

Trade-off in energy efficiencies and efficient frontier
— Relationship between GDP intensity and energy consumption per capita
and what it means —

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Summary

Energy efficiencies of countries is focused on frequently on issues relating to energy conservation, climate change and energy security. Energy consumption per GDP, or GDP intensity and energy consumption per capita can be listed as representative macro indicator of energy efficiency. While developed countries tend to insist that they are energy efficient due to their low GDP intensity, developing countries say often that they are energy efficient due to their low energy consumption per capita. Which indicator to use for comparing and analysing energy efficiency is highly controversial because it might be related to equity and fairness in climate change mitigation measures.

This paper aims to quantify the trade-off relationship between GDP intensity and energy consumption per capita and to show some implications induced by the quantification using data of G20 countries which account for three quarters of the global energy consumption and carbon dioxide emissions.

On “efficient frontier” — an empirical curve consists of a group of the most efficient tracks which have been achieved — the trade-off relationship between GDP intensity and energy consumption per capita, can be expressed as inverse proportion. This means also that medium- and long-term income elasticity of energy consumption on the curve is 0.5. Decomposition analysis in accordance with the efficient frontier shows that while European and American countries and Russia improved their efficiency toward the efficient frontier, China’s efficiency improvement progress was not as much as approaching the efficient frontier. Furthermore, it is shown that the environmental Kuznets curves (EKC) for energy consumption per capita does not stand up on the curve.

As is usually the case of international negotiations, countries tend to insist their “efficiency.” Determining the trade-off relationship between GDP intensity and energy consumption per capita quantitatively may help to understand the strength of countries’ past efforts for energy conservation and their future targets.

1. Introduction

Energy efficiencies of countries are focused on frequently on issues relating to energy conservation, climate change and energy security. There, however, are numbers of macro indicators for energy efficiency. Among them are energy consumption per gross domestic product or GDP — GDP intensity — and energy consumption per capita. Although both of them are calculated without considering factors determining energy consumption such as economic structure, climate, geographical features, etc., they have advantages including clearness, possibility of broad application and data availability.

In discussions on energy efficiency, while developed countries tend to insist that they are energy efficient referring to their low GDP intensity, developing countries say often that they are energy efficient due to their low energy consumption per capita. Which indicator is used for comparing and analysing energy efficiency is highly controversial because it might be related to equity and fairness in climate change mitigation measures.

Energy has duality as intermediate input to produce goods and services (or a factor of production in a wide sense) and as final goods used for space heating, water heating, travelling, etc. Then careful consideration of situation behind low energy consumption per capita reflects being truly energy efficient or just due to low income level and under-developed economy. Energy consumption per capita, however, is used often as an efficiency indicator because it is clear and its reduction could lead to reduction in emission of greenhouse-gases.

On the other hand, from the viewpoint that energy is consumed to support each country's economic activity and people's life style, energy consumption per GDP — a representative indicator of economic size —, or GDP intensity, is quite often used as an efficiency indicator. For instance, Chinese GDP intensity which is four times higher than that of Japan¹ tells us clearly there is still huge room to improve energy efficiency in China.

This paper aims to quantify relationship between these two efficiency indicators — GDP intensity and energy consumption per capita — and to show some implications induced by the quantification.

2. Trade-off in energy efficiency indicators and efficient frontier

2.1 Economic development and energy consumption

As income per capita grows due to economic development, energy consumption per capita tends to increase. This is led by the increase in demand by industrialisation and increase of production, increased ownership of energy consuming equipments like cars and electric appliances, increase in fuels for power generation to meet expanding electrification, etc.

