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MAJOR ECONOMIES: BLACK ENERGY INTENSITY AND POLICY IMPLICATIONS

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Abstract. This study attempted to identify common trends for the "black" economic development of the major developed and developing countries as well as exceptions to these trends. It investigated these economies' energy and carbon dependences in the last 44 years. Drawing on the traditional concept of "energy intensity," this study developed the term of "black energy intensity" to account for the intensity of fossil fuels in the total energy mix as opposed to that of renewable energy sources. Using time series of fossil fuels and nuclear power consumption, population, GDP data of 14 major economies and a combination of statistical analytical methods, it studied the trends of these economies in fossil and non-renewable fuel consumption and dependence and the related CO2 emissions individually and in groups. Based on the analysis of the group trends and exceptions of the main developed and developing economies' carbon-based energy intensities and carbon intensities, the study discussed the policy implications of these findings for these economies' future sustainable development.

Keywords: Black energy, Black energy intensity, Black energy Dependence, Oil dependence, Coal dependence, Gas dependence, Nuclear dependence, Carbon intensity

1. Introduction

Sustainable development was increasingly recognized as the only responsible way of development for the present and for the future. This important knowledge derived first from the understanding of the necessity and urgency for the mankind's action to reduce the carbon emissions of its economic activities and the resulting impact on global warming and climate change. However, this knowledge was generated from the vision that sustainable development could contribute to increasing the technological innovation for energy efficiency and renewable energy generation and consumption, and to strengthen the economy's competitive edge for sustaining its real economic growth by reducing its ecological impact on the planet (WBCSD 2000, Omer 2008, Chen et al. 2011, Garg et al. 2011, Kaygusuz 2012, Mansoor 2013).

Energy intensity (energy demand per unit of economic output), one of the most widely used indicators of energy efficiency in energy policy making and its research, has gained importance for the analysis of the economy's performance in the transition to sustainable development (Wang 2013, Anshasy and Katsaitia 2014, Samuelson 2014). This traditional concept, however, includes all energy sources, and does not distinguish between the carbon and nuclear non-renewable fuels and the renewable energy sources, making it difficult to see the changes taking place between the two groups. The use of

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this term was justified in the fossil and non-renewable fuel age, but has become more and more inconvenient in the transformative age of sustainable development, in which the accelerated deployment of renewable energy generation and consumption stand out as an urgent priority. In order to better understand this energy transformation as a process, a more differentiated methodology is needed.

To meet this research need, this study developed new terms such as "black energy intensity" drawing on the existing concept of "energy intensity," as well as various related "black energy dependences" and "carbon dependence" to account for an economy's intensity of fossil and non-renewable fuels in the total energy mix and its carbon energy reliance as opposed to its intensity of renewable energy sources to determine the degree of its transition to from the black energy generation and consumption to the green energy generation and consumption.

The major economies under investigation behaved and performed differently in this transformation, some proactively and the others reactively. Because of their economic powers in the world economy and the crucial role they have played and will continue to play in determining the direction of future globalization and climate change, their behaviors and performances have substantial economic and climate political impacts on the world economy. In other words, the major economies' moves will set the course for the further development of the globalization and climate and determine if the global economy and climate will evolve in a more sustainable way with irreversible consequences. In this sense, a focused study on their carbon intensity might shed lights on their susceptibility to oil price shocks and their competitiveness in the energy transformation.

This study attempted to explore this issue. It reviewed and analyzed the statistical data of major economies' fossil and non-renewable fuel dependence between 1969 and 2013 to see how these economies have transformed in terms of changes in their fossil and non-renewable fuel consumption, carbon emissions, and economic sizes. The major economies in this study were defined as economies with highest gross domestic outputs (GDP). The major economies involved in this study included the United States, China, India, Japan, Germany, Russia, Brazil, United Kingdom, France, Mexico, Italy, South Korea, Canada, and Spain.

More specifically, this study examined and analyzed the data of energy consumption (such as oil, gas, and coal, as well as shale gas and nuclear energy), CO2 emissions, GDP, and population from various sources. While the data of energy consumptions and CO2 emissions originated from BP Statistical Review of World Energy 2014, the population data came from the UN's World Population Prospects: The 2012 Revision, and the GDP data, adjusted to the 2005 US dollar, derived from World Bank World Development Indicators (WDI) 2014, IMF's International Financial Statistics (IFS) 2013, and International Macroeconomic Data Set, USDA Economic Research Service 2014.

Carbon dependence (Redclift 2009) is one of the defining characteristics of the existing economy since the industrial revolution, which is based on the production and consumption of carbon-based fossil fuels such as coal, oil, and natural gas. Since carbon based economic activities emit carbon dioxide (CO_2) and other pollutants that were found to cause climate change and other environmental and ecological degradations (UN 1987), the investigation on the major economies' carbon dependences and the exploration of its impacts on different types of economies—the developed and the developing economies—hold the key to the energy related transformation of these economies.

Nuclear dependence is another main characteristic of the traditional economy, which is based on the production and consumption of radioactive fuels such as uranium. Nuclear energy, in contrast to carbon-based energy sources, does not emit carbon dioxide (CO_2) and is seen by some as an alternative energy that could displace carbon-based fossil fuels. However, nuclear disasters caused by the Chernobyl nuclear accident in 1986 and the Fukushima nuclear accident in 2011 fundamentally questioned this view's validity, made the major economies more cautious about the development of this alternative energy, and caused some of them, especially Germany, to decide to phase out it (Sovacool 2008, Burgherr and Hirschberg 2008, Hippel 2011, Normile 2012, Revkin 2012, Hippel 2011). Therefore, examining the major economies' nuclear dependences and the implications of increasing or decreasing their nuclear dependences is equally important for the understanding of the energy related transformation of these economies.

The following sections present the results of the investigation of the changes in major economies' carbon and nuclear dependences. The term of black energy intensity includes both carbon-based and nuclear-based non-renewable fuels. It is defined in contrast to the term of green energy intensity, which includes all renewable energy sources. The term of carbon dependence used in this study is determined by two different methods. The first method looks at the share of the non-renewable fuels in the total black energy of the respective economy and the second calculated the correlation coefficient between the non-renewable fuels consumed and the GDP of the respective economy. Using this term, the major economies' oil dependences, and coal dependences, fossil and non-renewable fuel consumptions and CO_2 emissions, CO_2 emissions per capita, and carbon intensities are further comparatively examined.

The examination of the major economies' existing carbon and nuclear dependences is intended to help understand these economies existing strengths and weaknesses in meeting the economic and financial crises and energy related challenges of the globalized world economy and the needs for an energy transformation and related sustainable economic growth.

2. Black Energy Consumption

2.1. Total Black Energy Consumers

First, the study reviewed the total black energy consumptions of the major economies over a long period. The term "total black energy consumption" differs from the conventional term of "total primary energy consumption" in that it comprises all renewable fuels, including fossil fuels (coal, oil, gas) and non-renewable fuel (nuclear energy), but excludes all renewable energy, such as hydro, wind, and solar power, as well as biofuel. In this analysis, the data of the developed and developing economies' consumptions of carbon- and nuclear-based fossil or non-renewable fuels from 1969 to 2013 are examined.

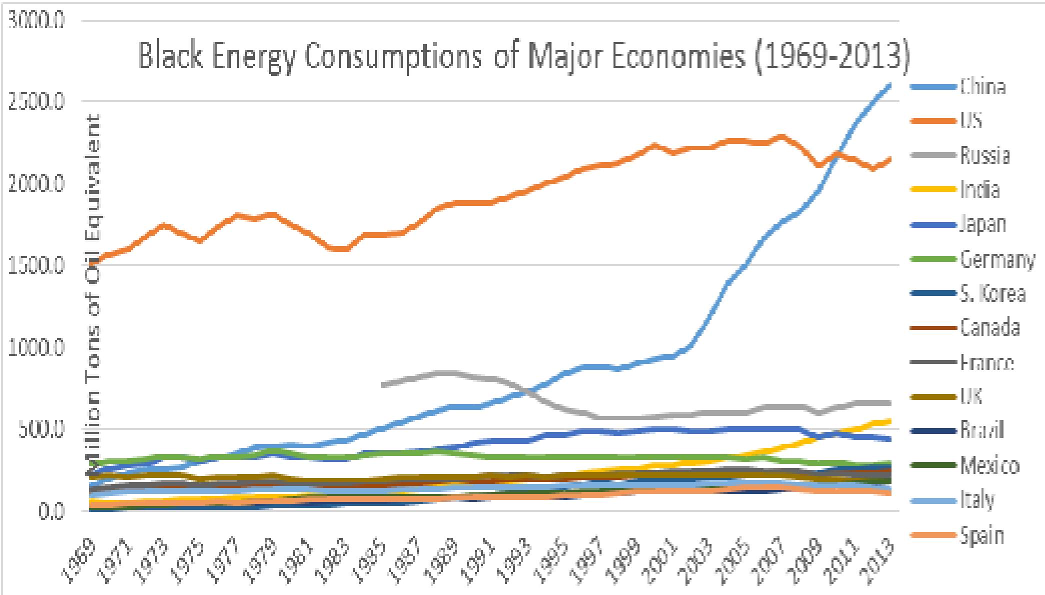

Figure 1. World's Top 14 Black Energy Consumers (1969-2013), Source: BP 2014

The comparative analysis of the world's top 14 black energy consumers found that the world's two top economies, the United States and China, stood out in their total black energy consumptions. The United States started with a top consumption level of 1516 MTOE in 1969 and grew gradually to 2146 MTOE in 2013 while China started with its black energy consumption at a modest level of 153 MTOE in 1969, which exceeded all other countries' black energy consumption levels except for the U.S. level in 1977, embarked on a steep upward trend since its accession to the World Trade Organization in 2002, and broke on its continued surge the U.S. "ceiling" in 2009. As a result, China exceeded the United States in black energy consumption by more than 21 percent in 2013.

With 2603 MTOE for China and 2146 MTOE for the United States, the world's two top economies' black energy consumptions dwarfed all other major economies' fossil and non-renewable fuel consumptions and hovered remotely over those of the next three top consumers, Russia, India and Japan, which consumed 658 MTOE, 553 MTOE and 446 MTOE of fossil and non-renewable fuel fuels in 2013.

