Hindawi
Discrete Dynamics in Nature and Society
Volume 2017, Article ID 6308073, 10 pages
https://doi.org/10.1155/2017/6308073

Research Article

The Dynamics of Structural and Energy Intensity Change

Lizhan Cao

School of Management, Harbin Institute of Technology, Harbin 150001, China

Correspondence should be addressed to Lizhan Cao; lzhcao@126.com

Received 18 December 2016; Accepted 7 March 2017; Published 22 March 2017

Academic Editor: Miguel Ángel López

In this study, an extended structural change model is adopted to explore the mechanisms of how structural adjustments influence the changes of energy intensity. Through adding an energy production sector to the standard model, we find that the change of sectoral energy intensity is determined by the differences of sectoral and energy production technologies. Moreover, the change of economy-wide energy intensity is shaped by both structural and sectoral energy intensity changes. According to theoretical findings and simulation exercises, structural change, initiated by technological growth rate and substitution elasticity, affects the growth rate of economy-wide energy intensity. (1) If the energy threshold technological growth rates are high or low enough, the overall energy intensity will develop monotonically. (2) If the energy threshold technological growth rate is moderate, and (i) substitution elasticity and initial final production technological growth rate meet some requirements, the economy-wide energy intensity will grow monotonically; otherwise, (ii) with the suitable combination of substitution elasticity and initial final production technological growth rate, the overall energy intensity can develop nonmonotonically, like U or inverted-U curves.

1. Introduction

With growing importance of energy intensity reduction as a policy objective over the world, many researchers have attempted to identify the mechanisms of energy intensity change with different data analytical methods, including index decomposition analysis (IDA, [1–3]), structural decomposition analysis (SDA, [4–6]), and production-theoretical decomposition analysis (PDA, [7, 8]), and some even further developed a comprehensive decomposition framework like [9]. One of the basic driving forces of the overall energy intensity change, according to the aforementioned approaches, is output composition change associated with structural adjustments among different industries. Moreover, the effect of structural change on overall energy intensity change may be either positive or negative during a particular period, which may lead to puzzles when the whole process covers both "positive" and "negative" parts. For example, the positive effect might get fully offset by the negative one in a given period, indicating that the overall influence of structural change on energy intensity change equals zero, while structural change may actually be the dominate driver in the change of economy-wide energy intensity (e.g., U or inverted-U curves). Of course, absolute contributions of structural change could be calculated in separate years and then summarized for analyzing its relative importance on the change of overall energy intensity. However, such data analytical approaches could not provide the underlying theoretical mechanisms, like structural change, and its impact on the economy-wide energy intensity change. Instead, a growth-theory-based framework is introduced to make theoretical analysis on structural and energy intensity change uniformly. That is, we aim to explore how the structural change occurs and then shapes the change curve of overall energy intensity.

To our knowledge, there has been a lack of theoretical approaches to explore the mechanisms of energy intensity change, with the exception of [10] that recently filled the gap. Reference [10] uses a theoretical model with directed technical change (DTC), marginally modified from the model of [11], to analyze the underlying mechanisms of the aggregate energy intensity change. Their model consists of two different intermediate sectors, with and without energy input. The underlying drivers of aggregate energy intensity cover exogenous energy price growth and the relative productivity of both sectors affecting the direction of technical change as well as the relative importance of Sector Effect (i.e., structural changes among industries) and Efficiency Effect (i.e., within-sector energy efficiency improvements).

Different from [10], this study has been inspired by the literature of structural change models aimed at underlying reasons for historical structural transformation (e.g., Kuznets facts [12]). There are two different chains in literature to explain structural change, the demand-driven one, and the supply-driven one. The first chain emphasizes differences in the income elasticities of demand across goods which shift the demand and production amid rising income (e.g., [13, 14]). The second chain, initiated by [15], attributes structural change to technological differences and further develops three alternative channels. One is extended by [16] from [15] highlighting sectoral differences in technological growth rates. The second one is proposed by [17], emphasizing the role of sectoral differences in the factor proportions. The last one, recently introduced by [18], indicates that sectoral differences on the degrees of capital-labour substitutability are an additional driving force for structural change. Such models have been applied and extended to analyze energy and climate change issues. For instance, [19] investigated the impact of structural change on the high oil price; [20] explored how climate change influenced the structural change and then how together they influenced the optimal fossil fuel consumption. However, there has been a lack of exploration on energy intensity change through structural change models, and this study is expected to provide an attempt to fill the gap.

Our analysis in this paper follows and extends the work of [16], in which structural change is driven by the technological differences of intermediate sectors as well as the substitution elasticity among the above intermediate goods when used to produce final goods. Compared to the model of [10], the differences and contributions of the present model are as follows. (1) We assume technological change to be exogenous rather than endogenous with DTC in [10]. (2) Our model consists of two standard intermediate sectors which take energy as intermediates equally. (3) Energy is supplied by an independent energy production sector in the model economy, indicating that energy price is somewhat endogenously determined. (4) Considering the above specifications, the mechanisms for changes of both sectoral and overall energy intensity are explored. For example, the former is shaped by the relative technology in intermediate and energy sectors while the latter is determined by both sectoral energy intensity change and structural change, which coincides with the results of data analytical methods. (5) The nonmonotonic change of economy-wide energy intensity could be investigated directly from the model economy, while [10] mainly focuses on the monotonic change of overall energy intensity and must combine different scenarios of energy price growth to work out the nonmonotonic change of overall energy intensity.

The remainder of the paper is structured as follows. Section 2 introduces the model economy. In Section 3, structural change is illustrated, which can be seen as a simplified and intensified version of [16]. Section 4 explores the changes of sectoral and economy-wide energy intensity. We first investigate technological conditions for sectoral monotonic energy intensity change. With regard to structural change, the economy-wide energy intensity grows differently, covering both monotonic and nonmonotonic changes. Section 5 simulates the structural and energy intensity change. Conclusions are demonstrated in Section 6.

2. Model Economy

General setting and competitive equilibrium are introduced in this section. The model developed here draws upon the model derived in [16]. The differences and extensions are as follows. (i) There is only one type of unique final consumption goods in this model while the other capital goods are also incorporated in [16]; (ii) an energy production sector is introduced in the preset model. We consider a closed and nonbalanced model economy, in which labour is considered as the unique primary input. For simplicity and without loss of generality, we assume labour is constant over time. Energy is produced by a part of labour and then used with the other part to produce sectoral intermediate goods.