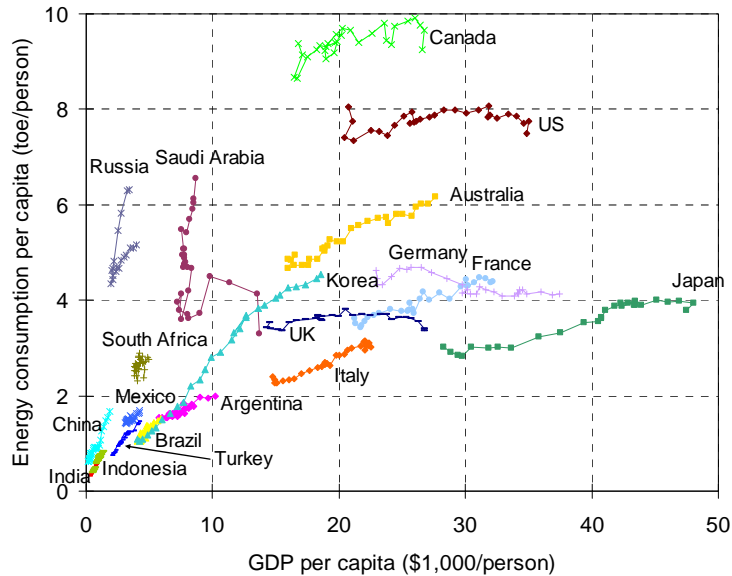
Real GDP² per capita and total primary energy supply³ per capita of G20 countries⁴ from

¹ Although China's GDP is almost the same as Japan's GDP, China consumes four times more energy than Japan.

² GDP is based on prices and dollar value of 1995 when the least imbalance of trade in G20 countries was recorded. Although the base year — mainly exchange rates — affects numbers in this paper, the

1980 to 2008 are shown in Figure 1. Generally speaking, growth in income leads to increase in energy consumption albeit the consumption level is dependent on countries.

Figure 1 GDP per capita and energy consumption per capita, 1980-2008



Source: Calculated with IEA, “Energy Balances” and World Bank, “World Development Indicators”

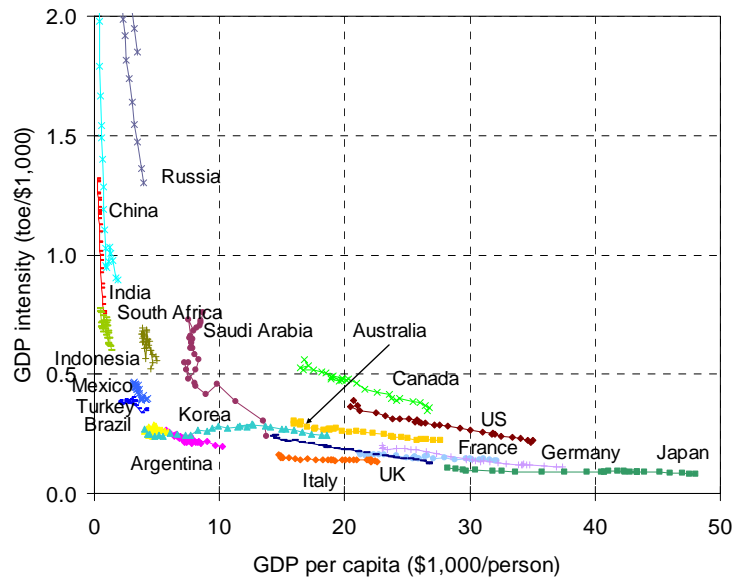
By contrast, as income per capita grows, GDP intensity tends to decline. This can be explained by saturation of income effect for energy demand, softer economic structure due to extension of services sector, penetration of advanced energy and environmental technologies, economies of scale, etc. GDP per capita and GDP intensity are shown in Figure 2.

implication is unchanged.

³ Input energy for primary electricity is re-evaluated with the average thermal efficiency of each country and in each year.

⁴ G20 consist of Argentina, Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Korea, Mexico, Russia, Saudi Arabia, South Africa, Turkey, United Kingdom, United States and European Union. European Union is excluded for the analyses in this paper as it is a region. In 2008, these 19 countries account for about three quarters of the global energy consumption and energy-related carbon dioxide emissions.