In terms of long-term trend over the period of 44 years, most developed economies' black energy consumptions were either increased slightly (for example, approx. 90 percent in Japan and the UK, 70 percent in France, 40 percent in the United States and Italy), remained the same (such in Germany), or reduced (such as 10 percent in the United Kingdom). Exceptions to the developed countries' trend of relative high yet stable consumptions were the fossil and non-renewable fuel consumptions of Spain and South Korea, which increased by 2.2 times and 21.4 times respectively over the investigated period.

In contrast to the group trend of developed economies' relative high yet stable black energy consumptions, the black energy consumptions in most major developing countries presented a different trend, which was characterized by very low consumption levels at the beginning and dramatically increased consumption levels over the period, such as 5.4 times in Mexico, 6.6 times in Brazil, 8.3 time in India, and 16 times in China. This group trend comparison indicates a close link between the black energy consumption with the development level of an economy. While the developed economies with high-level yet low-increasing economic activities and related energy demands determined their high yet stable black energy consumptions, the emerging developing economies with initially low-level and then high-increasing economic activities and related higher energy demands determined their low yet fast increasing black energy consumptions.

The black energy consumption of Russia, a transitional economy, reduced by 20 percent in 2013 from the 1985 consumption level, which resembled more the trend of the developed country group and represented thus exception to the developing country group's trend. This outlier phenomenon of Russia's black energy consumption was mainly caused by the significantly reduced energy demand because of the more than 56 percent economic downturn in the ten years after the disintegration of the former Soviet Union and the less than 1 percent average annual growth of the real GDP in the entire 44-year period of the investigation (USDA, 2014).

The results of the comparative dynamic study of the long-term trends of the two groups' black energy consumptions showed important policy implications. First, while the developed economies demonstrated a stable or even declining black energy consumptions, their existing high black energy consumption levels cannot be expected to be reduced drastically unless they invest significantly more in renewable energy innovations. Second, the drastic increases in black energy consumption levels driven by the developing economies' catch-up developmental energy needs can easily match or exceed the decreases in the developed economies' black energy consumption levels. The combined effect of these two trends of fossil and non-renewable fuel consumptions is an aggregated increased black energy demand in the near future, which will pose significant environmental and ecological challenges to the planet and require both developmental groups to make joint efforts to speed up energy transformation and sustainable development.

2.2. Black Energy Consumption Per Capita

Next, the study reviewed the black energy consumptions per capita of the selected economies over a long period. In this analysis, the data of black energy consumption and population of the 16 major developed and developing economies from 1969 to 2011 were used. The results of the per capita analysis of the energy consumption are presented in Figure 2, which showed a reversed picture to that of the results of the previous aggregated analysis of total black energy consumptions.

First, in contrast to the estimate of a previous study by Kontorovich et al. (2014) that the per capita energy consumption was reduced by more than 40 percent in the

United States, Great Britain, and France, and by approximately 20–30 percent in Germany, Canada, Switzerland, and Japan over the last 30–35 years, this study found that the per capita black energy consumption was reduced slightly by 7.2 percent, 21.4 percent, and 3.6 percent in the United States, the United Kingdom and Germany respectively; all other developed economies displayed increased black energy consumptions, i.e. by 15.3 times in South Korea, 1.3 times in Spain, around 35 percent in France, 57 percent in Japan, 18.5 percent in Italy in the 44-year period of investigation. While the discrepancies between the findings of these two studies on the developed economies' data might be partially explained by their different scopes of data, i.e. per capita energy consumption vs. per capita black energy consumption, exploring the discrepancies would be an interesting research topic of a dedicated study.

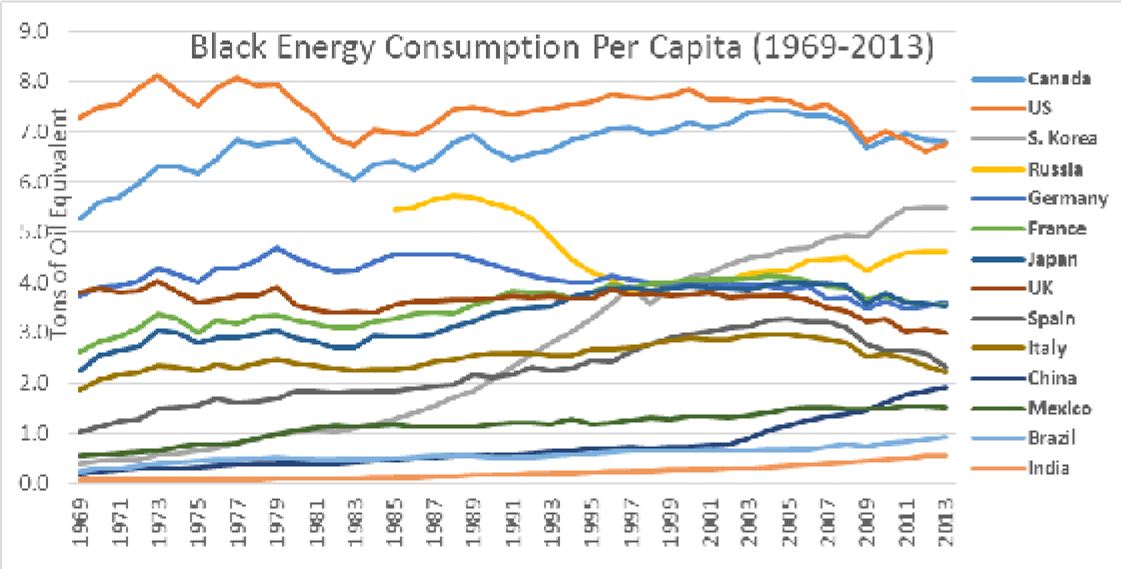

Figure 2. Black Energy Consumption per Capita of Major Economies (1969-2013)
Sources: BP 2014, Destatis 2014, NBS 2014, UNDESA 2014, WPS 2014

Second, as a group, the developing economies showed a trend of more rapidly rising black energy consumptions than the most developed economies. For example, China's increased by 8.9 times, India's by 8.3 percent, and Mexico's by 1.7 times. However, Russia's black energy consumption per capita was an exception to this trend. It started with a relatively high level in the 1980's (where its data started to become available in the compatible format) and showed a 15.3 percent decreased in 2013 from that initial level. However, it was still 1.4 times higher than China's in 2013.

Third, China was one of the four lowest black energy consumers per capita among the investigated major economies although it took the top position of this group since 2010, followed by Mexico, Brazil and India. Its black energy consumption per capita was consistently above India's in the entire period, but had an alternate position with Brazil's for a long period until 2002. That year, China's black energy consumers per capita took off from the levels of developing countries, and doubled between 2003 and 2013. As a result, it exceeded Brazil's in 2002 and Mexico's in 2009, and was poised to reach the bottom level (Italy's) of the developed economies' black energy consumptions per capita in the near future.

Fourth, all developed economies' black energy consumptions were still higher than China's in 2013. For example, Italy's were by 15.4 percent higher than China's, Spain's by 21.4 percent, UK's by 56.3 percent, Japan's by 84 percent, France's by 85.2 percent, Germany's by 88 percent, South Korea's by 1.9 times, the United States by 2.5 times and Canada's by 2.6 times higher.

Previous studies also showed that the average citizen's energy consumption was below the energy consumptions of the average citizens in developed nations and this energy consumption "inequality" was in line with the income inequality between the two groups (Duro et al. 2010, Duro and Padilla 2011a and 2011b, Andrich et al. 2013). The results of this study revealed that even if the total black energy consumptions of some developing economies caught up or even significantly exceeded those of the developed economies, the group disparity in per capita energy consumptions between the developed country group and the developing country group observed in previous studies still existed at the end of the investigated period; however, it was significantly reduced in recent years.

What stood out in this comparative study was that South Korea, a fast rising yet still smaller economy than China, Japan, and Germany, assumed the third place in black energy consumption per capita among the 14 major economies in 2000, which increased more than 13 times in this examination period, an even faster increase than that in China (8.9 times). This top rising speed of South Korea's black energy consumption per capita could be explained by a number of factors, including the initial low fossil and non-renewable fuel consumption level (0.4 TOEs vs. that at 7.6 TOEs in the United States and that at 0.2 TOEs in China), high share of energy intensive sectors in industrial energy consumption (62 percent in 2009), rising share of the main energy intensive sector, the steel making industry, since 1990 (33 percent in 2009), and rapidly rising energy demand driven by overall economic development (ABB 2011).

These findings for the sustainable economic transformation indicate that the determined yet fair global efforts of carbon reduction should not be merely based on the total amounts of black energy consumption and CO_2 emissions of an economy, but must also be based on the aggregated numbers in relation to other numbers such population sizes and GDPs. Accordingly, the global and national strategies and policies of carbon reduction and sustainable development should be informed and updated individual economies' developmental needs for energy consumption and the unequal per capita energy consumptions, which have been largely biased to the developed countries. For example, while the developed countries should primarily focus on carbon reduction, the developing countries can first focus on carbon intensity reduction, and then focus on carbon reduction when the energy disparity has reduced.

2.3. Black Energy Intensity

This section presents the findings from the analysis of energy intensity of the major economies. The term of black energy intensity was measured by dividing the total fossil fuels and nuclear energy consumed by the gross domestic product (GDP) of an economy. Accordingly, the data of total black energy consumptions and GDPs of 14 major economies from 1969 to 2013 will be examined.

Since purchase power parity (PPP) valuated GDPs can more accurately compare the long-term trends of various economies, this method was used for the years in which the PPP adjusted GDP data existed. However, since PPP-adjusted GDPs were only available for the period between 1980 and 2013 (IFM WEO, 2014), the exchange rate based real GDP data adjusted to 2005 dollar (USDA) were used for the period between 1969 and 1979. However, since 1979 was the year when China started its market-oriented reforms that dramatically impacted its energy policy, the division of the comparative analysis of black energy intensities into two different periods with the dividing year of 1979 has the unintended benefit of helping better understand the historical changes in China's black energy intensity in comparison with other major economies' in these two different periods. In the following, the results of the exchange rate-based analysis are shown in Figure 3 and those of PPP-adjusted in Figure 4.