2.1. Model Description. The economy produces unique final goods combined with two competitive sectoral intermediate goods using constant elasticity of substitution (CES) production functions:

$$Y(t) = \sum_{i=1}^{2} \left(\phi_i Y_i(t)^{(\varepsilon-1)/\varepsilon}\right)^{\varepsilon/(\varepsilon-1)}, \tag{1}$$

where $i = 1, 2$ throughout the text. $\varepsilon \in (0, \infty)$ is elasticity of substitution. $\phi_i > 0$ is distribution parameter which determines the relative importance of the two goods in the aggregate production, and $\sum_i^2 \phi_i = 1$. The sectoral intermediate goods are produced competitively with Cobb-Douglas production functions as

$$Y_i(t) = A_i(t) E_i(t)^{\alpha} L_{i,M}(t)^{1-\alpha}, \tag{2}$$

where the subscript M represents the intermediate sectors (sectors 1 and 2). $L_{i,M}$ and E_i are the quantities of labour and energy used in the intermediate sectors, and $L_M = \sum_{i=1}^2 L_{i,M}$ represents the part of labour assigned to the production of intermediate sectors. $\alpha \in (0, 1)$ is energy income share assumed to be equal across sectors following [16] in order to focus on the channel of technological differences on structural change. A_i denotes the exogenous sector specific technology and takes the form as

$$A_i(t) = A_i(0) \exp(\gamma_i t), \tag{3}$$

where $A_i(0) > 0$ is the initial technology and $\gamma_i > 0$ is the constant technological growth rate over time.

Considering that some real economies are heavily dependent on energy importing, *energy* is defined as secondary energy to further satisfy the closed economy assumption. Secondary energy is produced by labour as well as primary energy assumed costless following [21]. The amount of primary energy is fixed and normalized to be 1. Following [22, 23], the production of energy is thus given as

$$E(t) = A_E(t) L_E(t), \tag{4}$$

where the subscript E represents the energy sector. L_E denotes the other part of labour apart from those in the intermediate sectors (L_M). A_E denotes energy production technology with the following form:

$$A_E(t) = A_E(0)\exp(\gamma_E t), \tag{5}$$

where $A_E(0) > 0$ is the initial energy production technology and $\gamma_E > 0$ stands for the energy production technological growth rate.

2.2. Competitive Equilibrium

Definition 1. An equilibrium is given by prices for final goods $p(t)$, intermediate goods $p_i(t)$, energy $\xi(t)$, and labour $w(t)$, demands for intermediate goods $Y_i(t)$, energy $E_i(t)$, and labour $L_{i,M}(t)$ of sector $i = 1, 2$ and $L_E(t)$, such that, at the period t, producers maximize profits and markets clear as

$$\begin{gathered}\sum_{i=1}^{2} L_{i,M}(t) + L_E(t) = L,\\ \sum_{i=1}^{2} E_i(t) = E(t).\end{gathered} \tag{6}$$

Due to perfect market competition for the final goods, producers maximize their profits by choosing the quantities of sectoral intermediate goods:

$$\max_{Y_1(t),Y_2(t)} \quad p(t)Y(t) - \sum_{i=1}^{2} p_i(t)Y_i(t). \tag{7}$$

Referring to (1), profit maximization yields the following first-order conditions:

$$p_i(t) = p(t)\phi_i\left(\frac{Y(t)}{Y_i(t)}\right)^{1/\varepsilon}. \tag{8}$$

Moreover, goods in the intermediate sectors are produced competitively. Producers choose the quantities of labour and energy to maximize their profits:

$$\max_{L_{i,M}(t),E_i(t)} \quad p_i(t)Y_i(t) - w(t)L_{i,M}(t) - \xi(t)E_i(t), \tag{9}$$

and the first-order conditions of profit maximization are

$$w(t) = p_i(t)(1-\alpha)\frac{Y_i(t)}{L_{i,M}(t)}, \tag{10}$$

$$\xi(t) = p_i(t)\alpha\frac{Y_i(t)}{E_i(t)}. \tag{11}$$

Finally, energy producers are competitive and maximize their profits by choosing the amount of labour:

$$\max_{L_E(t)} \quad \xi(t)E(t) - w(t)L_E(t). \tag{12}$$

Solving the above maximization problem, we obtain

$$w(t) = A_E(t)\xi(t). \tag{13}$$

We then combine (10)–(13) and derive

$$\frac{w(t)}{\xi(t)} = \frac{1-\alpha}{\alpha}\frac{E_i(t)}{L_i(t)} = A_E(t). \tag{14}$$

Equation (14) makes the following clear. (i) The relative prices are proportional to the relative quantities of labour and energy. In equilibrium, wages and energy prices are equal across sectors, respectively, indicating an equality of energy-labour ratios amid different sectors. (ii) Moreover, the equilibrium energy-labour ratios will increase proportionally to energy technological development, which can be applied to investigate energy intensity. In sum, the properties of (14) can facilitate the following identification of the mechanisms of structural change and thus energy intensity change.

3. Structural Change

According to [16], structural change is defined as the reallocation of labour shares over time in at least one sector. Since output composition change is normally termed as structural change effect in decomposition methods, the equivalence of labour and output shares will be explored subsequently in this study.

First, we can obtain the relative outputs of sector 1 to sector 2 from (8):

$$\frac{Y_1(t)}{Y_2(t)} = \left(\frac{p_1(t)}{p_2(t)}\right)^{-\varepsilon}\left(\frac{\phi_1}{\phi_2}\right)^{\varepsilon}. \tag{15}$$

And then applying (14) to (2), we derive

$$\frac{Y_1(t)}{Y_2(t)} = \frac{A_1(t)}{A_2(t)}\frac{L_{1,M}(t)}{L_{2,M}(t)}. \tag{16}$$