Figure 2 GDP per capita and GDP intensity, 1980-2008

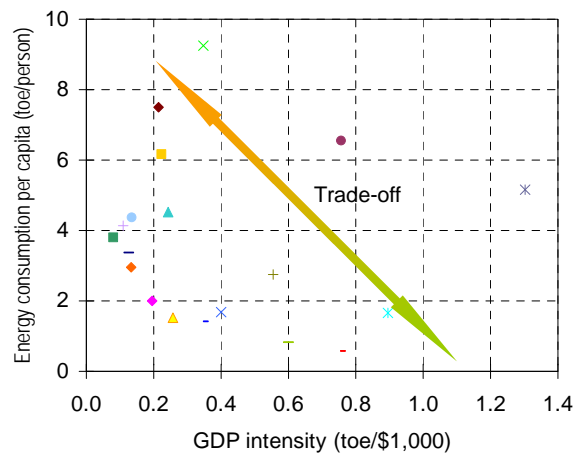


Source: Calculated with IEA, “Energy Balances” and World Bank, “World Development Indicators”

2.2 Trade-off in energy efficiency indicators

As income per capita grows, energy consumption per unit of GDP declines and energy consumption per capita increases. In other words, there is a trade-off relationship between the two efficiency indicators via income per capita. Rough trend between them can be found with cross section data but strict trade-off relationship may not be specified. This is partially affected by the fact that both GDP intensity and energy consumption per capita are calculated without considering factors determining energy consumption such as economic structure, climate, geographical features, etc.

Figure 3 Trade-off between GDP intensity and energy consumption per capita, 2008



Source: Calculated with IEA, “Energy Balances” and World Bank, “World Development Indicators”

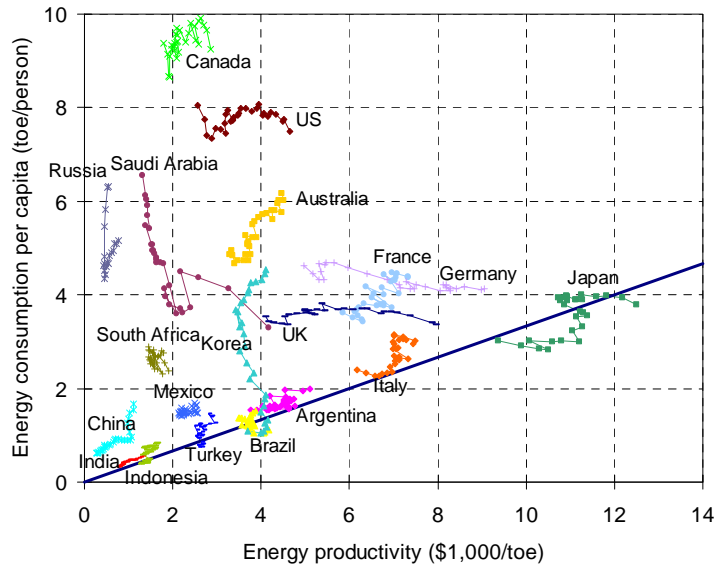
2.3 Derivation of an efficient frontier

Here we change the way viewing the data. GDP per energy consumption, which is a reciprocal number of GDP intensity, is known as energy productivity. No one may make an objection to say both high energy productivity and low energy consumption per capita, or being at lower right in Figure 4, means efficient. No strict trade-off relationship can be found among all of the countries but a linear relationship between two indicators among the most efficient countries; India, Indonesia, Turkey, Brazil, Argentina, Italy and Japan. That is

$$\frac{E}{N} = c \frac{Y}{E} \quad (1)$$

where E is energy consumption, N is population and Y is GDP. And constant c is estimated as much as $1/3$ [$\text{toe}^2/(\$1,000\cdot\text{person})$].