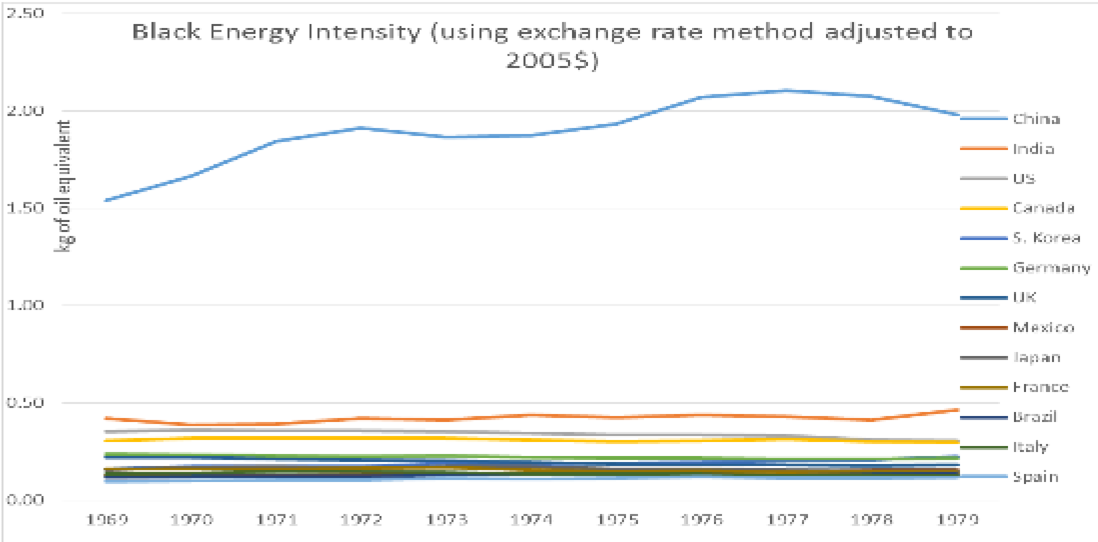

Figure 3. Foreign Exchange Based Energy Intensities of Major Economies
Data Sources: BP 2014, USDA 2014, World Bank 2014

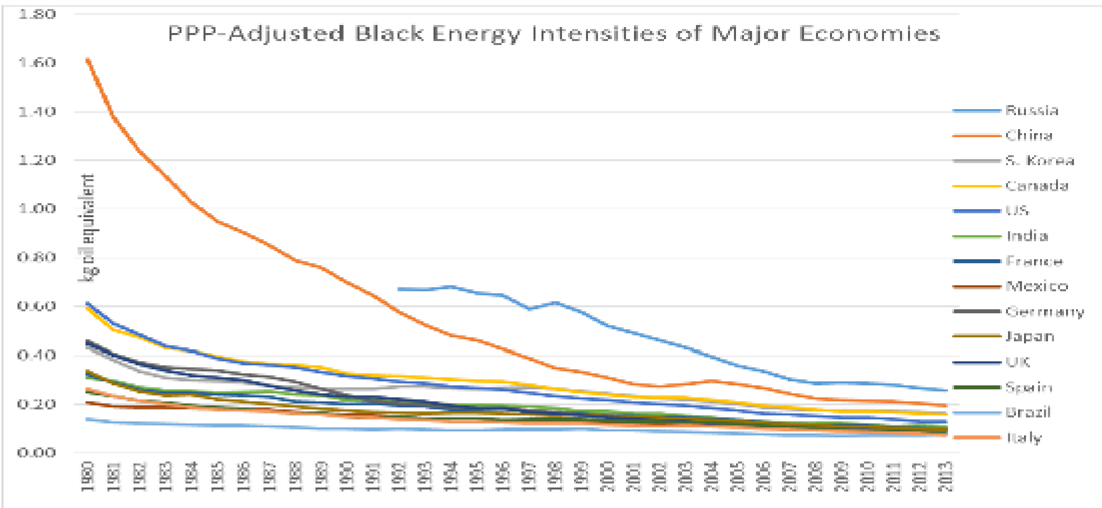

Figure 4. PPP Adjusted Black Energy Intensity of Major Economies, Data Sources: BP 2014, IMF 2014

It should be noted that Russia was not included in this analysis because of unavailability of the time series of the fossil and non-renewable fuel consumption and GDP data. The results of the exchange rate-based black energy intensity analysis reveal several insights.

First, China's black energy intensity was the highest among the 13 major economies, and much higher than all other economies' involved in this investigation, ranging from 2.7 times higher than India's to close to 15.5 times higher than Spain's in 1969 and from 3.3 times higher than India's to 15.9 times higher than Spain's in 1979.

Second, China's black energy intensity was increased by 28.4 percent during this period and, when it reached the top level in 1977—the year before China started its economic reforms, the increase in that year was by 37 percent from its initial level in 1969.

Third, China's black energy intensity increase was not a complete outlier in this period. As a matter of fact, the black energy intensities of 6 out of 13 major economies under examination experienced increases. For example, South Korea's black energy intensity increased by 39.3 percent (an even higher increase than China's), Spain's by 26 percent, Mexico's by 25.9 percent, Brazil's by 15.5 percent, and India's by 10.2 percent.

Fourth, the black energy intensities of more advanced economies were all decreased during this period; for example, the United Kingdom's decreased by 17.7 percent, the United States' by 12.8 percent, France's by 9.7, Germany's by 9.4, Italy's by 5.8 percent, Japan's by 2.9 percent, and Canada's by 2.1 percent.

Fifth, except for China's extremely high black energy intensity, there were no obvious group differences in black energy intensities that would distinguish developed countries from developing countries during this period.

It should first be noted that Russia was included in this PPP adjusted black energy intensity analysis, but because of lack of data, its time series did not cover the entire examination period, but started rather from 1992. The results of this PPP adjusted black energy intensity analysis showed some similarities to the previous exchange rate based analysis. For example, although the incomplete time series of Russia's black energy intensity made it impossible to see if Russia's black energy intensity per capita was higher than China's from the beginning of this period or even in the entire previous period, it was obvious that China continued to be one of the two top black energy intensive economies among the major economies during this examination period.

The two period black energy intensity analysis of the major economies showed that China's extraordinarily high energy intensity could be attributed to its dual historical status as both a Socialist economy (whose low black energy prices led to low black energy efficiency) like Soviet Union and a developing economy (whose low development level led to high black energy consumption) like India. The results also indicated that China's black energy intensity experienced a drastic reduction since its departure from the Socialist planned economic model and its new trajectory as a market based economy with increasing sophistication and maturity. This transitional feature of the Chinese economy explained China's exceptional reduction of energy intensity observed by earlier scholars such as Kepplinger et al. (2013).

At the same time, the comparative study revealed that as of 2013, China's black energy intensity still ranked second among the investigated major economies, only slightly below Russia's, but was still significantly higher than other major economies', ranging from 20 percent higher than South Korea's to 1.62 times higher than Italy's in 2013. This indicated that China still has to make substantial efforts to reduce its black energy intensity and improve its energy efficiency as black energy is still a central pillar of China's current energy policy.

On the other hand, the results of the recent period black energy intensity analysis also showed some distinctive trends that were not observed in the previous exchange rate based black energy intensity analysis of the earlier period.

First, as soon as China started its market based economic reforms in 1979, its black energy intensity per capita moved drastically and continuously downward, with a small rebound between 2003 and 2006. As a result, in contrast to the country's rising black energy intensity during the previous investigative period, China's black energy intensity decreased by 88 percent in 2013 from its beginning level in 1980 in the second investigative period.

Second, the decreasing black energy intensity was not a trend exclusive to China, but rather a general trend for all major economies included in this second examination period. Other developing economies' black energy intensities reduced by 64.6 percent for India, 53.2 percent for Mexico, 44.9 percent for Brazil in the period between 1980 and 2013, and 61.5 percent for Russia in the shorter period between 1991 and 2013. The developed economies, on the other hand, witnessed collectively even higher black energy intensity reductions, for example United Kingdom by 82.4 percent, Germany by 80.3 percent, the United States by 79.1 percent, Canada by 73.4 percent, Japan and Italy by 71.6 percent, France by 69.2 percent, Spain by 68.7 percent, and South Korea by 62.5 percent.

The finding that the developed economy group had a higher rate of black energy reduction than the developing economy group suggets that the black energy reduction was related to the development level, technological advancement and industrial structural change. This finding was in line with the findings of similar studies. For example, Samuelson (2014) observed that the reduction of energy intensity was faster than many policymakers realized and Voigt at al. (2014) found that except for Japan, the United States, Australia, Taiwan, Mexico and Brazil, the reduction of global energy intensity was more driven by technological change than by structural change. At the same time, South Korea's slower reduction rate of black energy intensity per capita and its current even higher black energy intensity than all major economies except for Russia and China suggests that South Korea's lower degree of industrial structure change and high economic growth played an important role in the slow pace of reducing black energy intensity.

This black energy intensity analysis has significant policy implications. It showed that developing and transition economies Russia, China, India, Mexico, and Brazil need to design and improve their policy tools to encourage innovation and technology investment in improving their black energy efficiency and further reducing their black energy intensities. At the same time, the study suggested that despite their advanced technologies, the developed economies also need to further move away from energy intensive sectors in order to more smoothly improve their energy efficiency.

2.4. Black Energy Consumption

2.4.1. Oil Dependence

First, the study examined the oil dependences of the 14 major economies and the oil dependence of the world economy as a whole. To better understand how the growths of the world economy and the individual major economies depended on oil, the study used the following two methods: a) the share of the oil consumption in the total energy mix and b) the correlation coefficient of the oil consumption with the real GDP of an economy. While the first method looked at the importance of the oil consumption in comparison with other forms of energy, the second method examined the interaction of the oil consumption with the economic growth of the individual major economies.

Using the first method, the study first looked at the share of the oil consumption in the total primary energy consumption for individual major economies and the world economy, and then compared these shares over the entire 44-year examination period.

This method examined how the individual major economies and the world economy changed their individual oil consumption in terms of their total energy consumptions annually and over the entire examination period. The results of this examination presented a more detailed and specific view of the black energy consumptions discussed in the previous section.

