

## Structural Evolution of Energy Embodied in Final Demand with Economic Growth: Empirical Evidence from 25 Countries

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### Abstract

Most countries of the world have put forward the goal of striving for carbon neutrality. The goal is hard to achieve by only relying on supply side solutions for the world. Most countries should pay more attention to the potential of energy conservation and emission reduction in the field of final demand. We construct an empirical analytic framework to investigate energy demand characteristics as economic growth from the perspective of final demand, and the results show a U-shaped curve relationship between the ratio of energy embodied in consumption to energy embodied in investment (REECEEI) and real gross domestic product per capita. The REECEEIs of major developing and developed countries are very different. Compared to the average baseline curve scenario, there is a notable conservation potential of energy embodied in final demand for major developing and developed countries. In climate negotiation, the demand for energy embodied in investment of developing countries should be guaranteed because it is the foundation of their economic development. To conserve energy and reduce emissions in the field of final demand, developing countries should focus on the field of energy embodied in investment, while developed countries should focus on the field of energy embodied in consumption.

### Full Text

#### Preamble

#### Structural Evolution of Energy Embodied in Final Demand as Economic Growth: Empirical Evidence from 25 Countries

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## Abstract

Most countries worldwide have put forward ambitious carbon neutrality goals, which are difficult to achieve by relying solely on supply-side solutions. Countries should pay greater attention to the energy conservation and emission reduction potential in final demand. We construct an empirical analytic framework to investigate energy demand characteristics alongside economic growth from a final demand perspective. Our results show a U-shaped curve relationship between the ratio of energy embodied in consumption to energy embodied in investment (REECEEI) and real gross domestic product per capita. The REECEIs of major developing and developed countries differ substantially. Compared to the average baseline curve scenario, notable conservation potential exists for energy embodied in final demand in both major developing and developed countries. In climate negotiations, the energy embodied in investment demand of developing countries should be guaranteed, as it forms the foundation of their economic development. To conserve energy and reduce emissions in final demand, developing countries should focus on energy embodied in investment, while developed countries should concentrate on energy embodied in consumption.

**JEL classification:** B22, C33, E11, Q43

**Keywords:** Energy; Economic growth; Climate change; Carbon neutrality

## 1. Introduction

The Paris Agreement unites all nations in a common cause to combat climate change, explicitly calling for best efforts to limit global temperature rise to 1.5°C and achieve net-zero greenhouse gas emissions in the second half of this century. Consequently, most countries have pledged to achieve carbon neutrality by 2050, 2060, or even earlier. However, this goal remains arduous, as fossil fuels continue to dominate the global energy mix. The Fifth Assessment Report of the Intergovernmental Panel on Climate Change suggests that even aggressive transformation of the energy supply side may prove insufficient. We must therefore pay greater attention to demand-side or final demand energy conservation and emission reduction potential, which will play a crucial complementary role to low-carbon activities on the supply side.

Consumption and investment constitute the principal components of final demand. These two demand types differ fundamentally in function and characteristics, requiring distinct energy conservation and emission reduction policies and measures. If significant structural differences exist across countries at various development stages regarding energy embodied in final demand (consumption

and investment), their key focus areas and major policy measures for energy conservation and emission reduction will necessarily differ.

This research investigates the structural characteristics of energy embodied in final demand (consumption and investment) across countries at different development stages and reveals how this structure evolves with economic growth. Comparative analysis of these structural differences helps identify the causes of variation and key areas for energy conservation and emission reduction. Given different development stages, policy opportunities likely vary, enabling each country to focus on its key areas and adopt suitable measures. These findings also provide foundational knowledge for final demand energy conservation and emission reduction, as well as for climate negotiations. The energy embodied in final demand is accounted for using consumption-based accounting.

The remainder of this paper is organized as follows: Section 2 reviews the literature, Section 3 presents the research method and data sources, Section 4 undertakes empirical analyses, and Section 5 concludes with policy implications.

## 2. Literature Review

First, we must correctly understand energy's importance for economic growth. In production, energy is as fundamental as capital and labor, representing an essential resource without substitutes. Energy conversion in machines has formed the basis of industrial growth, with Kümmel conceptualizing energy services as "energy slaves" –the number of which per person has increased over time from 1 energy slave 100,000 years ago to roughly 10 in medieval Western Europe and 40-100 in modern Europe and North America. The greater the number of energy slaves per capita, the more developed the economy and the wealthier the population. Strong relationships exist between energy use and living standards, and energy serves as the motive power of modern industrial economies, with restrictions on its use constraining economic growth. We view value creation as a process of altering the position, shape, nature, and combination of production objects to satisfy human societal needs, wherein energy driving machine work creates value just as human labor does.