Figure 4 Energy productivity and energy consumption per capita, 1980-2008



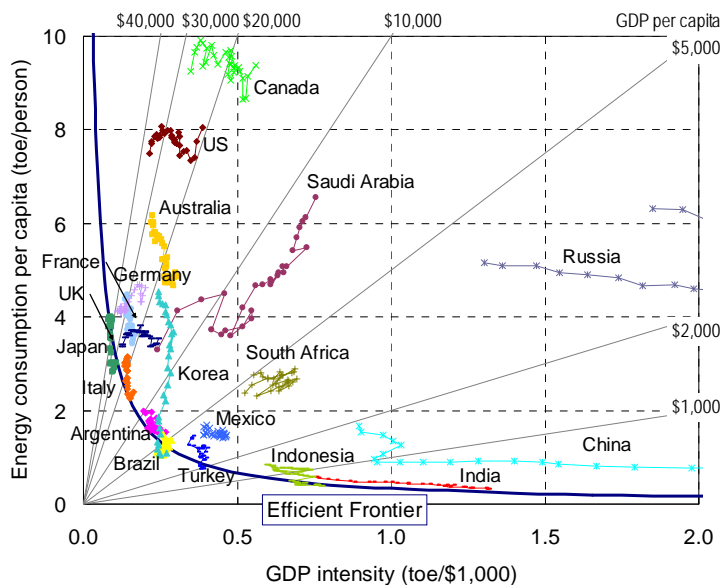
Source: Calculated with IEA, “Energy Balances” and World Bank, “World Development Indicators”

If we go back to GDP intensity and energy consumption per capita, the line is transformed to

$$\frac{E}{N} = c \left(\frac{E}{Y} \right)^{-1} \quad (2)$$

Then the trade-off relationship between the two efficiency indicators can be expressed as inverse proportion.

Figure 5 GDP intensity and energy consumption per capita, 1980-2008



Source: Calculated with IEA, “Energy Balances” and World Bank, “World Development Indicators”

In this paper, we call the empirical curve “efficient frontier.” The efficient frontier is a group of the most efficient tracks which have been achieved actually. If an economy develops or moves from lower right to higher left in Figure 5, along the efficient frontier, we can say that the economy achieves the most efficient energy path in terms of historical data.

2.4 Efficient frontier and GDP elasticity of energy consumption

According to equation (2), the relationship energy and GDP and population in the efficient frontier can be shown as

$$E = c^{\frac{1}{2}} N^{\frac{1}{2}} Y^{\frac{1}{2}} \tag{3}$$

That means medium- and long-term GDP (income) elasticity of energy consumption is 0.5 in the most efficient energy path which have been achieved already; 1% of increase in GDP leads to 0.5% of increase in energy consumption.⁵

Hereafter, analyses applying natures on the efficient frontier are shown.

3. Decomposition analysis in accordance with efficient frontier

3.1 Standard decomposition analysis

When people analyse change in energy consumption quantitatively, decomposition analysis in accordance with the identity below consisting of population, GDP per capita and GDP intensity

⁵ Similarly, population elasticity is 0.5, less than 1. This may sound a bit strange but it is not so wired. For visible micro example, we can point that energy consumption per household does not increase twice even if population of the household increases twice.

is often used.

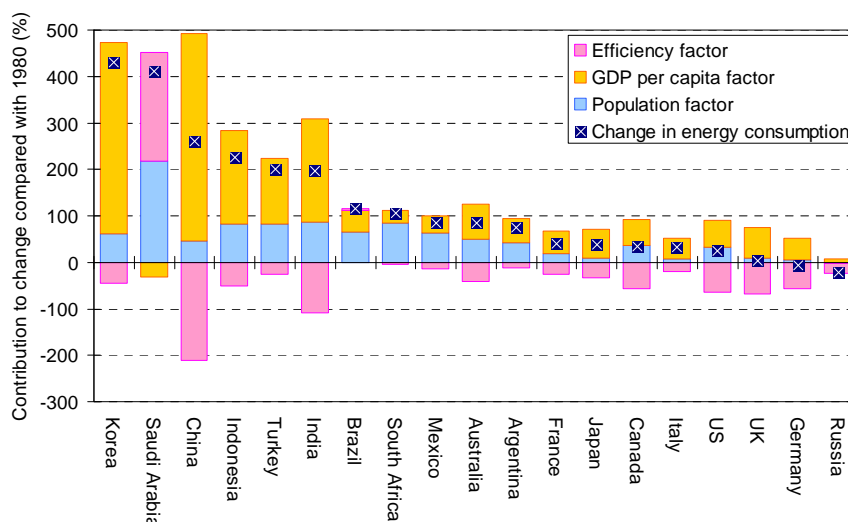
$$E = N \frac{Y}{N} \frac{E}{Y} \tag{4}$$