Plugging the production function of Y_i into (10) or (11) yields the relation between the relative prices and technologies:

$$\frac{p_1(t)}{p_2(t)} = \left(\frac{A_1(t)}{A_2(t)}\right)^{-1}. \tag{17}$$

Combining (15)–(17), the allocation of labour is given as

$$\frac{L_{1,M}(t)}{L_{2,M}(t)} = \frac{l_{1,M}(t)}{l_{2,M}(t)} = \left(\frac{A_1(t)}{A_2(t)}\right)^{\varepsilon-1}\left(\frac{\phi_1}{\phi_2}\right)^{\varepsilon}, \tag{18}$$

$$\begin{aligned} l_{1,M}(t) = \frac{L_{1,M}(t)}{L_M(t)} &= \frac{{\phi_1}^{\varepsilon}A_1(t)^{\varepsilon-1}}{{\phi_1}^{\varepsilon}A_1(t)^{\varepsilon-1} + {\phi_2}^{\varepsilon}A_2(t)^{\varepsilon-1}}\\ &= \frac{1}{1 + (A_1(t)/A_2(t))^{-(\varepsilon-1)}(\phi_1/\phi_2)^{-\varepsilon}}.\end{aligned} \tag{19}$$

By differentiating (17) and (18), we could conclude that growth rates of relative sectoral labour shares merely depend on the differences amid sectoral technological growth rates (or sectoral prices) together with the elasticity of substitution:

$$\frac{\dot{p_1}(t)}{p_1(t)} - \frac{\dot{p_2}(t)}{p_2(t)} = -(\gamma_1 - \gamma_2), \tag{20}$$

$$\begin{aligned}\frac{\dot{l_{1,M}}(t)}{l_{1,M}(t)} - \frac{\dot{l_{2,M}}(t)}{l_{2,M}(t)} &= (1-\varepsilon)\left(\frac{\dot{p_1}(t)}{p_1(t)} - \frac{\dot{p_2}(t)}{p_2(t)}\right) \\ &= -(1-\varepsilon)(\gamma_1 - \gamma_2).\end{aligned} \tag{21}$$

Proposition 2. *In equilibrium, the rate of change of the relative price of goods 1 to 2 equals the difference between the technological growth rates of sector 2 and sector 1. The differences in growth rates of labour shares are proportional to the differences in the growth rates of the relative prices, with the factor of proportionality given by one minus the elasticity of substitution.*

Proposition 3. *Necessary and sufficient conditions for structural change are that $\varepsilon \neq 1$ and that $\gamma_1 \neq \gamma_2$. If $\varepsilon > 1$, the sector of higher technological growth rate would expand faster than the other, or alternatively if $0 < \varepsilon < 1$, the sector of lower technological growth rate would expand faster.*

Propositions 2 and 3 are directly derived from (20) and (21), which are, respectively, the analogs of Propositions 1 and 2 in [16]. Actually, the two propositions presented in this study are expected to serve as simplifications of those in [16]. Specifically, only two intermediate sectors are covered in the model of this study without identifying how to use the final goods (i.e., consumption, investment). However the model in [16] consists of m sectors and identifies two different kinds of final goods, one for consumption and the other for investment.

Combining (1) and (14), the production of final goods can thus be written as

$$Y(t) = A(t)\,E(t)^{\alpha}\,L_M(t)^{1-\alpha}. \tag{22}$$

And the production technology of final goods is

$$A(t) = \left[\sum_{i=1}^{2}\left(A_i(t)^{\varepsilon-1}\phi_i^{\varepsilon}\right)\right]^{1/(\varepsilon-1)}. \tag{23}$$

By differentiating (23) and combining (19), the dynamics of final goods production technology are identified as

$$\gamma(t) = \sum_{i=1}^{2} l_{i,M}(t)\,\gamma_i. \tag{24}$$

Obviously, the final production technological growth rate is quite different from that of sectoral goods since $\gamma(t)$ is no longer exogenously given and varies in line with structural change.

Next, we consider the labour allocation between final goods sector (i.e., the aggregate intermediate sectors) and energy production sector. From (14) we can easily derive

$$\frac{E_i(t)}{L_{i,M}(t)} = \frac{E(t)}{L_M(t)} = \frac{\alpha}{1-\alpha}A_E(t). \tag{25}$$

Through plugging energy production function of (4) into (25), we acquire

$$\frac{l_M(t)}{l_E(t)} = \frac{L_M(t)/L}{L_E(t)/L} = \frac{1-\alpha}{\alpha}. \tag{26}$$

Lemma 4. *In the model economy, the relative quantities of labour between final and energy sector equal the relative income shares of labour and energy.*

Lemma 4 is derived directly from (26), implying that, given factor income shares, the labour input structure keeps constant between the final and energy sectors regardless of growth in total labour. In other words, the labour assigned to intermediate sectors and energy sector keeps constant over time when factor income shares are given; that is, $L_M(t) = L_M$, $L_E(t) = L_E$.

We then explore the equivalence of labour and output shares for measuring the (relative) industrial structure since the latter is commonly used in data analytical framework.

With the combination of (15)–(17), we get

$$\frac{p_1(t)\,Y_1(t)}{p_2(t)\,Y_2(t)} = \frac{L_{1,M}(t)}{L_{2,M}(t)}. \tag{27}$$

Equation (27) indicates that it keeps consistent for labour and output value to measure industrial structure between intermediate sectors. Moreover, it also implies an equality between total labour employed in sectoral economy and the labour employed in the final economy (see (22)). Therefore, is it the same case for the output value variable?

Combining (8) and (1), we derive the price of the final goods as

$$p(t) = \left[\sum_{i=1}^{2}\phi_i^{\varepsilon}p_i(t)^{1-\varepsilon}\right]^{1/(1-\varepsilon)}, \tag{28}$$

and the relationship between the aggregate intermediate goods values and the final goods value can be explored by

$$\begin{aligned}\sum_{i=1}^{2} p_i(t)\,Y_i(t) &= \sum_{i}^{2} p_i(t)\left[\frac{p(t)\,\phi_i}{p_i(t)}\right]^{\varepsilon} Y(t) \\ &= \left\{\left[\sum_{i=1}^{2}\phi_i^{\varepsilon}p_i(t)^{1-\varepsilon}\right]^{1/(1-\varepsilon)}\right\}^{1-\varepsilon} p(t)^{\varepsilon}\,Y(t) \\ &= p(t)\,Y(t).\end{aligned} \tag{29}$$

Combining (27) and (29), we can obtain the equivalence of labour and output value for industrial structure as

$$\frac{p_i(t)\,Y_i(t)}{p(t)\,Y(t)} = \frac{L_{i,M}(t)}{L_M}. \tag{30}$$

Lemma 5. *In the model economy, it is equivalent to measure industrial structure by both labour and output value shares.*

Lemma 5 implies that, instead of output value shares, labour shares could be used to investigate the structural change effect on the change of overall energy intensity.