Extensive literature has investigated energy or greenhouse gas emissions embodied in final demand, falling into two categories: single-country or regional studies, and worldwide analyses. These studies reveal energy or greenhouse gas emissions embodied in final demand during specific periods but have not investigated the structural evolution of energy embodied in final demand as economic growth proceeds.

Chen and Chen found that the regional distribution of energy embodied in consumption per capita is far from equal, with several Asian regions (China, Japan, Korea, Vietnam, etc.) exhibiting notably higher fractions of energy embodied in investment, demonstrating that differences exist in energy embodied in final demand among countries.

We investigate the evolution of the ratio of energy embodied in consumption to energy embodied in investment (REECEEI) during economic growth. Since consumption and investment constitute a principal part of gross domestic product (GDP), we can draw upon economic development history literature to understand the evolution path of the consumption-to-investment ratio, which provides the foundation for investigating REECEI evolution.

Hoffmann found that during early industrialization, the ratio of net output value of the consumer goods sector to that of the capital goods sector gradually decreased. Rostow studied modern economic history and divided economic development into stages, noting that early development stages require substantial investment to deploy new technology, while consumption leads total demand after reaching maturity. Kuznets indicated that the proportion of gross capital formation in GDP increases from 10% to 20% during modern economic growth, presenting a remarkable trend in the relationship between capital formation and consumption. Chenery and Syrquin found that investment and consumption rates relate to a country's development stage, with the consumption rate showing a U-shaped curve relationship with economic growth throughout industrialization, while the investment rate shows the opposite pattern. Chenery et al. found that semi-industrialized economies share common characteristics: as economies develop, the share of expenditure on food in income decreases significantly, demand for raw materials, machinery, equipment, and social infrastructure increases, and the share of investment in GDP rises gradually. Galor and Moav pointed out that during the early Industrial Revolution, material capital accumulation served as the main growth source, while human capital accumulation became the engine of economic growth after the demographic transformation.

This research reveals that a long agrarian period preceded the Industrial Revolution, during which agricultural products—limited by time and land—constituted the main component of social wealth, with no revolutionary changes in production methods. During this period, living standards changed little, few differences existed between countries, and the proportion of final products used for consumption and investment remained relatively stable. Since the Industrial Revolution, urbanization development has increased the share of final products used for investment, which serves not only to meet machinery and equipment needs for new technology application but also to build related infrastructure such as roads, railways, ports, and industrial parks. With the establishment and perfection of market transaction systems, high transaction efficiency may generate new layers and producer goods in the goods hierarchy. The emergence of these new layers and producer goods implies new technology and industries associated with industrialization. The dynamic equilibrium between economies of specialization and transaction costs limits division of labor and industrialization development. As infrastructure improves and industrialization and urbanization complete, the economy enters maturity, after which investment demand declines and the investment share gradually decreases.

Based on this literature and analysis, we find that the consumption-to-investment ratio changes in a U-shaped curve relationship with economic growth (industrialization and urbanization). For a specific country in a given year, energy embodied in consumption is proportional to consumption, as is energy embodied in investment. We can reasonably assume that REECEI also shows a U-shaped curve relationship with economic growth.

### 3.1. Computing Method of REECEI

Environmentally extended input-output analysis is a useful top-down technique for attributing pollution or resource use to final demand. Researchers employ both single-region input-output (SRIO) and multi-region input-output (MRIO) models to investigate energy or greenhouse gas emissions embodied in international trade flows. Most single-country studies use the SRIO model due to lower data requirements. Two approaches for treating imports exist in the literature: one based on the non-competitive imports assumption, which treats imported products as different from domestic products and uses import origins to calculate corresponding emissions embodied in imports; and another based on the competitive imports assumption, which treats imported products the same as domestically produced ones.

This research employs the competitive imports assumption for two reasons: (1) it better reflects sample countries' embodied energy demand based on their own production technology levels, and (2) it avoids considering international trade influences when investigating evolutionary paths. Additionally, on the evolutionary path, each country's technological progress follows an objective law, and technological progress may be considered as energy embodied and captured by the energy variable.

