The solid points represent the observed data, and the curves represent the estimated life cycles.

5.1.1. Comparison with the logistic substitution model

Energy wave transition is inspired by the logistic substitution model. The only difference between these two models is that, in our proposed model, we pressume that an energy life curve will undergo all the stages as illustrated in Fig. 3. Therefore, we use the quadratic logistic functions to fit the data. The logistic substitution model also transforms the data for energy consumption into energy consumption shares before fitting the curve. We draw the curves for coke and LPG used by rural households in China according to the logistic substitution model by using Loglet Lab[1] (Figs. 7 and 8) and compare them with the curves in Figs. 5.c and 5.d according to our proposed model. The results estimated by Loglet Lab are shown in Table 4.

By using Loglet Lab, we adopted a bi-logistic model to fit the coke and LPG consumption data (Figs. 5.c and 5.d). As shown in Fig. 7, two components of the logistic models are used to fit the data. The saturation is 0.014, indicating that the ceiling of the coke consumption share is 1.4%, which is slightly bigger than the predicted share in our model (1.1%). As shown in Table 4, the midpoint of the first component is 1991, which indicates that the coke consumption share is predicted to reach 0.0055% in 1992. The midpoint of the second component is 2007, which indicates that the coke consumption share is predicted to reach 0.0015% in 2017. By contrast, our model shows only one midpoint in 1999, suggesting that the coke consumption share is predicted to reach the ceiling in 1999.

For LPG used by rural households in China, as shown in Fig. 8, the saturation is 13%, which is slightly lower than the prediction of our model (15%). The midpoint of the first component is 1995, whereas that of the second component is 2008 (Table 4). By contrast, our model shows only one midpoint in 2004, indicating that the LPG consumption is predicted to reach the ceiling in 2004.

Table 4.
Loglet Lab results for coke and LPG used by rural households in China.

	Coke		LPG	
	Phase 1	Phase 2	Phase 1	Phase 2
Saturation (K)	0.011	0.003	0.105	0.025

[1] The software is available at http://phe.rockefeller.edu.

Midpoint (tm)	1992	2017	1995	2008

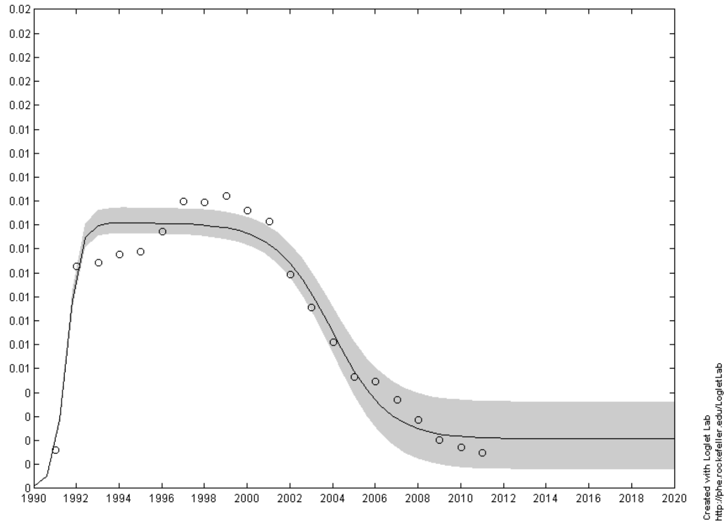

Fig. 7.

Energy life curve of coke in Loglet Lab.

The horizontal and vertical axes represent time and the energy consumption shares, respectively.

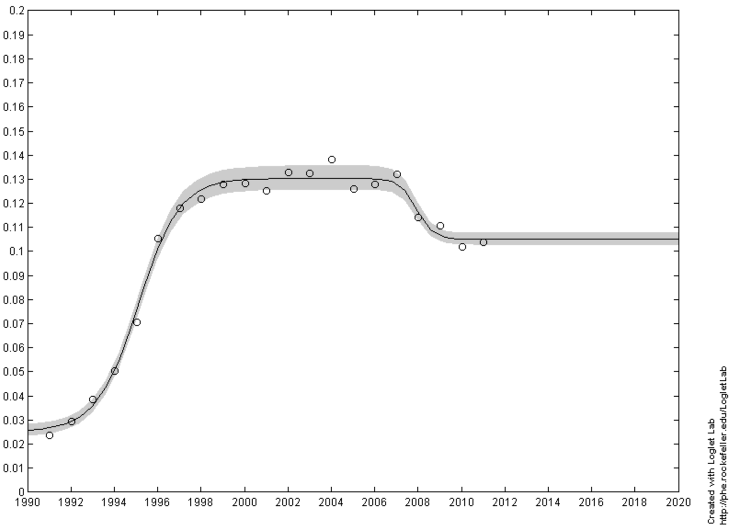

Fig. 8.