4. Energy Intensity Change

In this section, we identify the mechanisms of both sectoral and economy-wide energy intensity change. First, we analyze the technological conditions for the sectoral energy intensity change.

Considering (25) and (26) (or Lemma 4), (2) could be deduced as

$$\begin{aligned}\frac{E_i(t)}{Y_i(t)} &= \frac{1}{A_i(t)}\left(\frac{E_i(t)}{L_{i,M}(t)}\right)^{1-\alpha} \\ &= \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha}\frac{A_E(t)^{1-\alpha}}{A_i(t)}.\end{aligned} \tag{31}$$

And the dynamics of (31) is

$$\frac{\dot{E_i(t)/Y_i(t)}}{E_i(t)/Y_i(t)} = \Lambda - \gamma_i, \tag{32}$$

where $\Lambda = (1-\alpha)\gamma_E$; the energy technological growth rate weighted by labour income share serves as the threshold determining directions of sectoral energy intensity change. Therefore, the following proposition could be generated directly.

Proposition 6. *The sectoral energy intensity change depends on the differences of sectoral and energy (threshold) technological growth rates. If sectoral technological growth rate is high enough, that is, $\gamma_i > \Lambda$, the sectoral energy intensity will decrease. If sectoral technological growth rate is low enough, that is, $\gamma_i < \Lambda$, the sectoral energy intensity will increase. Specially, if $\gamma_i = \Lambda$, the sectoral energy intensity keeps constant over time.*

Proposition 6 shows the mechanisms of sectoral energy intensity change in the model economy presented in this study. Since the technological growth rates are assumed exogenous and constant over time, it could be explored that the change of sectoral energy intensity is monotonic. It is different from that in the model by [10], where technology is endogenously determined with DTC.

Considering Lemma 5 and through procedures of (31)-(32), the change of overall energy intensity follows:

$$\frac{E(t)}{Y(t)} = \left(\frac{\alpha}{1-\alpha}\right)^{1-\alpha}\frac{A_E(t)^{1-\alpha}}{A(t)}, \tag{33}$$

$$\frac{\dot{E(t)/Y(t)}}{E(t)/Y(t)} = \Lambda - \gamma(t) = \sum_{i=1}^{2} l_{i,M}(t)(\Lambda - \gamma_i). \tag{34}$$

Equation (34) indicates that the change of economy-wide energy intensity can be decomposed into output composition change and sectoral energy intensity change disaggregated by decomposed methods, or Sector Effect and Efficiency Effect introduced in [10]. Furthermore, compared to the monotonic change of sectoral energy intensity, the change of economy-wide energy intensity may be nonmonotonic since (34) adds a variable structure factor ($l_{i,M}(t)$) which just reflects the special influence of structural change on the overall energy intensity change.

Without loss of generality, we impose the assumption of sectoral technological growth rates as $\gamma_1 < \gamma_2$ throughout the text. Then the change of economy-wide energy intensity could be expressed in the following proposition.

Proposition 7. *The economy-wide energy intensity change is determined by sectoral energy intensity change as well as structural change. With the assumption of $\gamma_1 < \gamma_2$, there exist monotonic change of economy-wide energy intensity if the energy threshold technological growth rate is (i) high enough, that is, $\Lambda \geq \gamma_2$, (ii) low enough, that is, $\Lambda \leq \gamma_1$, or (iii) medium, that is, $\gamma_1 < \Lambda < \gamma_2$, and not bigger than the initial final production technological growth rate, that is, $\Lambda \leq \gamma(0)$ for $\varepsilon > 1$, or bigger than the initial final production technological growth rate, that is, $\Lambda > \gamma(0)$, for $0 < \varepsilon < 1$. Moreover, (iv) the economy-wide energy intensity will develop nonmonotonically if the energy threshold technological growth rate is medium, that is, $\gamma_1 < \Lambda < \gamma_2$ and $\Lambda > \gamma(0)$ for $\varepsilon > 1$ or $\Lambda \leq \gamma(0)$ for $0 < \varepsilon < 1$.*

Proof. Given $\gamma_1 < \gamma_2$, we can obtain that $\gamma_1 \leq \gamma(t) \leq \gamma_2$ following (24) and the equality holds when only one sector survives in the evolutionary process.

When $\gamma_2 \leq \Lambda$ ($\gamma_1 \geq \Lambda$), we can easily derive that $\gamma(t) \leq \Lambda$ ($\gamma(t) \geq \Lambda$) and $(\dot{E(t)/Y(t)})/(E(t)/Y(t)) \geq 0$ ($(\dot{E(t)/Y(t)})/(E(t)/Y(t)) \leq 0$) from (34), and the cases (i) and (ii) are proved.

In order to prove the cases of (iii) and (iv), we take derivation of (34) to t and consider the labour share change of sector 1:

$$\begin{aligned} d\frac{\left((\dot{E(t)/Y(t)})/(E(t)/Y(t))\right)}{dt} &= -\frac{d\gamma(t)}{dt} \\ &= \dot{l_{1,M}}(t)(\gamma_2 - \gamma_1). \end{aligned} \tag{35}$$

Given $\gamma_1 < \gamma_2$, we follow Lemma 4 and Proposition 3 to get that the labour share of sector 1 will shrink if $\varepsilon > 1$ or expand if $0 < \varepsilon < 1$, which indicates

$$\begin{aligned} &\dot{l_{1,M}}(t) \leq 0 \\ &\qquad d\frac{\left(\left(\dot{E(t)/Y(t)}\right)/(E(t)/Y(t))\right)}{dt} = -\frac{d\gamma(t)}{dt} \leq 0 \\ &\text{or } \dot{l_{1,M}}(t) \geq 0 \\ &\qquad d\frac{\left(\left(\dot{E(t)/Y(t)}\right)/(E(t)/Y(t))\right)}{dt} = -\frac{d\gamma(t)}{dt} \geq 0 \end{aligned} \tag{36}$$

accordingly.