The examination using this method generated several findings. First, the major economies' average oil share reduced from 49 percent in 1980 to 42 percent in 1990 and to 35 percent in 2013 whereas the world economy's average oil share reduced from 45 percent in 1980 to 39 percent in 1990 and to 33 percent in 2013, a worldwide average decrease by 27 percent from 1980 to 2013 and 16 percent from 1990 to 2013. This indicates that both the major economies and the world economy presented a general downward trend in their shares of oil consumptions in total energy mixes.

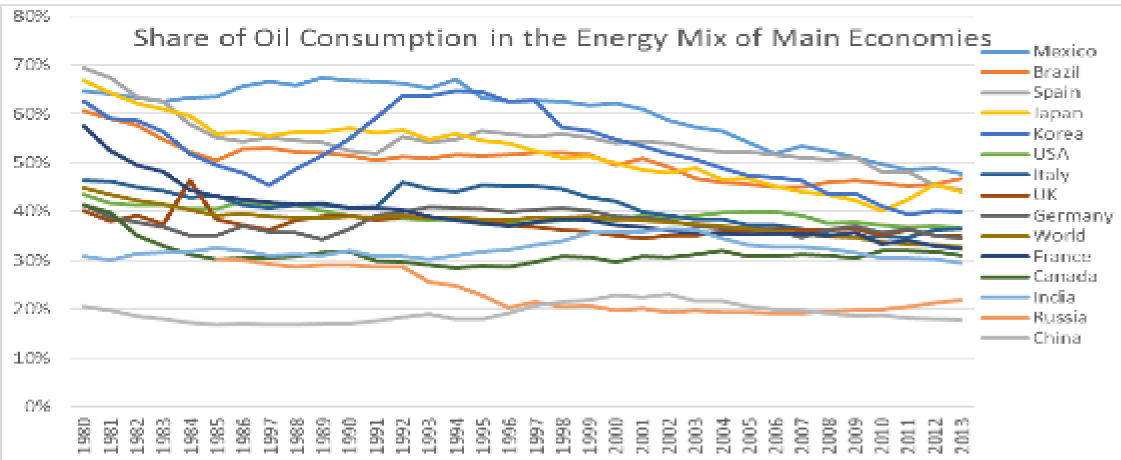

Figure 5. Oil Dependence of the Major economies: Share of Oil Consumption in Total Energy Mix

Second, the decreases of individual economies' oil shares in 2013 from 1980 ranged from 44 percent in France and 36 percent in Spain and South Korea to 13 percent in China and 5 percent in India. Interestingly, the different decrease rates of the five major economies were related with their initial levels of oil shares, with 69 percent for Spain, 63 percent for South Korea and 57 percent for France versus 31 percent for India and 20 percent for China. In other words, the three developed economies with higher initial oil shares had much bigger decreases than the two most populous developing economies with lower initial oil shares. Considering that both China's and India's oil consumptions increased 5.3 percent on average annually, the decreases in their oil shares in 2013 from 1980 and the further decreasing trend in the last five years were mainly caused by the even faster increases of their coal consumptions (5.8 percent and 5.5 percent annually).

Third, the above divergent "trends" between the three main developed economies and the two main developing economies did not, however, apply to other developing major economies under examination. For example, the top two major economies with highest oil shares in 2013 were both developing economies, i.e. Mexico (48 percent) and Brazil (47 percent), and the reductions of their oil shares (26 and 23 percent respectively) in 2013 from 1980 were also bigger than those of many developed economies, such as Germany (17 percent), the United States (16 percent), Italy (21 percent), the United Kingdom (13 percent).

Fourth, the comparison of the major economies' average annual oil shares from 1980 to 1990 with those from 1991 to 2013 revealed that while all major economies had decreasing oil shares in the first period, this downward trend stopped in India and China in the second period with slight increases in their average annual oil shares by 1 percent and 2 percent respectively over the first period, and the two major economies thus became exceptions to the trend of decreasing oil shares.

Using the second method, this study examined the relationship of the oil consumption with the economic growth. It first identified the annual changes in the real world GDP (adjusted to 2005 dollar) and the real GDPs (adjusted to 2005 dollar) of the individual major economies and the world economy and the annual changes in their oil consumptions during the period between 1980 and 1990 and during the period between 1991 and 2013 and then ran the correlation analysis between these two time series of the oil consumption and real GDP in these two periods for the major economies and the world economy. The separation of the 44 examination years into these two periods was designed to gain a better understanding of how the oil dependences of the individual major economies and the world economy based on the second method have changed between the two different periods.

The results of the investigation using the second method, which are presented in Figure 6, demonstrate that the world economy was heavily dependent of the oil consumption in the entire investigative period although its oil dependence slightly reduced from .82 in the earlier period (1980-1990) to .78 in the recent period (1991-2013). The changes in individual major economies' oil dependences are discussed as follows.

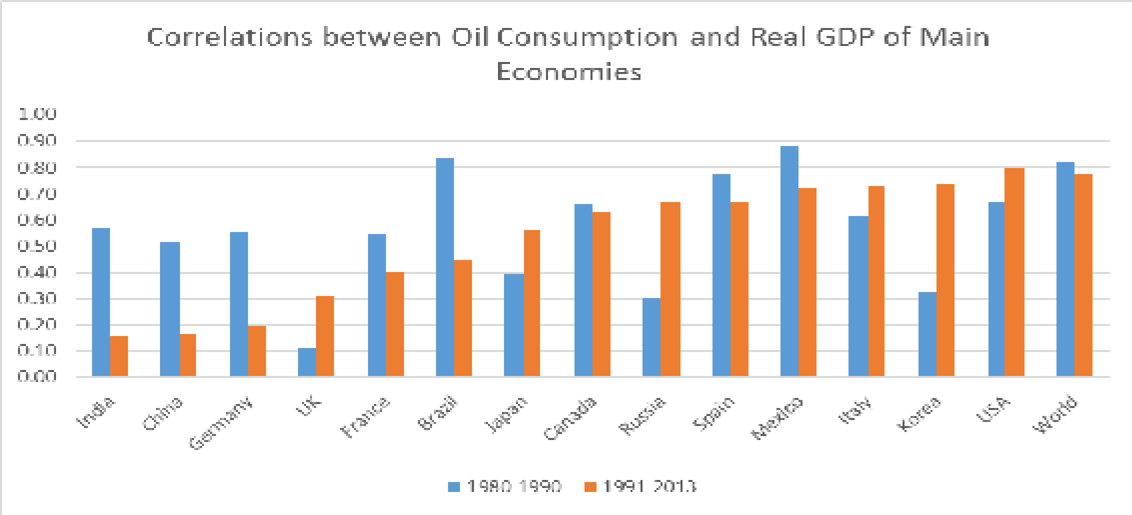

Figure 6. Oil Dependences of the Major Economies: Correlation Coefficients between Oil Consumption and Real GDP of Major Economies in 1980-1990 vs. 1991-2013, Sources: BP 2014, USDA 2014

The major economies that had relatively high oil dependences in the first period and reduced oil dependences in the second period included Mexico (from .89 to .72), Brazil (from .84 to .45), Spain (from .78 to .67), and Canada (from .66 to .63). On the other hand, the economies that had relatively low oil dependences in the first period and even lower oil dependences in the second period included India (from .57 to .16), China (from .52 to .16), Germany (from .55 to .19), and France (from .55 to .41).

In contrast, the United States had a relatively high oil dependence in the first period and even higher oil dependence in the second period (from .66 to .80), thus having become the most oil dependence economy among the 14 major economies. Major economies that had initially low oil dependences, but significantly higher oil dependences in the second period were Korea (from .33 to .73) and Russia (from .30 to .67). Economies with increased oil dependences in the second period also included Italy (.61 to .73), Japan (from .40 to .56), and the United Kingdom (from .11 to .31).

While China’s low oil dependence in the recent period can be explained by its lower level of economic development and purchasing power, Germany’s significantly reduced oil dependence in this period cannot be explained with the same reasons of low development level. As matter of fact, Germany’s oil dependence that was much lower than those of all other developed economies, especially the United States and South Korea was untypical for a highly productive, manufacturing developed economy and represented an exception to the oil dependence of the developed countries. The finding of Germany’s much lower oil dependence helps explain in part why the German economy proved “particularly resistant against recent crisis pressures,” such as the oil price hikes prior to the world financial and economic crisis in 2008-2009 and the acute current Euro Zone fiscal crisis (Funk 2012).

The findings of the U.S. and German economies’ extremely different oil dependences have several implications. First, the findings allow us to confidently associate the rise in the oil consumption with the growth in the world economy and the

U.S. economy and vice versa during the recent ten years. At the same time, these revelations expose the U.S. economy's and the world economy's soft underbelly, their heavy reliance on oil making them extremely vulnerable to the short-term oil shocks such as oil supply shortages, oil price hikes, and long-term oil crises such as oil peak and oil depletion.

In addition, this revelation also suggested that if the U.S. economy and the world economy do not make effort to change their heavy oil reliance in the future, the future short-term oil shocks will have severe long-term implications for these oil dependent economies. It indicated that it is not only in the interest of the U.S. economy, but it is also its moral responsibility as the world's top economy to reduce its overreliance on oil in order to reduce these vulnerabilities in the face of short-term and long-term oil crises.

2.4.2. Coal Dependence

Next, this study moved on to examine the coal dependence of the major economies. Like the oil dependence analysis in the previous section, the coal dependence analysis in this section was based on two methods, first the method of analyzing the shares of coal consumptions in the total energy mixes, and then the method of analyzing the correlations between the coal consumptions and real GDPs.

In the coal share analysis, the study first looked at the share of the coal consumption in the total primary energy consumption for individual major economies and the world economy on an annual basis, and then compared these annual coal shares over the entire 44-year examination period. The findings of this analysis are discussed as follows.

First, the four major economies with highest coal shares (67 percent, 55 percent, and 30 percent respectively) in 2013 were China, India, South Korea and Japan. The coal dominances of these major economies were associated with two features: a) all these coal intensive economies were located in Asia, and b) the top two of the three most coal intensive economies, China and India, were also the two least oil intensive economies as discussed in the previous section.