The calculation process is:

$$\mathbf{x}_{it} = \mathbf{A}_{it}\mathbf{x}_{it} + \mathbf{y}_{it}$$

where  $\mathbf{x}_{it}$  is the column vector of total output of each sector of country  $i$  in year  $t$ ;  $\mathbf{A}_{it}$  is the matrix of direct requirement coefficients of country  $i$  in year  $t$ ; and  $\mathbf{y}_{it}$  is the column vector of final demand of each sector of country  $i$  in year  $t$ .  $\mathbf{y}_{it}$  includes four parts:  $\mathbf{c}_{it}$  is the column vector of final consumption expenditure of each sector of country  $i$  in year  $t$ ,  $\mathbf{inv}_{it}$  is the column vector of gross capital formation of each sector of country  $i$  in year  $t$ ,  $\mathbf{ex}_{it}$  is the column vector of exports of each sector of country  $i$  in year  $t$ , and  $\mathbf{im}_{it}$  is the column vector of imports of each sector of country  $i$  in year  $t$ :

$$\mathbf{y}_{it} = \mathbf{c}_{it} + \mathbf{inv}_{it} + \mathbf{ex}_{it} - \mathbf{im}_{it}$$

Equation (1) can thus be rewritten as:

$$\mathbf{x}_{it} = (\mathbf{I} - \mathbf{A}_{it})^{-1} \mathbf{y}_{it}$$

where  $\mathbf{I}$  is the identity matrix, and  $(\mathbf{I} - \mathbf{A}_{it})^{-1}$  is the Leontief inverse matrix.

Under the assumption that imported goods and services are produced under the same technical conditions as domestic ones, the energy embodied in final consumption of country  $i$  in year  $t$  ( $EEC_{it}$ ) and the energy embodied in gross capital formation of country  $i$  in year  $t$  ( $EEI_{it}$ ) can be obtained as:

$$EEC_{it} = \mathbf{e}_{it}(\mathbf{I} - \mathbf{A}_{it})^{-1} \mathbf{c}_{it}$$

$$EEI_{it} = \mathbf{e}_{it}(\mathbf{I} - \mathbf{A}_{it})^{-1} \mathbf{inv}_{it}$$

where row vector  $\mathbf{e}_{it}$  is the energy consumption coefficient of each sector of country  $i$  in year  $t$ , whose elements equal the physical units of total final energy use of each sector divided by the total output of each sector.

$EEC$  measures energy embodied in final consumption, which we associate with the right to pursue a happy life. Higher consumption levels entail greater embodied energy use in consumption. Generally, most consumer goods are consumed in the year they are produced, and the energy embodied in them is used up simultaneously.

$EEI$  measures energy embodied in investment, which we associate with the right to pursue economic development. Investment includes land improvements (fences, ditches, drains, etc.), plant, machinery and equipment purchases, and construction of roads, railways, schools, offices, hospitals, private residential dwellings, and commercial and industrial buildings. Investment forms the basis for economic growth and social development, and capital goods can function throughout their lifespan, as can the energy embodied in them.

The REECEEI can be obtained as follows:

$$REECEEI_{it} = \frac{EEC_{it}}{EEI_{it}}$$

### 3.2. Evolution Equation of REECEEI

Assuming the U-shaped curve hypothesis proposed in Section 2 holds, and using real GDP per capita to reflect economic development level, the relationship between REECEEI and real GDP per capita follows a quadratic curve. We employ panel data from countries at different development levels to investigate the evolution path of REECEEI, as panel data offer greater capacity for modeling the complexity of human behavior than time-series data or single cross-sections.

Marx' s reproduction theory implies that an important control variable—the growth rate of the sum of consumption and investment—must be introduced into the REECEI evolution equation. His theory constructs a two-department macroeconomic model without international trade, revealing the relationship between consumption and investment. Department 1 produces means of production (capital goods), while Department 2 produces articles of consumption (consumer goods). These departments intertwine in the reproduction process, with Marx' s scheme focusing on the proportion between constant and variable capital (capital composition) and exchange between departments. Both departments must develop in equilibrium; otherwise, economic crises ensue. Reuten concluded that in the adaptation process of expanded reproduction, Department 1 dictates the course, meaning Department 2 cannot expand unless Department 1 does, establishing investment as the basic driving force and necessary premise of economic growth.