Energy life curve of LPG in Loglet Lab.

The horizontal and vertical axes represent time and the energy consumption shares, respectively.

5.2 Energy wave transition over income

Fig. 6 shows the life cycle curves of several energy goods over income and per capita income, which are similar to the curves over time shown in Fig. 5. The similarity is natural in this case because the income of Chinese households has continuously increased over the last two decades. Fig. 9.a shows the life cycle curves of the three energy groups being used by Chinese households over income. As can be seen, solid energy consumption continuously decreases along with higher income. Such decrease becomes slower after income (represented by GDP) reaches 10 trillion RMB. The consumption rates of both liquid and clean energy tend to increase with income even though the increase in clean energy is much faster. The energy transforms from solid to liquid and to clean energy along with increasing income. The Energy Transition Point from solid to clean energy is at the income level of around 6 trillion of GDP, whereas that from solid to liquid energy is predicted to be at the income level of 16 trillion RMB. We reach similar conclusion if GDP is replaced with per capita income. Fig. 9.b shows the life cycle curves of coke and LPG being used by Chinese rural households over income (represented by per capita GDP). The Energy Transition Point from coke to LPG is at the income level of around 1000 RMB, whereas the Energy Vertex Interval is around 1000 RMB.

Based on the above mentioned results, the energy ladder and energy stacking models are supported to some extent in the energy wave transition model. Specifically, the energy ladder model is supported because the liquid energy overcomes solid energy even though the latter will not fade in a long time. However, the energy stacking model seems more suitable for Chinese households at the moment. Figure 6.a shows that more than one energy source may be observed at any time, of which some energy sources are increasing and some are decreasing.

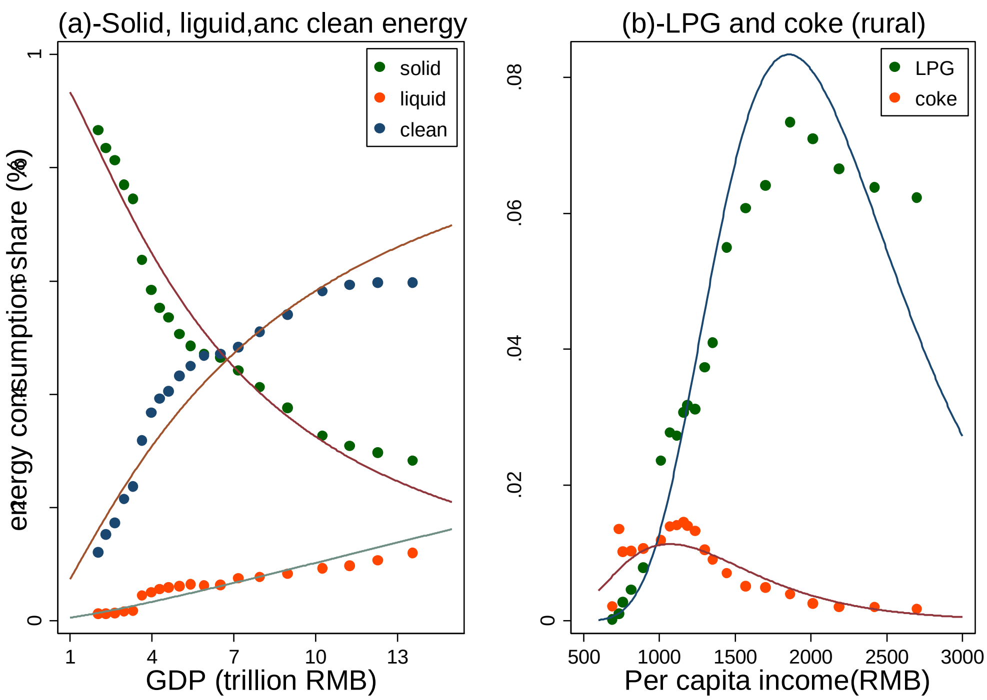

Fig. 9. Energy wave transition over income in Chinese households.
The solid points represent the observed data and the curves represent the estimated life cycles. GDP and per capita income are calculated at 1990 constant prices.