Change in energy consumption can be decomposed into factors of population, GDP per capita and efficiency.

$$\underbrace{\Delta E}_{\text{Change in energy consumption}} = \underbrace{EN^{-1} \cdot \Delta N}_{\text{Population factor}} + \underbrace{ENY^{-1} \cdot \Delta \frac{Y}{N}}_{\text{GDP per capita factor}} + \underbrace{Y \cdot \Delta \frac{E}{Y}}_{\text{Efficiency factor}} + \text{crossover} \tag{5}$$

The decomposition analysis based on equation (4) can be interpreted that it assumes implicitly that GDP elasticity of energy consumption is 1. When growth of energy consumption is less than growth of GDP, it is regarded that the efficiency factor, or GDP intensity, contributes to all of the energy saving.

Figure 6 Decomposition analysis of change in energy consumption, standard, 1980-2008



Note: 1990-2008 for Russia

3.2 Decomposition analysis in accordance with efficient frontier

It, however, is not necessary that growth of energy consumption is equal to growth of GDP. We see often GDP elasticity lower than 1.⁶ This can be explained by change in economic structure, improvement of stock efficiency by replacing energy equipments in views of time series, and economies of scale in views of cross section data.

As shown above, GDP elasticity is 0.5 on the efficient frontier. Allowing for it, we

⁶ Autonomous Energy Efficiency Improvement, or AEEI, can be regarded as another interpretation that GDP elasticity is less than 1.

decompose change in energy consumption in accordance with the curve. It does not mean countries can realise windfall GDP elasticity of less than 1 but is to measure additional energy saving to approach the efficient frontier.

Considering equations (2) and (3), energy consumption can be expressed by definition as follows⁷:

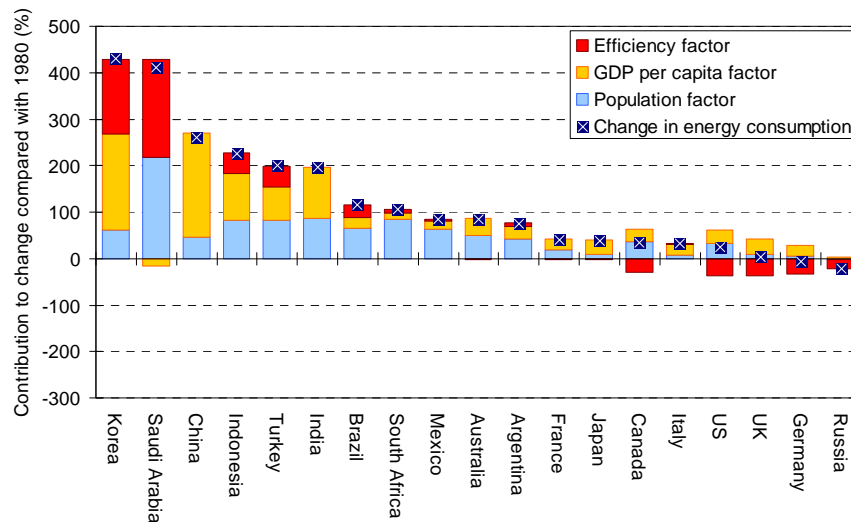
$$E = N \left(\frac{Y}{N} \right)^{\frac{1}{2}} \left(\frac{E}{Y} \right)^{\frac{1}{2}} \left(\frac{E}{N} \right)^{\frac{1}{2}} \quad (6)$$