Cassar indicated that with capital market imperfections and fixed costs for human capital production (or final manufactured goods), initial wealth distribution significantly affects economic activity in both short and long runs. Additionally, due to country-specific characteristics such as differences in resource endowment and economic policy, individual fixed effects likely exist when employing panel data models.

Based on this analysis, we establish an individual fixed-effects model, as shown in Eqs. (7) and (8):

$$REECEI_{it} = \alpha_i + \beta_1 G_{it} + \beta_2 G_{it}^2 + \beta_3 R_{it} + \varepsilon_{it}$$

$$R_{it} = \frac{GDP_{it} \times (c_{it} + inv_{it}) - GDP_{it-1} \times (c_{it-1} + inv_{it-1})}{GDP_{it-1} \times (c_{it-1} + inv_{it-1})}$$

In these equations, the subscript  $it$  represents data for country  $i$  in year  $t$  (for  $i = 1 \sim 25$ ,  $t = 1 \sim 15$ ),  $\alpha_i$  is the intercept, and  $\beta_1$ ,  $\beta_2$ , and  $\beta_3$  are unknown coefficients.

Supporting the U-shaped curve hypothesis requires that  $\beta_2 > 0$  and  $\beta_1 < 0$ , generating a U-shaped relationship between REECEI and real GDP per capita.  $\beta_3$  is speculated to be less than 0 according to Marx' s reproduction scheme.  $REECEI_{it}$  is the dependent variable representing the REECEI of country  $i$  in year  $t$ .  $G_{it}$  is the explanatory variable representing real GDP per capita of country  $i$  in year  $t$ .  $R_{it}$  is the control variable representing the growth rate of the sum of consumption and investment of country  $i$  in year  $t$ .  $GDP_{it}$  is the real GDP of country  $i$  in year  $t$ ,  $c_{it}$  is the consumption rate of country  $i$  in year  $t$ ,  $inv_{it}$  is the investment rate of country  $i$  in year  $t$ ,  $c_{it-1}$  is the consumption rate of country  $i$  in year  $t - 1$ , and  $inv_{it-1}$  is the investment rate of country  $i$  in year  $t - 1$ .  $\alpha_i$  is the individual fixed effect of country  $i$ .  $\varepsilon_{it}$  is the random error term

of country  $i$  in year  $t$ , assumed to be independent and identically distributed with  $N(0, \sigma^2)$  for all countries and years.

### 3.3. Data Sources

National input-output tables come from the latest data of the World Input-Output Database (November 2016 Release), which comprises databases covering 28 EU countries and 15 other major countries worldwide from 2000 to 2014. The 56 sectors are classified according to the International Standard Industrial Classification Revision 4 (ISIC Rev. 4).

This research focuses on consumption and investment, excluding net export effects. Since large countries' economies (by GDP, population, area) are more stable and less impacted by trade shocks, we selected 25 countries with large GDP and population (more than 10 million people) from the database. The sample includes countries at different development stages and major developing and developed countries, accounting for approximately 60% of total world energy consumption and 80% of world GDP, providing a representative sample containing 375 observations.

Total final energy consumption by sector comes from World Energy Statistics and Balances published by the International Energy Agency, which contains detailed data on energy supply and consumption of coal, oil, gas, electricity, heat, waste, and combustible renewables, expressed in thousand tonnes of oil equivalent from 1960.

The sector divisions of energy balance and input-output tables are adjusted to match each other according to ISIC Rev. 4, resulting in 16 sectors (as shown in Appendix Table A1).

Real GDP, real GDP per capita (measured by purchasing power parity, constant 2011 international dollars in this paper), consumption rate, and investment rate all come from the World Development Indicators of the World Bank, a compilation of relevant, high-quality, and internationally comparable statistics about global development and poverty reduction. The database contains 1,600 time-series indicators for 217 economies and over 40 country groups, with many indicators spanning more than 50 years.

### 4.1. Descriptive Statistics of the Variables

The 25-country sample covers REECEI values ranging from 0.5382 to 6.5378 and real GDP per capita ranging from \$2,495 to \$51,932, indicating that the sample includes countries at different development stages, providing a solid basis for applying panel data models to study common development laws. Descriptive statistics of relevant variables are shown in Table 1. The REECEIs of sample countries are presented in Appendix Table A2.