6. Discussion

Previous studies have recognized the energy ladder and energy stacking models as theoretical background to explain household energy transition. Both models describe the relations between energy use and income of households. In this paper, we develop the energy wave transition model that describes the relations between energy use and income of households as well as the relations between household energy use and time.

The energy wave transition model provides plausible explanations for the cases as described by the energy ladder and energy stacking models. The initial energy ladder model assumes only one energy source used by a household at a given income level. So far, the only example to satisfy the assumption is that biomass has been the only energy source used by households for a long period in the history. Hence, the assumption of the energy ladder model has been relaxed to allow multiple energy sources along with household income growth and replaced by another assumption that biomass finally will be abandoned by wealthy households. The new assumption can be explained well by the energy wave transition model as illustrated in Fig. 2.a if the time in the X-axis of the figure is changed to be household income. If biomass is finally abandoned by wealthy households, then the life cycle curve of biomass use would overlap the X-axis in the end of its floor stage. In this sense, the energy ladder model becomes a special case of the energy wave transition model.

On the other hand, the energy stacking model assumes multiple energy sources used by wealthy households. By this assumption, when households become richer and start to use new energy sources, they continue to use the old energy sources. The energy wave transition model also allows for multiple energy sources used by households although it further assumes that the shares of the old energy sources in total energy would gradually decrease until a rather stable low level while the shares of new energy sources would increase to become the main energy sources used by households.

Technology substitution in an economy drives the energy transition of households. When the technology for the use of new energy sources develops from its infant to mature, households gradually adopt the technology to use the new energy sources and the technology supporting the use of old energy sources becomes out of date. In the energy wave transition model, energy consumption shares are used to captures the feature by comparing relative importance of energy sources. Further studies should be made to identify driving forces of the technology substitution. The energy stacking model has classified driving forces of household energy transition into two groups: pushing and pulling forces. Both forces could drive the technology substitution behind the household energy transition.

Similar to other technology substitution models, the energy wave transition model can be used for forecast. The model would be powerful to forecast the energy consumption shares in total energy used by households as illustrated in Section 5, but would not be plausible for predicting total energy consumption. In the present paper, we focus on the “typical” bell-shaped life cycle curves of energy use estimated by quadratic-logistic functions, where only three parameters are required to estimate. By contrast, six parameters have to be estimated by the usually used bi-logistic model, which does not assume bell-shaped life cycle curves.

7. Conclusion

In this study, we has assumed bell-shaped life cycle curves of energy use not only over time, but also along with income growth. This assumption has been supported by previous studies. If we draw the life cycle curves of the various energy sources that are simultaneously being used by households over time or income, we obtain a sketch of wavy lines. The wave transition of energy used by households can be quantitatively studied using logistic functions, which are adopted in few energy transition studies along with income growth. Our introduction of the logistic function into energy transition over income will enable us to examine this issue further using cross-sectional data if time-series data are unavailable.

The new energy wave transition model can explain the cases described by two extant models, namely, the energy ladder and stacking models. The new model can explain cases of more than two energy sources in use as described by the energy stacking model and cases of gradually phasing-out of old energy sources until its abandonment as described by the energy ladder model.

We have proposed two indicators, namely, Energy Transition Point and Energy Vertex Interval, to measure the energy transition speed. These two indicators have to be calculated based on the estimated life cycle curves of the energy being used by households. We illustrate these curves using the energy that is consumed by households in China between 1991 and 2011. The energy sources used in Chinese households transform from solid energy to clean and liquid energy. The energy transition level of rural households is far behind that of urban households.

Finally, we focus on the shares of energy used by households in our analysis. Alternatively, we can focus on the total amount of energy use and the purpose of using such energy depending on our interest.

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