Second, among other major economies whose coal shares were also below the world economy's average coal share (30 percent), six had coal shares between 27 percent and 11 percent (i.e. Japan 27 percent, Germany 25 percent, United States 20 percent, and the United Kingdom 18 percent, Russia 13 percent and Italy 11 percent) and five had coal shares low than 10 percent (i.e. Spain 8 percent, Mexico 7 percent, Canada 6 percent, and both France and Brazil 5 percent).

Third, examining the long-term change in the major economies' coal shares, the EU economies' coal shares experienced more drastic reductions then other major economies from 1980 to 2013. For example, France's coal shares reduced 66 percent, Spain's 56 percent, and the United Kingdom's 48 percent, and Germany 36 percent. While the most coal intensive economies, China and India, insignificantly reduced their coal shares (7.9 percent and 1 percent), Japan and Mexico significantly increased their coal shares, i.e. 67 percent and 1.2 times respectively. Comparing the changes in coal shares between the 1980-1990 period and the 1991-2013 period, most reductions of coal shares, especially in EU economies, took place in the second period. However, major increases in coal shares of several economies also took place in the second period, for example, 1.2 times in Mexico, 54 percent in Japan, 24 percent in South Korea.

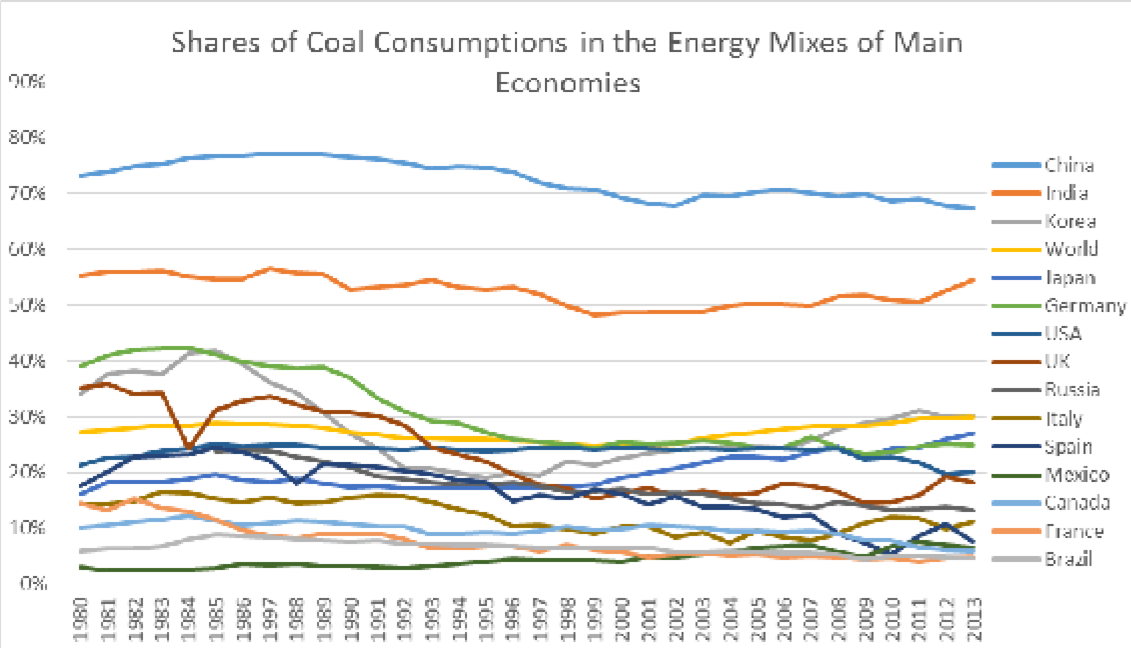

Figure 7. Coal Dependence: Share of Coal in Total Energy Mix of Major Economies, Source: BP, 2014

In the coal-GDP correlation analysis, this study used the coal consumption data and the real GDP data of the major economies during the period between 1980 and 2013. This study first looked at the annual changes in the world GDP and the GDPs of the 14 major economies and the annual changes in these economies' coal consumptions during the period and then ran the correlation analysis between these two time series. The correlation analysis between the GDP and coal consumption of the five investigated economies resulted in respective correlation coefficients of these economies to indicate their individual coal dependences.

The results of this correlation examination showed more a much more complicated picture than the coal share examination. First, economies with high coal shares tended to have high coal-GDP correlation coefficients. China was an outstanding example; with an annual average coal share of 75 percent in the period between 1969 and 1979, its coal-GDP correlation coefficient was .81, the highest among the major economies in the period. Similarly, when Germany and South Korea had relative high annual average coal shares of 43 percent and 36 percent in the same period, their coal-GDP correlation coefficients reached 58 percent and 50 percent respectively.

However, other factors such as the differences between the changes in the coal share and the GDP also significantly determined the coal-GDP correlation coefficients. For example, although China reduced its annual coal share by only 7.9 percent in the period between 1980 and 2013, its coal-GDP correlation coefficient reduced significantly to .44 in this period compared with .81 in the previous period because it maintained a high annual GDP increase of around 10 percent in the same period. Similarly, when France, Spain, the UK and Germany dramatically reduced their coal shares by approximately 66 percent, 56 percent, 48 percent and 36 percent, their coal-GDP correlation coefficients reduced to .21, .16, .17 and .15 respectively in the period between 1980 and 2013. Conversely, because of the dramatic increase of 67.4 percent in Japan's annual coal share in this period, its coal-GDP correlation coefficient reached 58 percent despite its much lower coal shares of 20 percent.

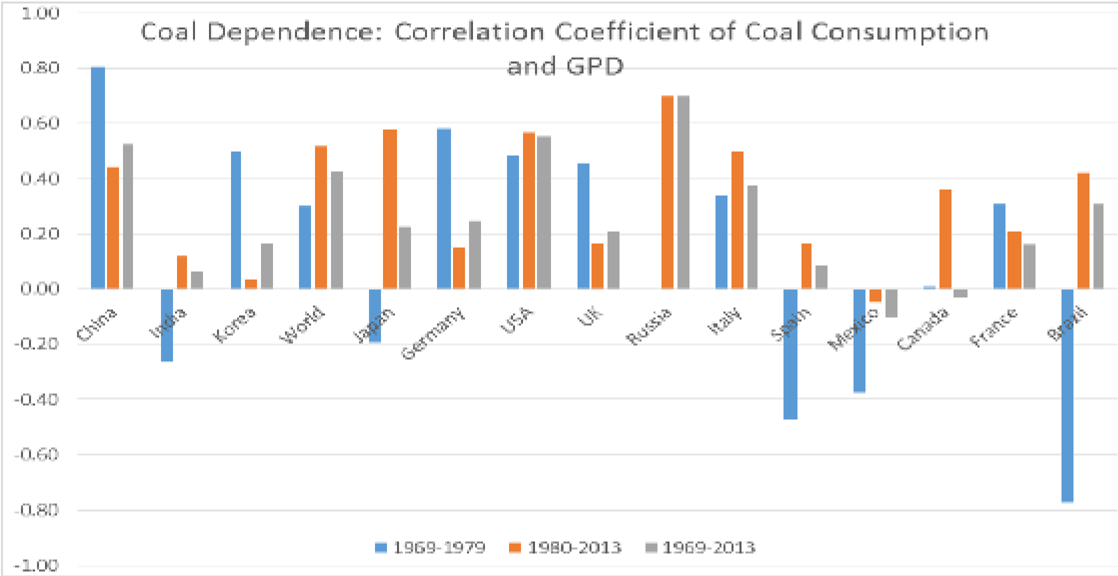

Figure 8. Coal Dependences of the Major Economies: Correlation Coefficient between Coal Consumption and Real GDP of Major Economies in 1969-1979 vs. 1980-2013 vs. 1969-2013
Sources: BP 2014, USDA 2014

However, India and Russia were the two economies whose coal-GDP correlation coefficients posed more challenges to their interpretations. India had the second highest average annual coal shares (57 percent in the first period and 55 percent in the second period), but its coal-GDP correlation coefficients in these two periods were only -.27 percent and 12 percent respectively. Since the changes in its average annual coal shares, its negative and low coal-GDP correlation coefficients in these two periods were mainly associated with low and irregular economic growth. In contrast, although Russia had relatively low coal share (23 percent) in the period between 1980 and 2013, its coal-GDP correlation coefficient in this period reached .70, the highest in the second period. Since the average low coal share reflected a decrease by 31 percent, its high coal-GDP correlation coefficient was mainly associated with its drastically reduced economic size in the 1990s and the virtually stagnant economic growth during the entire investigative period.

One important issue arose after the Germany's decision to phase out its nuclear power plants in the wake of the Fukushima nuclear disaster (Sovacool 2008, Burgherr and Hirschberg 2008, Hippel 2011, Normile 2012, Revkin 2012, Hippel 2011) if and to what extent the governments' decisions impacted Germany's coal consumption, and more generally, if the nuclear disasters had negative impacts on coal consumptions in the major economies. To acquire insights into these two issues, this study investigated the annual changes in coal consumptions of the major economies before and after the Chernobyl nuclear disaster and since the Fukushima nuclear disaster. The results of this investigation, which are presented in Figure 9, did identity a negative impact of the German government's decision after Fukushima. Germany's annual average changes in coal consumption rose from 0.4 percent before the Chernobyl nuclear disaster and -2.4 percent between the Chernobyl disaster and the Fukushima disaster to 3.4 percent since the Fukushima nuclear disaster, which Pearce (2014) considered Germany's "detour" on its road to green energy.