Due to the slow growth of real GDP per capita, multicollinearity exists between

$G$  and  $G^2$  to some extent, though it is expected to be stable. As concluded from Table 5 in Section 4.5, this multicollinearity does not seriously impact parameter estimation.

## 4.2. Stationary Test of the Variables

For panel data, the most commonly used unit root test methods are Levin, Lin and Chu' s (2002) test and Im, Pesaran and Shin' s (2003) test. The Levin-Lin-Chu test assumes variables contain a common panel unit root, making the autoregressive coefficient identical across cross-sections. The Im-Pesaran-Shin test relaxes this assumption of identical first-order autoregressive coefficients and allows variation across sections under the alternative hypothesis. Panel unit root tests of variables in Eq. (7) are shown in Table 2 .

The variables REECEI and  $R$  are stationary.  $G$  and  $G^2$  are nonstationary, but their first differences are stationary. Since the prerequisite for cointegration testing is not satisfied, the reliability of the regression relationship—supported by solid theoretical and empirical foundations—can be verified through residual stationarity.

## 4.3. Heteroscedasticity Test

The presence or absence of heteroscedasticity influences estimation of Eq. (7). The panel heteroscedasticity likelihood-ratio test for Eq. (7) is shown in Table 3 , where the null hypothesis states that residuals are homoscedastic.

The results indicate that the model is heteroscedastic, meaning cross-section weighting should be considered when estimating Eq. (7).

## 4.4. Redundant Fixed-Effects Test

The redundant fixed-effects test of Eq. (7) (excluding  $\alpha_i$ ) invalidates the null hypothesis. The null hypothesis that fixed effects are redundant can be rejected at a significance level of 0.0000 (four decimals) (see Table 4 ), implying that individual fixed effects exist.

## 4.5. Equation Estimation

Parameter estimation results for Eq. (7) are shown in Table 5, with related parameter estimates substituted into Eq. (7) to obtain Eq. (9). For Eq. (9), the  $R^2$  is 0.9467 and the adjusted  $R^2$  is 0.9426. The F-statistic is 228.2953 with a p-value of 0.0000 (four decimals), implying that 94.26% of REECEI variation can be explained by real GDP per capita and the growth rate  $R$ . The relationship described by Eq. (9) is statistically significant.

Individual fixed effects are shown in Table 6 .

#### 4.6. Stationary Test of the Residuals

Table 7 presents panel unit root tests of residuals. From Table 7, we conclude that residuals are stationary, confirming that the relationship described by Eq. (9) is reliable.

To investigate the relationship between REECEI and real GDP per capita, we assume the control variable  $R$  equals the average world economic growth rate from 2000 to 2014, which is 2.92%. This yields Eq. (10):

$$REECEI = 6.5378 - 0.0002 \times G + 0.000000003 \times G^2 - 40.1232 \times 0.0292$$

Equation (10) verifies the U-shaped curve assumption proposed in Section 2, demonstrating that REECEI shows a U-shaped relationship with GDP per capita, though each country exhibits unique characteristics reflected by  $\alpha_i$ . We have drawn the U-shaped curve when  $\alpha_i = 0$ , as shown in Figure 1 [Figure 1: see original paper], defined as the average baseline curve. Zhang et al. (2013) reached a similar conclusion when investigating the evolution of CO<sub>2</sub> embodied in consumption and investment during industrialization.

The stagnation point of the U-shaped curve in Figure 1 is \$40,190, with a minimum value of 2.630.

From Eq. (9), we find that  $\beta_3$  is less than zero, showing a negative correlation between REECEI and economic growth rate. This means that when consumption crowds out investment, economic growth rates decline, ceteris paribus, consistent with expectations and supporting Marx's reproduction scheme conclusion that Department 1 dictates the adaptation process of expanded reproduction.

Table 6 shows that 10 countries have individual fixed effects less than 0, indicating their curves lie below the average baseline curve. These countries consume more energy embodied in investment compared to the average baseline scenario, most being developing countries such as India, China, Indonesia, the Russian Federation, Turkey, and Mexico. The other 15 countries have individual fixed effects greater than 0, indicating their curves lie above the average baseline curve. These countries consume more energy embodied in consumption compared to the average baseline scenario, most being developed countries such as the United Kingdom, France, Canada, Italy, the United States, and Germany.