Then

$$\frac{\Delta E}{E} = \underbrace{EN^{-1} \cdot \Delta N}_{\text{Population factor}} + \underbrace{\frac{1}{2} ENY^{-1} \cdot \Delta \frac{Y}{N}}_{\text{GDP per capita factor}} + \underbrace{\frac{1}{2} Y \cdot \Delta \frac{E}{Y} + \frac{1}{2} N \cdot \Delta \frac{E}{N}}_{\text{Efficiency factor}} + \text{crossover} \quad (7)$$

When an economy moves on the efficient frontier and/or parallel curves, the last two terms representing efficient factor offset each other and the contribution is zero. On the other hand, it is negative value, or contributes to decrease, when an economy approaches the efficient frontier.

Figure 7 Decomposition analysis of change in energy consumption in accordance with efficient frontier, 1980-2008



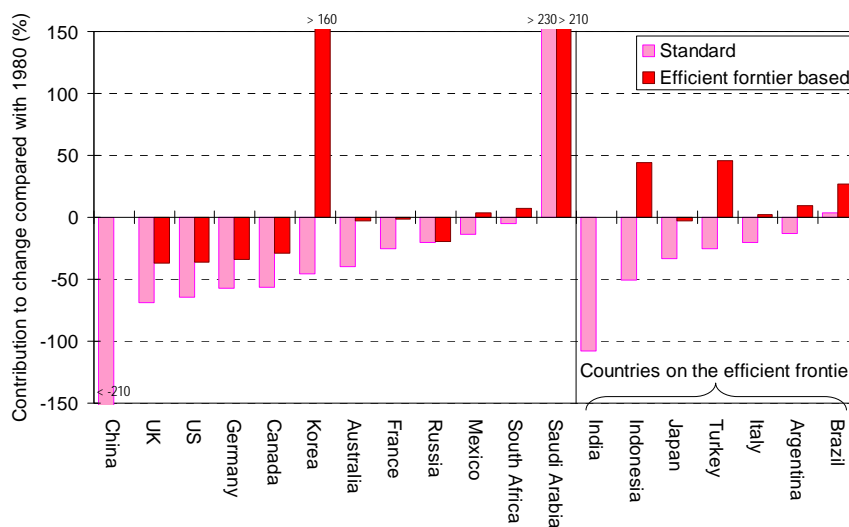
Note: 1990-2008 for Russia

3.3 Comparison of the efficiency contribution

Contribution by the efficiency factor in the two decomposition analyses is picked up and shown in Figure 8.

⁷ The criterion of per square root of GDP not per GDP gives some similar impression with Argentine proposal for voluntary target at the fifth session of the UNFCCC conference of the parties, or COP 5.

Figure 8 Contribution to change in energy consumption by efficiency factor, 1980-2008



Note: 1990-2008 for Russia

Naturally, we can find the efficiency factor contributing to decrease in energy scarcely in the countries on the efficient frontier because the curve consists of group of the most efficient tracks which have been achieved. Some of them — Indonesia, Turkey and Brazil — have efficiency factor contributing to increase in energy consumption rather than decrease as their efficiency got worse and diverged from the efficient frontier.

Meanwhile in many of European and American countries and Russia, which are not on the efficient frontier, the efficiency factor contributes to decrease in energy consumption. This means their relatively inefficient energy demand-supply structure was improved. Contrary to them, China and Korea show different situation. As seen in the standard decomposition analysis, China also improved its inefficient energy demand-supply structure. The progress, however, was rather moving in parallel with the efficient frontier than approaching the curve; the efficiency contribution in China is almost zero. If China keeps this trend, its inefficiency will be more tangible as the other countries are approaching the efficient frontier. Korea shows decreasing contribution by the efficiency factor too in the standard decomposition analysis due to energy conservation in each final consumption sector. However, it diverged from the efficient frontier with rapidly increasing energy consumption per capita because of change in the economic structure by growing industry sector and electrification.