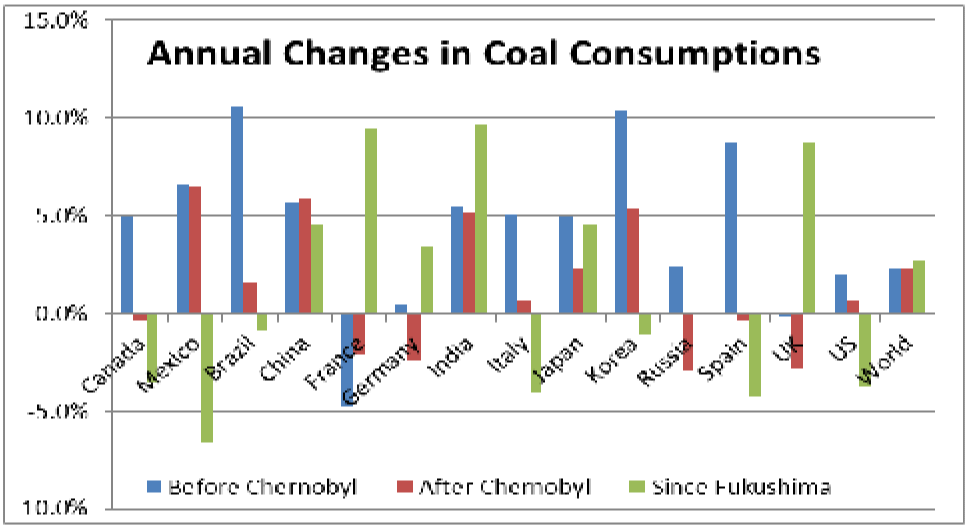

Figure 9. Change in Coal Dependence before Chernobyl, between Chernobyl and Fukushima, and since Fukushima, Source: BP, 2014

However, the Fukushima nuclear disaster seemed to have a more notable impact than the Chernobyl nuclear disaster on the coal consumptions in India, France, Japan and Germany as the reduced growth rates or increased decrease rates in the nuclear power consumptions (1.7 percent vs. 9.8 percent, -2.1 percent vs. 2.3 percent, -53.9 percent vs. 1 percent, and -5 percent -0.5 percent respectively) since the Fukushima nuclear disaster helped drive coal consumptions by 9.6 percent, 9.5 percent, 4.5 percent, and 3.4 percent a year respectively versus 5.2 percent, -2.1 percent, 2.3 percent and -2.4 percent respectively in the previous period between the two nuclear disasters.

The coal dependence analysis in this and the previous section revealed that there was a divide between the developed countries and developing countries in coal dependence. While developing countries were largely stuck with coal, a less expensive energy source, the developed countries were able to move away from this most polluting and most carbon intensive energy source. These converging trends in the two groups' compositions of black energy consumption determined the higher yet declining CO_2 emissions in developed economies and lower yet rising CO_2 emissions in developing economies.

The coal dependences of the two fast growing industrializing countries indicated important policy implications by explaining the daunting environmental and health challenges and costs these two countries' economic developments face as they have become the world's energy intensive manufacturers. At the same time, all major developed countries, including Germany that had relatively lower oil dependences had lower coal dependences than the developing countries China and India in the entire investigated period. However, while the United States' and Japan's coal dependences were initially low, was not changed significantly over the course of 44 years, and German's coal dependence was initially high, but has experienced a significant decrease to a low level (around 25 percent) similar to Japan's in 2013.

Considering Germany's relative low oil dependence as discussed earlier, its significant departure from its initial coal dependence was a very important transformation that needs more dedicated research, whose results could have some implications for China's and India's transformation from their major coal dependences. Combined with its relatively low oil dependence, Germany's departure from its coal dependence constituted the decarbonization of its economic development, which can be seen as a role model for other developed economies (OECD 2012).

2.4.3. Natural Gas Consumption

In addition to major economies' dependences on oil and coal, the study also examined their natural gas consumptions. The focus of the investigation was the shares of their natural gas consumptions in their respective total fossil and non-renewable fuel consumptions. The results of the study informed us of several interesting characteristics and trends, which have significant implications for the global energy transformation.

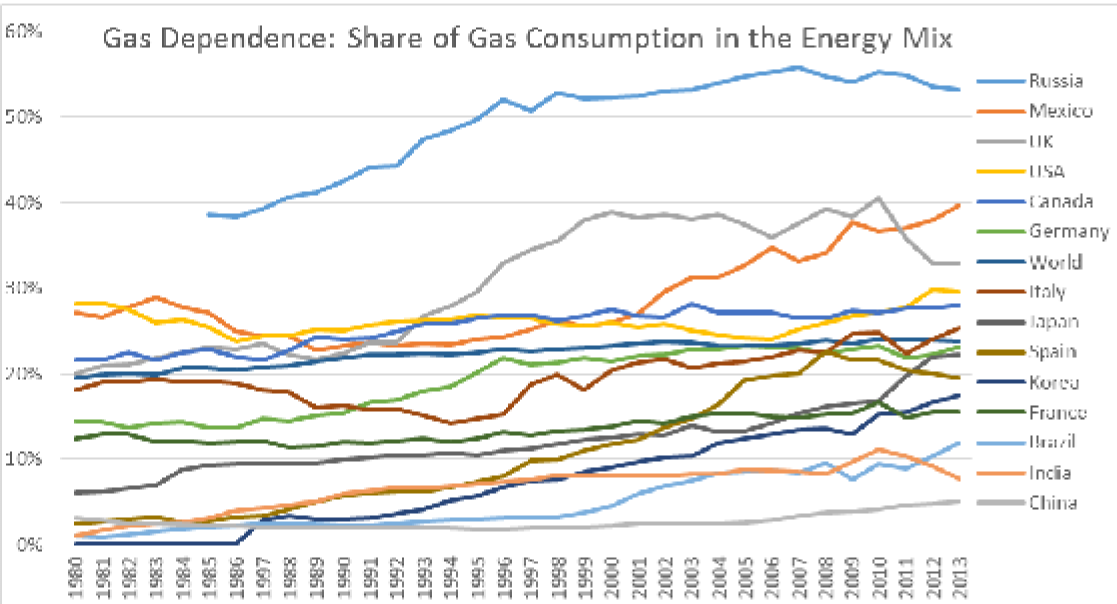

Figure 10. Gas Dependence: Shares of Natural Gas in Total Energy Consumptions of Major Economies (1980-2013), Sources: BP 2014.

First, all major economies have increased their natural gas shares during the investigative period. The increases in their natural gas shares ranged from only 5 percent for the United States to approximately 2.6 times, 5 times, 6.5 times, 7 times, and 11.3 times for Japan, South Korea, India, Spain, and Brazil respectively.

Second, the natural gas shares of Russia (54 percent), Mexico (40 percent), the United Kingdom (33 percent), the United States (30 percent), Canada (28 percent) and Italy (25 percent) in 2013 were above the world average (24 percent).

Third, the three major developing economies—China, India, and Brazil, had lowest natural gas shares, i.e. 5 percent, 8 percent, and 12 percent respectively in 2013. Since natural gas has lowest CO_2 emissions among the carbon fossil fuels, the low natural gas shares of these fast growing major developing economies indicated a disadvantage of their black energy structure, which put a rising climate change pressure on their rapid economic rises.

Since the carbon emissions of natural gas is around 27 percent lower than oil, and between 43 and 49 percent lower than coal depending on its quality (EIA, 2012), most developed economies' higher natural gas shares in fossil fuels constituted an additional favorable, competitive edge of over the three fast growth developing economies in carbon intensity reduction.

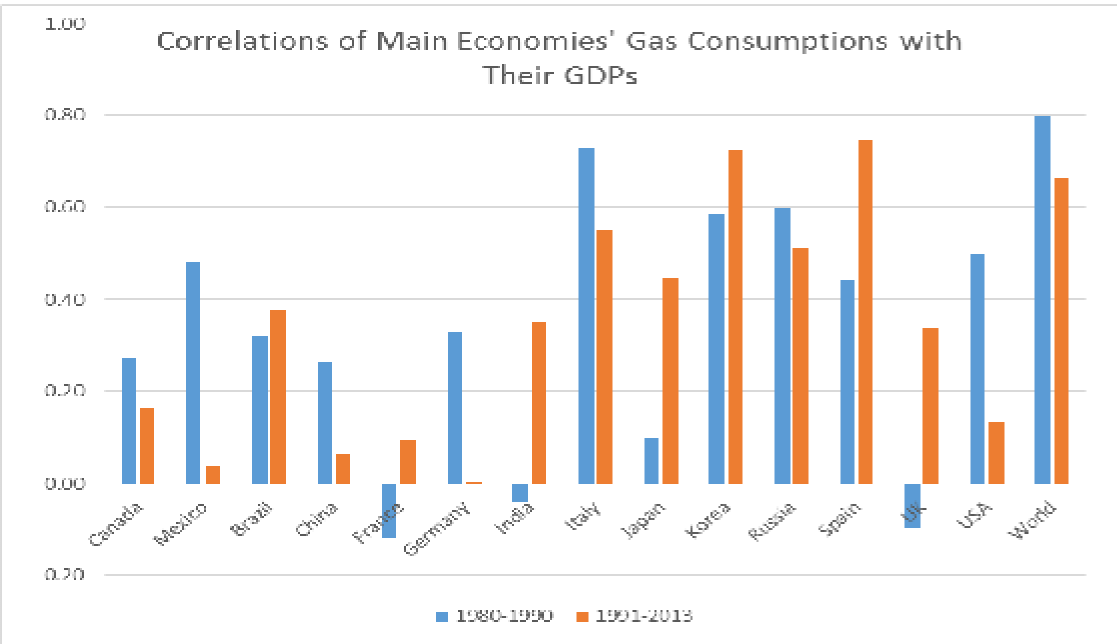

Figure 11. Gas Dependence: Correlation Coefficients between Natural Gas Consumption and Real GDP of Major Economies in 1980-1990 vs. 1991-2013, Sources: BP 2014, USDA 2014

The comparative correlation analysis of the natural gas consumptions and real GDPs of the major economies showed several interesting findings. First, major economies with high natural gas consumption shares had relatively higher correlation coefficients between natural gas consumptions and real GDPs. For example, Russia which had top natural gas shares of 40 percent for the period 1980-1990 and 52 percent for the period 1991-2013 respectively had correlation coefficients of .60 and .51. Similarly, other major economies with relatively high natural gas shares also had high natural gas-GDP coefficients. For example, high natural gas-GDP coefficients for Italy, Spain, and South Korea were.73 and .55, .44 and .75, and .58 and .72 for the two investigative periods.

In contrast, major economies with low natural gas shares had also relatively low correlation coefficients between natural gas consumptions and real GDPs. For example, the natural gas-GDP correlation coefficients for China, which had natural gas shares of 2 percent and 3 percent in the two period, were only .27 and .07.