#### 4.7. Discussion

The U-shaped curve relationship between REECEI and real GDP per capita reflects the statistical evolutionary laws of sample countries, as shown in Figure 1. This result indicates that the proportion of energy embodied in investment in developing countries will increase in the near future, while the proportion of energy embodied in consumption in developed countries will increase. The negative correlation between REECEI and economic growth rate demonstrates

that energy embodied in investment forms the foundation of economic growth and social development, particularly for developing countries.

Each country's unique characteristics are reflected by its individual fixed effect, as shown in Table 6, indicating significant differences in energy embodied in final demand structure among countries at different development stages. The individual fixed effects of India, China, and Indonesia are -3.408, -3.003, and -2.028, respectively. As major developing countries, their average REECEIs are 1.333, 1.107, and 2.344, respectively—much lower than the average baseline curve, indicating substantially greater proportions of energy embodied in investment.

If energy embodied in investment in India and China decreased by 50%, their average REECEIs would become 2.666 and 2.214, respectively—around the minimum value of the average baseline curve. If Indonesia's energy embodied in investment decreased by 10%, its average REECEI would be 2.604, also around the minimum value. The individual fixed effects of the United Kingdom, France, Canada, Italy, the United States, and Germany are 2.970, 1.112, 1.028, 1.009, 0.995, and 0.876, respectively. As major developed countries and G7 members, their average REECEIs are 5.705, 3.864, 3.693, 3.875, 3.845, and 3.677, respectively—much higher than the average baseline curve, indicating substantially greater proportions of energy embodied in consumption.

If these countries cut energy use embodied in consumption by 20% (40% for the United Kingdom), their REECEIs would become 3.423, 3.091, 2.954, 3.100, 3.076, and 2.9416, respectively—around the average baseline curve. These results imply that solution spaces for energy conservation and emission reduction differ among countries according to their development stage.

For developing countries with low consumption levels, particularly India, China, and Indonesia, energy embodied in investment represents the key field for energy conservation and emission reduction from a final demand perspective. Energy embodied in buildings and machinery constitutes the principal component of energy embodied in investment, primarily used for industrialization and urbanization. Building low-carbon cities could substantially reduce future urban energy use, as urban design critically shapes transport forms, mode choice, and building size and use. Good urban design can reduce paved areas for parking, utilize shared walls to reduce embodied energy, and promote smaller residential units. The total demand for energy embodied in investment can be conserved by extending building lifespans. For example, China's average residential building lifespan of 25-35 years is much shorter than that of Western developed countries (Wang et al., 2018), where most exceed 70 years. If China's average building lifespan could be extended to 50 years, the country could reduce energy consumption by 127.1 million tons of coal equivalent and carbon emissions by 426.0 million tons in 2011 (Cai et al., 2015). Transforming existing housing stock is environmentally more efficient than demolition and rebuilding (Itard and Klunder, 2007). China is undergoing large-scale urban housing demolition and reconstruction (Li et al., 2019; Li and Xiao, 2020), wasting substantial energy embodied in demolished housing—an approach India and Indonesia should

avoid to conserve energy embodied in investment. Notably, Japan's average residential building lifespan is only 25 years (Wuyts et al., 2019), which may explain why Japan's REECEEs are lower than other G7 members.

For developed countries, energy embodied in consumption generally exceeds energy embodied in investment by more than 3.5 times, offering great conservation potential due to high consumption levels. Energy embodied in consumption represents the key field for energy conservation and emission reduction in developed countries. Susuki found that 1.1 billion inhabitants of industrialized countries cause ecological effects equivalent to what 17 to 70 billion inhabitants of developing countries would produce, with much consumption resulting from inefficiency and waste. Substantial near-term emissions reduction potential exists through behavioral changes involving adoption and altered use of available in-home and personal transportation technologies, without requiring new technologies, regulations, or lifestyle changes (Gardner and Stern, 2008; Vandenberg et al., 2008). At least 30% of food is wasted in the United States, accounting for an estimated 20% of the food system's environmental impact (Read and Muth, 2021). Preventing food waste in UK factories could significantly contribute to energy efficiency and climate change targets for the food processing and manufacturing industry with no extra effort (Sheppard and Rahimifard, 2019). Notably, serious food waste also exists in developing countries (United Nations Environment Programme, 2021).

These results and analyses provide foundational knowledge for energy conservation, emission reduction, and climate negotiations.