4. Effective frontier and environmental Kuznets curves

Environmental Kuznets curves, or EKC, are empirical curves drawing inverted U shape; at first as income per capita grows, environmental degradation increases but environmental degradation decreases once income per capita surpasses certain level.

It depends on kind of environmental degradation whether EKC stands up actually or not. So

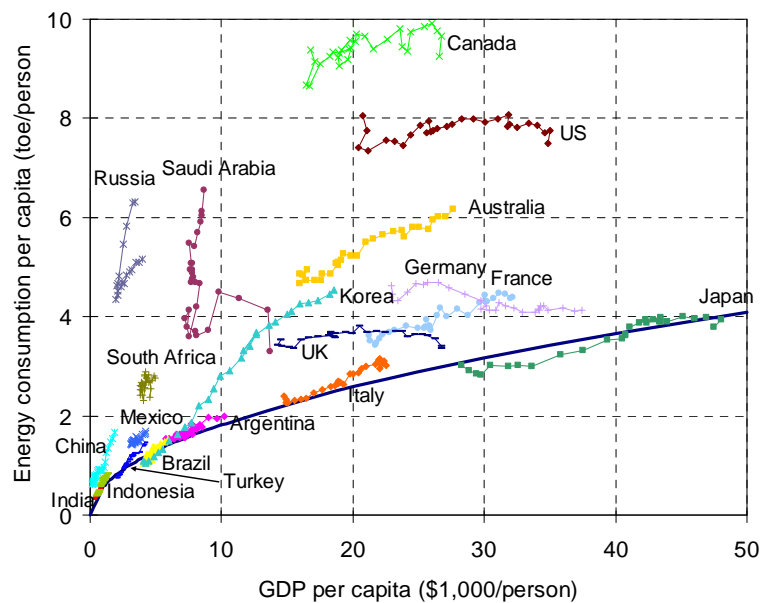
far, EKC for nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) are regarded as existing. On the contrary, existence of EKC for energy and carbon dioxide (CO₂) is controversial. Although countries have been urged to reduce emission of greenhouse-gases, especially energy-related carbon dioxide, no country has shown big decline of carbon dioxide emission per capita enough to draw an inverted U-shape curve.

Meanwhile on the efficient frontier, relationship between GDP per capita and energy consumption per capita can be shown from equation (2) as follows:

$$\frac{E}{N} = c^{\frac{1}{2}} \left(\frac{Y}{N} \right)^{\frac{1}{2}} \quad (8)$$

This means energy consumption per capita monotonically increases as GDP per capita grows. In other words, EKC for energy consumption per capita does not stand up on the efficient frontier (Figure 9). EKC is drawn only if efficiency gets worse then improves later.

Figure 9 GDP per capita and energy consumption per capita, 1980-2008



5. In closing

GDP intensity and energy consumption per capita are the most frequently used indicators to represent macro energy efficiency. As these indicators are calculated without considering factors determining energy consumption, it is hard to specify strict quantitative relationship between them. Only a trend that as income per capita grows, GDP intensity declines and energy consumption per capita increases can be generally found.

This paper presents a naive empirical curve, efficient frontier, which is a group of the most efficient tracks which have been achieved. On the efficient frontier, the trade-off relationship between GDP intensity and energy consumption per capita can be expressed as inverse

proportion. This means also medium- and long-term income elasticity of energy consumption is 0.5. While European and American countries and Russia, improved their efficiency toward the efficient frontier, China's efficiency improvement progress was not as much as approaching the efficient frontier. Furthermore, it is shown that EKC for energy consumption per capita does not stand up on the curve.

As is usually the case in international negotiations, countries tend to insist their "efficiency." To determine the trade-off relationship between GDP intensity and energy consumption per capita quantitatively may help to understand strength of countries' past efforts for energy conservation and their future targets.

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