When considering $\gamma(t)$, we conclude that it is nondecreasing of t (i.e., $\gamma(t) \geq \gamma(0)$) if $\varepsilon > 1$ or nonincreasing of t (i.e., $\gamma(t) \leq \gamma(0)$) if $0 < \varepsilon < 1$. Together with the conditions that $\gamma_1 < \Lambda < \gamma_2$ and $\Lambda \leq \gamma(0)$ ($\Lambda > \gamma(0)$), we can obtain $\Lambda \leq \gamma(t)$ if $\varepsilon > 1$ ($\Lambda \geq \gamma(t)$ if $0 < \varepsilon < 1$). According to (34), the monotonic change of overall energy intensity is proved for case (iii).

Table 1: Parameters.

Parameters	Case 1		Case 2		Case 3		Case 4	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
ε	3	0.5	3	0.5	3	0.5	3	0.5
$1-\alpha$	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$\varphi_1 = \varphi_2$	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
γ_1	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
γ_2	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
γ_E	0.06	0.06	0.01	0.01	0.05	0.05	0.05	0.05
Λ	0.042	0.042	0.007	0.007	0.035	0.035	0.035	0.035
$A_1(0)$	100	100	100	100	0.5	0.5	100	100
$A_2(0) = A_E(0)$	1	1	1	1	1	1	1	1
$\gamma(0)$	0.020	0.038	0.020	0.038	0.036	0.028	0.020	0.038

We next provide the proof of nonmonotonic change of overall energy intensity for case (iv).

Referring to the fact that $\gamma(t)$ is nondecreasing of t, that is, $\gamma(t) \geq \gamma(0)$ when $\varepsilon > 1$, with further assumption of $\gamma_1 < \Lambda < \gamma_2$ and $\Lambda > \gamma(0)$, we can find a $t^* \in [0, \infty)$ to satisfy $\gamma(t^*) = \Lambda$, and the growth rate of overall energy intensity satisfies

$$\left(\frac{E(t)\dot{/}Y(t)}{E(t)/Y(t)}\right)\bigg|_{t=t^*} = 0. \qquad (37)$$

Since

$$d\frac{\left(\left(E(t)\dot{/}Y(t)\right)/\left(E(t)/Y(t)\right)\right)}{dt} = -\frac{d\gamma(t)}{dt} \leq 0, \qquad (38)$$

we obtain directly that

$$\begin{aligned} &\frac{E(t)\dot{/}Y(t)}{E(t)/Y(t)} \geq 0 \quad \text{for } t \in [0, t^*], \\ &\frac{E(t)\dot{/}Y(t)}{E(t)/Y(t)} \leq 0 \quad \text{for } t \in [t^*, \infty), \end{aligned} \qquad (39)$$

indicating that the economy-wide energy intensity will grow nonmonotonically like an inverted-U curve. When considering the case of $0 < \varepsilon < 1$ and $\Lambda \leq \gamma(0)$, the proof is parallel to the case of $\varepsilon > 1$ and $\Lambda > \gamma(0)$ and is omitted. In this case, the overall energy intensity will develop like a U curve. □

5. Numerical Analysis

Propositions 2–7 provide the basic mechanisms of structural and energy intensity change driven by underlying technological differences. In this section, simple calibration and simulation exercise are employed to investigate the theoretical findings. Without loss of generality, we assume a set of four-category parameters in Table 1.

We assume substitution elasticities to be (a) $\varepsilon = 3$ and (b) $\varepsilon = 0.5$ so as to explore different structural changes. Labour income share $(1-\alpha)$ uses the general proportion in national income following, for example, [24]. The distribution parameters are assumed to be equal for simplicity; that is, $\phi_1 = \phi_2 = 0.5$. The values of technological growth rates of intermediate sectors are set following the assumption of $\gamma_1 < \gamma_2$, and γ_E is set to satisfy different requirements of Λ. Finally, we choose suitable values of initial technology for different sectors and set $A_2(0) = A_E(0) = 1$ for simplicity.

Simulations, based on the four cases in Table 1, are proposed in Figures 1–4, respectively. Moreover, parametric calibrations of Cases 1–3 refer to the cases for monotonic change of economy-wide energy intensity in Proposition 7, while Case 4 depicts the nonmonotonic change of economy-wide energy intensity.

First, Figure 1 demonstrates uptrends of economy-wide energy intensity of high energy threshold technological growth rate (i.e., $\Lambda = 0.042$). Given $\gamma_1 < \gamma_2$, $\varepsilon = 3$ in Figure 1(a) indicates that the labour flows out of sector 1 to sector 2; that is, the labour share of sector 1 decreases but that of sector 2 increases. Figure 1(b) illustrates the other case for $\varepsilon = 0.5$ which results in an increasing labour share of sector 1 and a decreasing labour share of sector 2. The above structural changes follow Proposition 6 directly, since structural change can be solely determined by substitution elasticity when given $\gamma_1 < \gamma_2$. According to the assumed technological parameters, energy intensities of both sectors increase. Following Proposition 7, the overall energy intensity also increases; however, with different growth rates affected by structural change, cases of Figures 1(a) and 1(b) are accompanied with declining and increasing growth rates, respectively.

Second, Figure 2 depicts downtrends of economy-wide energy intensity when both sectoral energy intensities are decreasing. Specifically, Figure 2(a) illustrates the energy intensity development for high elasticity of substitution, that is, $\varepsilon = 3$, while Figure 2(b) depicts the other case for $\varepsilon = 0.5$. It shows that the dynamics of labour shares of sectors 1 and 2 stay in line with that of Figures 1(a) and 1(b), respectively. Furthermore, due to low energy threshold technological growth rate (i.e., $\gamma_E = 0.01$), the sectoral energy intensity decreases, tracked by the overall energy intensity. However, similar to Figure 1, structural adjustments between the two sectors influence the overall downtrend of economy-wide energy intensity, for instance, the growth rate of the decrease in Figure 1(a) gets eased while that in Figure 1(b) extends.