Next, increased natural gas shares were often paralleled by higher correlation coefficients between natural gas consumptions and real GDPs. For example, when the natural gas shares in the United Kingdom, Japan, Spain, South Korea, Brazil, and India were increased from 22 percent, 8 percent, 3 percent, 2 percent, 2 percent and 3 percent in 1980-1990 to 35 percent, 14 percent, 14 percent, 10 percent, 6 percent, and 8 percent in 1991-2013 respectively, their correlation coefficients between natural gas consumptions and real GDPs also rose from .10 to .44, .44 to .75, .58 to .72, .32 to .37, and -.04 to .35 respectively.

In addition, recent growth in shale gas production played a significant role in the growth in the U.S. natural gas production. According to EIA data (2013), the shale gas's contribution to total U.S. gas production rose from less than 2 percent in 2005 to more than 20 percent in 2010, and set another record for U.S. natural gas production in 2013 and thus raised the share of natural gas consumption in the total fossil fuel consumption from 27 percent in 2007 to 32 percent in 2013 as the result of shale gas growth, with total daily dry output for the first ten months of 2012 averaging 1.77 Gm3/day (62.7 Bcf/day). It was projected that the U.S. natural gas production would increase around 40 percent from 2013 to 2040 (EIA, 2013).

The natural gas's relative lower CO_2 emissions than coal's and the potential displacement of coal by shale gas in power generation were also used as black "green" arguments for shale gas producing companies to support their business expansion and advertised by shale gas investors as a "bridge" of the current carbon-based economy to a renewable energy-based economy.

However, a comprehensive modeling by fourteen teams from different organizations (Romm, 2013) suggested that abundant and cheap natural gas would displace carbon-free energy rather than coal, and therefore have little net impact on reduction of the U.S. CO_2 emissions, especially after 2020.

Wang et al. (2014) also confirmed that shale gas production increased 12 fold from 2000 to 2010, contributing to not only significantly cheaper price of US domestic natural gas price of about $2 per million British Thermal Unit (BTU) in the first half of 2012, but also sharply reduced US carbon emissions from fossil-fuel combustion by 430 million ton between 2006 and 2011 and increased new jobs by 600,000 in the US by 2010.

At the same time, Wang et al. also pointed out the hydraulic fracturing's adverse impacts on long-term environmental sustainability because of the associated intensive water use, pollution in the ground water, significant methane emissions during the shale gas exploration and production, and possibility of inducing earthquakes, and called on enforcement of stronger regulations to minimize environment and health risks.

However, other studies, while recognizing the economic contribution of shale gas revolution, found that significant methane leaks during the shale gas exploration and production could be attributed to high US methane emissions (Arthur et al. 2008; Adams et al. 2011; Belvalkar and Oyewole 2010; Peduzzi and Harding 2012; Pearce, Fred. 2013; Tollefson 2013; Busch and Gimon 2014). Since methane is a much more potent greenhouse gas, these studies dispute the perceived positive role of shale gas replacing coal in reducing CO_2 emissions and warned instead that could accelerate global warming.

In addition, an International Energy Agency (IEA, 2012) report found that the growth of shale gas production would, on the one hand, have both positive and negative impact on deployment of renewables, and, on the other, have to overcome substantial social and environmental concerns associated with its extraction, an intensive industrial process which imposes a larger environmental footprint than conventional natural gas development.

3. Carbon Dependence

3.1. Fossil Fuel Consumption and CO_2 Emissions

Next, this study moved on to examine the major economies' fossil fuel consumptions and related CO_2 emissions. For this analysis, both the total fossil consumption data and the total CO_2 emission data of the United States, Germany and China in the period between 1965 and 2013 were examined.

This examination has generated several interesting observations. First, while the fossil consumption and CO_2 emissions in the examined period correlated perfectly in the United States (.99653) and China (.99998), they displayed a negative correlation in Germany (-0.73982), indicating that while the energy structures in the United States and China remained largely unchanged carbon, the energy structure in Germany has experienced a tangible transformation away from the fossil fuels.

This remarkable difference in the energy structures between Germany on the one hand and the United States and China on the other was also confirmed by the dramatic change in Germany's coal dependence (see Figure 7 and Figure 8).

Second, while the fossil fuel consumption in Germany largely remained the same with a slight reduction and its related CO_2 emissions were reduced 12.7 percent in this period, the fossil fuel consumptions and CO_2 emissions in both the United States and China experienced drastic increases. This was especially true for China since its accession to the World Trade Organization (WTO) in 2002 (see Figure 12).

With China's dramatically increased fossil fuel consumption, the even more dramatic surge in its CO_2 emissions was much more startling in the face of the need of, and the global effort in, reducing CO_2 emissions. The relentless upward trend of China's CO_2 emissions in the recent years indicated the dilemma the developing country China is facing in terms of its economic development; it has to face unprecedented challenges that the developed countries did not have to face in their industrial revolution and economic development (Andersson and Karpestam 2013, Li et al. 2013, Tian et al. 2013, Zhou et al. 2013, Zhao et al. 2013, Zhou et al. 2013, Li et al. 2014, Rene et al. 2014, Shao et al. 2014, Yuan et al. 2014, Zhang and Lahr 2014).

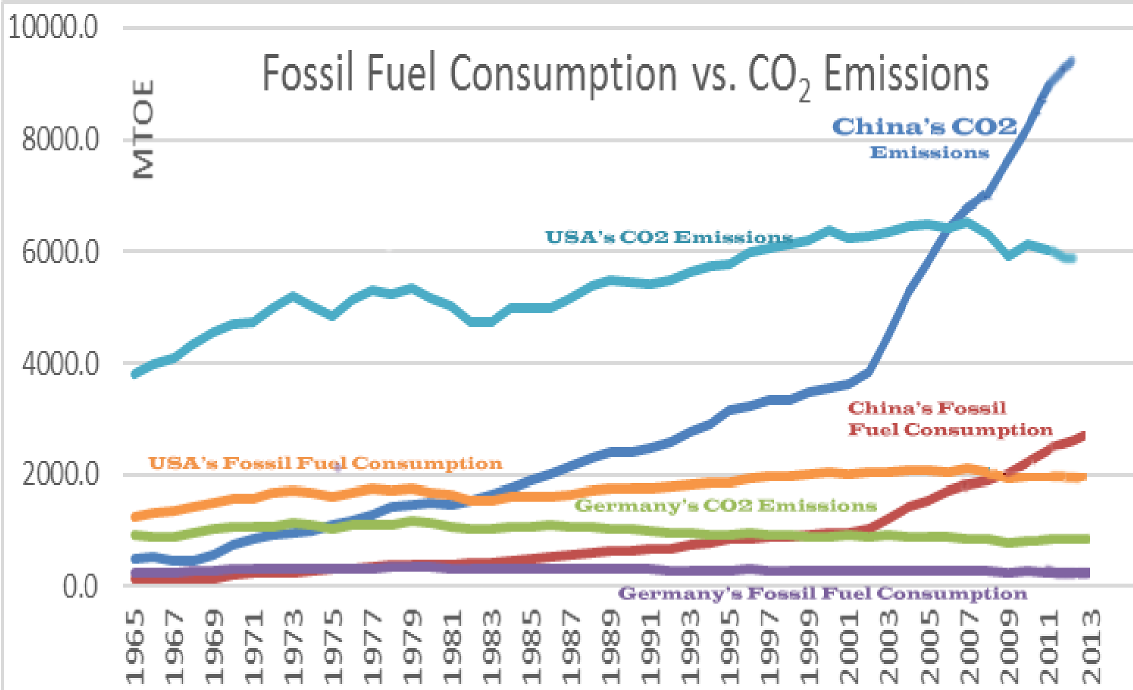

Figure 12. Fossil Fuel Consumption and CO_2 Emissions of Selected Economies (1965-2013), Sources: BP 2014

The developing countries now urgently need to implement effective policy tools to reverse this rising trend and to adopt different strategies than the developed countries to manage their carbon reduction plans. At the same time, as these fast industrializing countries produce goods not only for their domestic consumption, but also for the consumption of the developed countries, the developed countries have the responsibility to do their shares to help these countries green their manufacturing and mitigate the resulting environmental and ecological impacts.

While the number of total fossil fuel consumption and the related CO_2 emissions indicated the needs for addressing the ecological impact of the economic development in general terms, comparing various countries' black energy consumption per capita provided us the information on equity issues and the information how to address the ecological impact of the economic development in the differentiated manner.

3.2. Carbon Intensity

Next, this study took a look at the carbon intensity of the major economies, or the CO_2 emitted by generating a unit of GDP. A two-step approach were involved in this investigation. Both steps used the data of annual CO_2 emissions of the 14 major economies from 1969 to 2013. The difference between the two steps was that the first approach used in addition the data of real (adjusted to the 2005 U.S. dollar) GDP of the

14 major economies from 1969 to 2013, and the second step used in addition the data of annual PPP-adjusted GDPs of the 14 major economies from 1980 to 2013.

This two-step approach was designed as a combined solution to the gap between the needed comparability and the partial data availability. Ideally, using PPP-adjusted GDP data would be more accurately compare the carbon intensities of the developed economies with those of the developing economies. However, PPP-adjusted GDP data were only available for the period since 1980 from the *IMF World Economic Outlook*. Limiting the investigation to using the PPP-adjusted GDP data would make the investigation of the earlier period between 1969 and 1980 impossible, in which the carbon intensities of some developing or transition economies, especially China, were much higher. This approach would allow more accurate comparison of the major economies' carbon intensities for the more recent period, but greatly impair the historical comparison for a longer period, thus the value of the investigation. Using this two-step approach instead allowed the study to not only to examine the accuracy of the carbon intensity comparison for the more recent period between 1980 and 2013, but also look into the historical background of the carbon intensity dynamics in a longer period than the period with the available PPP-adjusted GDP data. The graphic illustrations of the results of this two-step investigation are presented side by side in Figure 13 and Figure 14.