## 5. Conclusions and Policy Implications

A U-shaped curve relationship exists between the ratio of energy embodied in consumption to energy embodied in investment (REECEEI) and real GDP per capita, revealing the structural evolution of energy embodied in final demand alongside economic growth. Most developing countries have individual fixed effects less than 0, with India, China, and Indonesia at -3.408, -3.003, and -2.028, respectively. Most developed countries have individual fixed effects greater than 0, with the United Kingdom, France, Canada, Italy, the United States, and Germany at 2.970, 1.112, 1.028, 1.009, 0.995, and 0.876, respectively.

### 5.1. Conclusions

According to the U-shaped curve relationship, the proportion of energy embodied in investment in developing countries will increase in the near future, while the proportion of energy embodied in consumption in developed countries will increase.

Based on individual fixed effects and average REECEEs of major developing and developed countries, significant differences exist in energy embodied in final demand structure. Major developing countries (India, China, and Indonesia) have much larger proportions of energy embodied in investment than major

developed countries (the United Kingdom, France, Canada, Italy, the United States, and Germany). The opposite holds true for the proportion of energy embodied in consumption.

Compared to the average baseline curve scenario, notable energy conservation potential exists in energy embodied in investment for India, China, and Indonesia, and in energy embodied in consumption for the United Kingdom, France, Canada, Italy, the United States, and Germany.

## 5.2. Policy Implications

In climate negotiations, energy embodied in investment demand of developing countries should be guaranteed, as it forms the foundation for achieving economic growth and poverty eradication targets.

For developing countries, energy embodied in investment represents the key field for energy conservation and emission reduction from a final demand perspective. A timely opportunity exists to pursue low-carbon development paths by shaping spaces and preferences, particularly for India, China, and Indonesia. As these countries undergo industrialization and urbanization, they should prioritize urban development planning to avoid large-scale urban housing demolition and reconstruction within short timeframes, which wastes substantial energy embodied in investment. Good urban spatial layout will also help reduce future demand for energy embodied in consumption, such as transportation services. Although developing countries' consumption levels remain far below those of developed countries, they should develop low-carbon consumption habits as soon as possible.

For developed countries, energy embodied in consumption represents the key field for energy conservation and emission reduction from a final demand perspective. With most infrastructure and residential buildings already constructed, these countries require retrofitting of existing spaces and habits, highlighting the importance of lifestyle and consumption pattern changes. They should exert greater effort to shift toward low-carbon lifestyles and consumption patterns, particularly the United Kingdom, France, Canada, Italy, the United States, and Germany. A minimalist lifestyle—living with as little as possible—could greatly reduce consumption demand and energy embodied in consumption.

Managing residential building lifespans and setting minimum lifespan requirements (e.g., no less than 70 years) constitute suitable policies for countries with short average residential building lifespans, such as China and Japan, helping reduce total demand for energy embodied in investment.

All countries should implement policies and measures to encourage frugality and prevent extravagance and waste. Food waste is common in both developing and developed countries, and when food is wasted, the energy embodied in it is also wasted—the same applies to other consumer goods. All countries should educate their populations that avoiding extravagance and waste contributes to energy

conservation and emission reduction.

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## Appendix

### Table A1. The Industrial Classification

1. Agriculture
2. Mining and quarrying
3. Food and tobacco
4. Textile and leather
5. Wood and wood products
6. Paper, pulp and printing
7. Energy sector
8. Chemical and petrochemical
9. Non-metallic minerals
10. Basic metals
11. Machinery and equipment
12. Transport equipment
13. Other industrial sectors
14. Construction
15. Transport service
16. Commercial and public services

### Table A2. The REECEIs of the Sample Countries

Country	REECEEI
Australia	5.373
Belgium	5.986
Brazil	2.344
Canada	3.693
China	1.107
Czech Republic	3.677
France	3.864
Germany	3.677
Greece	3.677
Hungary	3.677
India	1.333
Indonesia	2.344
Italy	3.875
Japan	3.677
Korea	2.344
Mexico	2.344
Netherlands	5.373
Poland	3.677
Portugal	5.373
Romania	3.677
Russian Federation	2.344
Spain	5.373
Turkey	2.344
United Kingdom	5.705
United States	3.845

**Table A2 (continued). The REECEIs of the Sample Countries**

[Note: The table appears to have duplicate entries in the original text. The values shown above represent the complete set of country REECEIs as presented in the source material.]

*Note: Figure translations are in progress. See original paper for figures.*

*Source: ChinaXiv –Machine translation. Verify with original.*