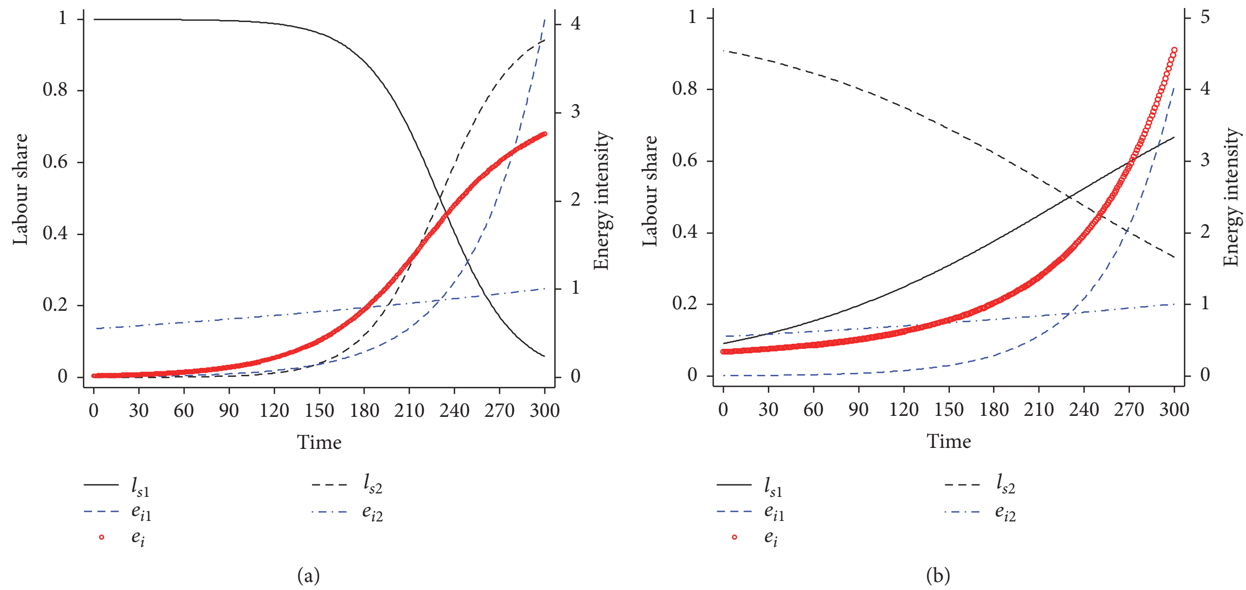

Figure 1: Increasing trend of economy-wide energy intensity with high energy technological growth rate, (a) $\varepsilon = 3$ and (b) $\varepsilon = 0.5$.

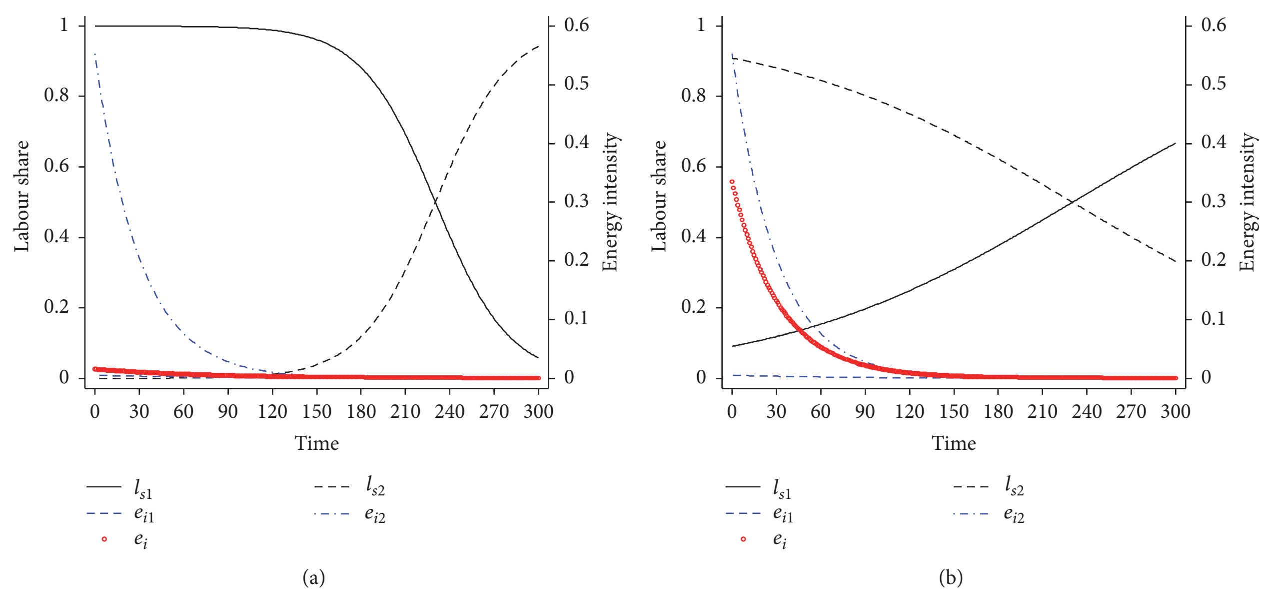

Figure 2: Decreasing trend of economy-wide energy intensity with low energy technological growth rate, (a) $\varepsilon = 3$ and (b) $\varepsilon = 0.5$.

Third, Figure 3 follows the specifications of Case 3 in Table 1. Similar to Figures 1 and 2, the labour in Figure 3 is reallocated from sectors 1 to 2 for $\varepsilon = 3$ and from sectors 2 to 1 for $\varepsilon = 0.5$. Moreover, the assumed energy threshold technological growth rate (i.e., $\Lambda = 0.035$) is bigger than the assumed technological growth rate of sector 1 but smaller than that of sector 2, implying a decreasing trend of energy intensity for sector 1 and an increasing trend of energy intensity for sector 2. The change of economy-wide energy intensity is thus determined by the relative influential magnitude of structural change and the dynamic sectoral energy intensity gaps. In Figure 3(a) ($\varepsilon = 3$) and Figure 3(b) ($\varepsilon = 0.5$), the assumption of $\gamma(0) \geq \Lambda$ ($\gamma(0) < \Lambda$) indicates that both the sectoral energy intensities grow separately since the very beginning without any crossing over time, which finally results in the monotonic change of economy-wide energy intensity.

Finally, following the specifications of Case 4 in Table 1, there exist two different stages for the change of economy-wide energy intensity, as illustrated in Figure 4. Moreover, the inverted-U and U shapes of overall energy intensity are shown in Figures 4(a) and 4(b), respectively. A comparison of both figures demonstrates that the underlying reason for different change shapes of economy-wide energy intensity lies in different substitution elasticities, that is, $\varepsilon = 3$ for Figure 4(a) and $\varepsilon = 0.5$ for Figure 4(b). Above all, the assumed

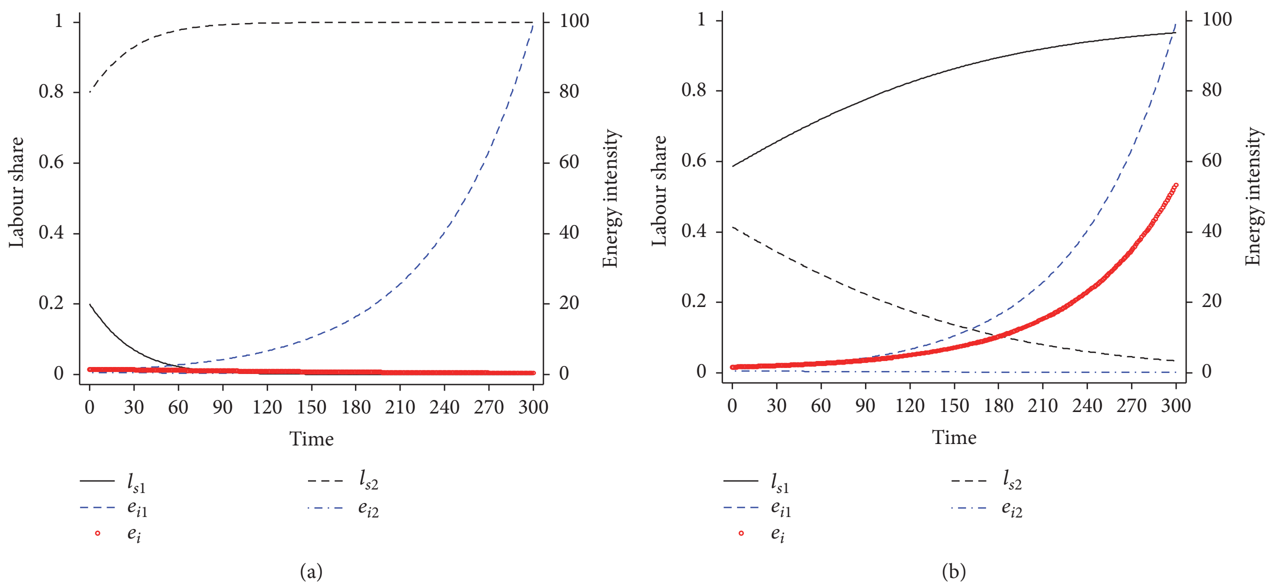

FIGURE 3: Monotonic change of economy-wide energy intensity with medium energy technological growth rate, (a) $\varepsilon = 3$ and (b) $\varepsilon = 0.5$.

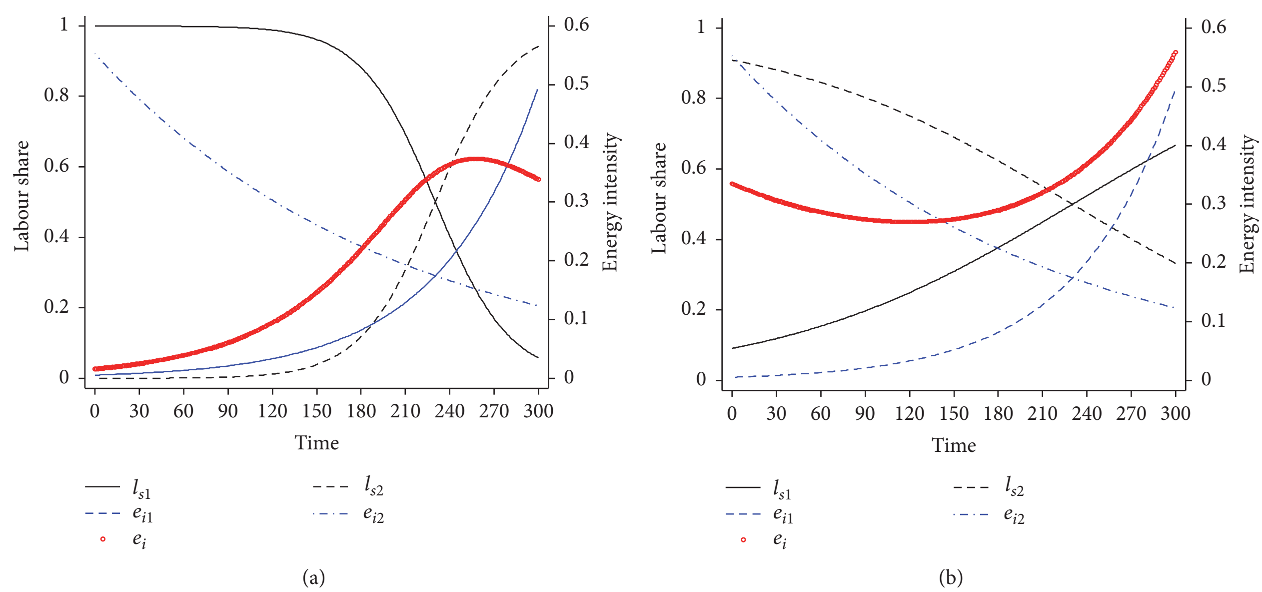

FIGURE 4: Nonmonotonic change of economy-wide energy intensity with medium energy technological growth rate, (a) $\varepsilon = 3$ and (b) $\varepsilon = 0.5$.

medium energy threshold technological growth rate provides the necessity for nonmonotonic change of the economy-wide energy intensity, and the substitution elasticity turns into the underlying driving force for the specific shape of economy-wide energy intensity change through structural change.

6. Conclusions

Until recently, there has been an abundance of empirical studies on the analysis of energy intensity change. However, little research has aimed to explore the underlying mechanisms through theoretical approaches, with the exception of [10] that provides a marginally modified model of [11] with DTC as a trial to fill the gap. In this paper, we introduce a different theoretical model extended from [16] with an inclusion of endogenous energy production sector, focusing on the exploration of how structural change occurs and affects the change of overall energy intensity.

Compared with [10], sectoral technological developments in this model are exogenously determined by given technological growth rates. With these specifications, the mechanisms of sectoral and economy-wide energy intensity changes become more concise and intensified than those of [10]. For instance, (1) the sectoral energy intensity change is driven by the differences amid sectoral and energy technological growth rates, (2) the change of economy-wide energy intensity is subject to a combined effect of structural and sectoral energy intensity change, and (3) this model is more flexible for analyzing nonmonotonic change of economy-wide energy intensity (i.e., U or inverted-U curves), whereas separate scenarios of energy price growth must be combined together to work it out indirectly in [10].

Through theoretical model and simulation exercises, major findings in this research are concluded as follows. (i) Structural change affects the growth rates of economy-wide energy intensity. (ii) When the energy threshold technological growth rates are high (or low) enough, the overall energy intensity will increase (or decrease). (iii) Given moderate energy threshold technological growth rate and suitable combination of substitution elasticity and initial final production technological growth rate, the economy-wide energy intensity will grow monotonically; on the contrary, with the other suitable combination, the economy-wide energy intensity will grow nonmonotonically, like U or inverted-U curves. The above findings can be applied to further explain the heterogenous energy intensity developments in different countries.

This paper tries to provide an alternative framework to explore the underlying mechanisms of energy intensity change. However, we only explain how structural change occurs and how it influences the overall energy intensity change, but do not consider the other driving force, that is, energy transition, which also plays an important role in the energy intensity change, especially in the long run (see [25]). Therefore, how to build a theoretical framework combining structural change and energy transition to better explore the underlying mechanisms of energy intensity change is an interesting and valuable work. On the other hand, technological differences are only one of the underlying reasons for structural change, so whether the other mechanisms can explain the change of economy-wide energy intensity as well (or better) is worth studying.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work was supported by the National Social Science Foundation of China (no. 14AJY011).

References

[1] C. A. Jenne and R. K. Cattell, "Structural change and energy efficiency in industry," *Energy Economics*, vol. 5, no. 2, pp. 114–123, 1983.

[2] G. Boyd, J. F. McDonald, M. Ross, and D. A. Hansont, "Separating the changing composition of U.S. manufacturing production from energy efficiency improvements: a divisia index approach," *The Energy Journal*, vol. 8, no. 2, pp. 77–96, 1987.

[3] B. W. Ang, "Decomposition analysis for policymaking in energy: which is the preferred method?" *Energy Policy*, vol. 32, no. 9, pp. 1131–1139, 2004.

[4] B. W. Gould and S. N. Kulshreshtha, "An interindustry analysis of structural change and energy use linkages in the Saskatchewan economy," *Energy Economics*, vol. 8, no. 3, pp. 186–196, 1986.

[5] J. M. Gowdy and J. L. Miller, "Technological and demand change in energy use: an input-output analysis," *Environment and Planning A*, vol. 19, no. 10, pp. 1387–1398, 1987.

[6] B. Su and B. W. Ang, "Structural decomposition analysis applied to energy and emissions: some methodological developments," *Energy Economics*, vol. 34, no. 1, pp. 177–188, 2012.

[7] C. Wang, "Decomposing energy productivity change: a distance function approach," *Energy*, vol. 32, no. 8, pp. 1326–1333, 2007.

[8] C. Wang, "Changing energy intensity of economies in the world and its decomposition," *Energy Economics*, vol. 40, pp. 637–644, 2013.

[9] E. L'Heureux, B. Milkereit, E. Adam, E. L'Heureux, B. Milkereit, and E. Adam, "3D seismic exploration for mineral deposits in hardrock environments," *CSEG Recorder*, vol. 30, no. 9, 2005.

[10] C. Haas and K. Kempa, "Directed technical change and energy intensity dynamics: structural change vs. energy efficiency," MAGKS, Discussion Paper 10-2016, 2016.

[11] D. Acemoglu, P. Aghion, L. Bursztyn, and D. Hemous, "The environment and directed technical change," *American Economic Review*, vol. 102, no. 1, pp. 131–166, 2012.

[12] S. Kuznets, "Modern economic growth: findings and reflections," *The American Economic Review*, vol. 63, no. 3, pp. 247–258, 1973.

[13] K. Matsuyama, "Agricultural productivity, comparative advantage, and economic growth," *Journal of Economic Theory*, vol. 58, no. 2, pp. 317–334, 1992.

[14] R. Foellmi and J. Zweimüller, "Structural change, Engel's consumption cycles and Kaldor's facts of economic growth," *Journal of Monetary Economics*, vol. 55, no. 7, pp. 1317–1328, 2008.

[15] W. J. Baumol, "Macroeconomics of unbalanced growth: the anatomy of urban crisis," *The American Economic Review*, vol. 57, no. 3, pp. 415–426, 1967.

[16] L. R. Ngai and C. A. Pissarides, "Structural change in a multisector model of growth," *The American Economic Review*, vol. 97, no. 1, pp. 429–443, 2007.

[17] D. Acemoglu and V. Guerrieri, "Capital deepening and nonbalanced economic growth," *Journal of Political Economy*, vol. 116, no. 3, pp. 467–498, 2008.

[18] F. Alvarez-Cuadrado and N. V. Long, "Capital-labour substitution, structural change and growth," IZA Discussion Paper 8940, 2015.

[19] R. Stefanski, "Structural transformation and the oil price," *Review of Economic Dynamics*, vol. 17, no. 3, pp. 484–504, 2014.

[20] G. Engström, "Structural and climatic change," *Structural Change and Economic Dynamics*, vol. 37, pp. 62–74, 2016.

[21] P. Dato, "Energy transition under irreversibility: a two-sector approach," *Environmental and Resource Economics*, pp. 1–24, 2016.

[22] N. Gemmell and P. Wardley, "Output, productivity and wages in the British coal industry before 1914: a model with evidence from the Durham region," *Bulletin of Economic Research*, vol. 48, no. 3, pp. 209–240, 1996.

[23] M. Fröling, "Energy use, population and growth, 1800–1970," *Journal of Population Economics*, vol. 24, no. 3, pp. 1133–1163, 2011.

[24] B. N. Dennis and T. B. Işcan, "Engel versus Baumol: accounting for structural change using two centuries of U.S. data," *Explorations in Economic History*, vol. 46, no. 2, pp. 186–202, 2009.

[25] B. Gales, A. Kander, P. Malanima, and M. Rubio, "North versus South: energy transition and energy intensity in Europe over 200 years," *European Review of Economic History*, vol. 11, no. 2, pp. 219–253, 2007.