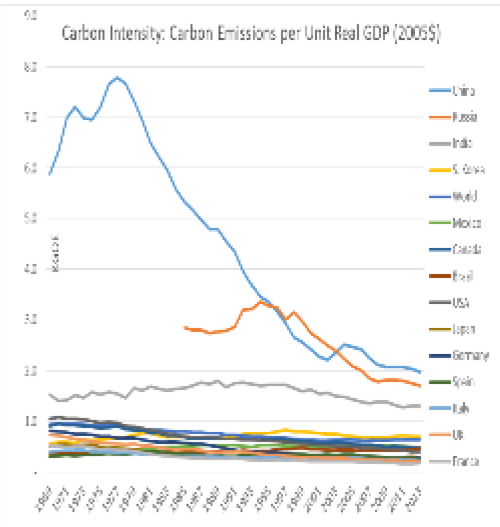

Figure 13. Carbon Intensity of Major Economies (Real GDP, Adjusted to 2005$) (1969-2013)
Sources: BP 2014, USDA 2014.

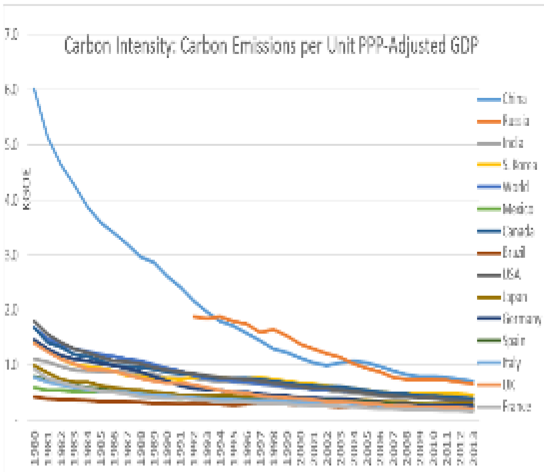

Figure 14. Carbon Intensity of Major Economies (PPP-Adjusted GDP) (1980-2013)
Sources: BP 2014, IMF 2014.

The results of the carbon intensity investigation revealed several interesting insights. First, China's high carbon intensity stood out from all other major economies' using both the real GDP method and the PPP-adjusted GDP method. In the starting year of 1969 using real GDP method, China's carbon intensity was extremely high, much higher than those of all other major economies, ranging from almost four times to more than 11 times other economies' examined. It reached the top level in 1978—the year China started its economic reforms—almost five to more than 16 times other economies' carbon intensities examined. Since then, it went continuously downward with a small rebound between 2003 and 2006.

Second, other transitional (former Socialist) and developing economies shared similar feature of high carbon intensity, with Soviet Union/Russia's carbon intensity tripling the developed economies' and India's doubling them. Third, the developed countries collectively had relatively low carbon intensities.

The carbon intensity analysis of the major economies indicated that China's high carbon intensity has historical reasons as a both Socialist and developing country, and its high carbon intensity has been decreasing as it moved away from the developing pattern of a Socialist command economy and its market economy grew more and more mature. On the other hand, as of 2013, China's carbon intensity was still much higher than other major economies, ranging from 20 percent higher than Russia's and 10.4 times higher than France's using real GDP method or 10 percent higher than Russia's and 3.2 times higher than France's using PPP-adjusted GDP method. On average, China's carbon intensity was 4.5 times higher than other major economies using real GDP method or 1.5 times higher than other major economies using PPP-adjusted GDP method. This indicated that China still has to make substantial efforts to reduce its carbon intensity.

This carbon intensity analysis has significant policy implications. It suggested that China, Russia, and India need to focus their carbon reduction efforts on reducing their carbon intensities. In this sense, China's d and China's determination to reduce its carbon intensity by 40-45 percent from 2005 to 2020 was a necessary and important energy policy that considered a combination of several factors, including China's current relatively low per capita black energy consumption and income, its high carbon intensity and high total high carbon emissions, and its current position in the world economy as a manufacturing center with heavy industry (Shapiro 2012, World Bank 2014).

At the same time, it also indicated that even if China accomplished its 40-45 percent carbon intensity reduction goal by 2020, its carbon intensity would still be much higher than the developed countries'. This indicated that in addition to accomplishing its 40-45 percent carbon intensity reduction goal by 2020, China needs continue reducing its carbon intensity after 2020 (Dou 2013, Gambhir et al. 2013, Lu et al. 2013, Wang and Liang 2013, Wang et al. 2013, Wu et al. 2013, Lin and Long 2014, Qi et al. 2014, Wang et al. 2014, Yu et al. 2014, Yuan et al. 2014).

3.3. CO_2 emissions Per Capita

Next, this study examined the major economies' CO_2 emissions per capita. For this analysis, the CO_2 emission data of the United States, South Korea, Japan, Germany, China, Brazil, and India in the period from 1969 to 2013 and their population data in the same period are used.

The results of the comparative analysis revealed both common characteristics and trends and exceptions to these common trends. Generally speaking, the annual CO_2 emissions per capita in the developed countries were decreasing, but they were still significantly higher than those of the developing economies. This was true for the United States, Germany, the United Kingdom, and France, in which the CO_2 emissions per capita decreased from 21.9, 13.1, 12.9, and 8.6 tons oil equivalent (TOEs) in 1969 to 18.7, 10.4, 8.2, and 6 TOEs in 2013, by 14.5 percent, 20 percent, 37 percent, and 30 percent respectively.

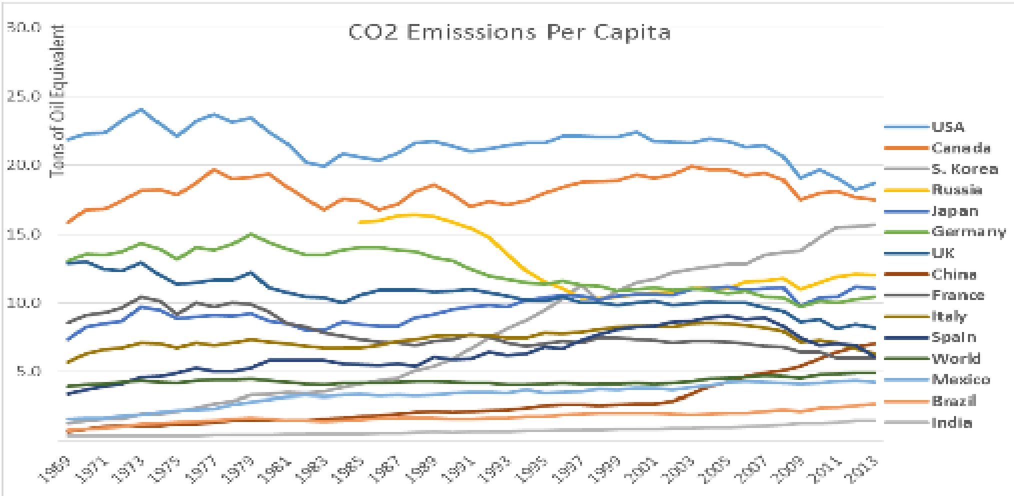

Figure 15. CO_2 Emissions Per Capita of Major Economies (1969-2013)
Sources: BP 2014, UNDESA 2014

However, exceptions to this common trend for developed countries were Canada, Japan, South Korea, Italy, and Spain. While the CO_2 emissions per capita rose in Canada, Japan, Italy, and Spain from 15.8, 7.4, 5.7, and 3.4 TOEs in 1969 to 17.5, 11, 6.3, and 6.1 TOEs in 2013 by 10.3 percent, 50 percent, 10 percent and 81 percent respectively, South Korea's CO_2 emissions per capita soared by 10.6 times from 1.3 TOEs in 1969 to 15.7 TOEs in 2013, a level only lower than those of the United States and Canada and much higher than those of all other major economies under investigation.

The common trend for the developing countries was initially low but then rising CO_2 emissions per capita. This was true to different extents for China, India, and Brazil. While the CO_2 emissions per capita in India and Brazil rose from .4 and .8 TOEs in 1969 to 1.5 and 2.7 TOEs respectively in 2013, they soared in China by 8.5 times from .7 TOE in 1969 to 7 TOEs in 2013, a level still lower than those of most developed economies, such as the United States, Canada, South Korea, Japan, and German, and the United Kingdom, but higher not only than those of other developing economies such as Mexico, Brazil, and India, but already those of the developed economies Spain, Italy and France. Exception to this developing and transition economy group trend was Russia, which had initially high but then decreasing CO_2 emissions per capita, from 15.8 TOEs in 1985 to 12 TOEs in 2013, a decrease by 24 percent.

A trend of carbon shift from some developed economies to developing economies was observable during the investigative period. For example, the carbon emissions reduced from the highest annual per capita CO_2 emissions of 24.1 TOEs in 1973 to the lowest annual per capita CO_2 emissions of 18.2 TOEs in 2012 in the United States, from 15 TOEs in 1979 to 9.7 TOEs in 2009 in Germany, from 13 TOEs in 1973 to 8.1 TOEs in 2011 in the United Kingdom, and from 10.5 TOEs in 1973 to 6 TOEs since 2011 in France were all "balanced" by the carbon increase from the lowest annual per capita CO_2 emissions of 1.3 TOEs in 1969 to the highest annual per capita CO_2 emissions of 15.7 TOEs in 2013 in South Korea, from 0.7 TOEs in 1969 to 7 TOE in 2013 in China. Obviously, the wealthier economies have reduced their carbon emissions in considerable part because manufacturing and heavy industries have left these countries.

These insights confirmed the findings of previous studies, which attributed the international inequality in per capita CO_2 emissions and the between-group inequality mainly to the inequalities in per capita income levels (Duro and Padilla 2006). The group trends indicated that the developed countries, especially the United States, Canada, and South Korea, have the moral and economic responsibilities to dramatically and drastically reduce their CO_2 emissions per capita. While the decreasing trend of CO_2 emissions per capita in main developed economies was encouraging, the rising trend of CO_2 emissions per capita in some other main developed economies with high CO_2 emission levels was alarming. Also concerning was the CO_2 emission rising level in rapidly growing and most populous developing economies, especially China, whose per capita CO_2 emission level has already reached the low end of the developed economies.

3.4. Changes in GDPs, CO_2 Emissions, and Carbon Intensities

In addition, this study investigated the changes in GDPs, CO_2 emissions, and carbon reductions of the selected countries and compared these data with each other. For this investigation, three sets of data—annual changes in GDP, CO_2 emissions, and carbon intensities of Russia, Italy, the United Kingdom, Germany, France, Spain, Japan, the United States, Canada, Mexico, Brazil, India, South Korea, and China, as well as those of the world average, were used from the examination period from 1970 to 2013. The results are presented in the following Figure 16.

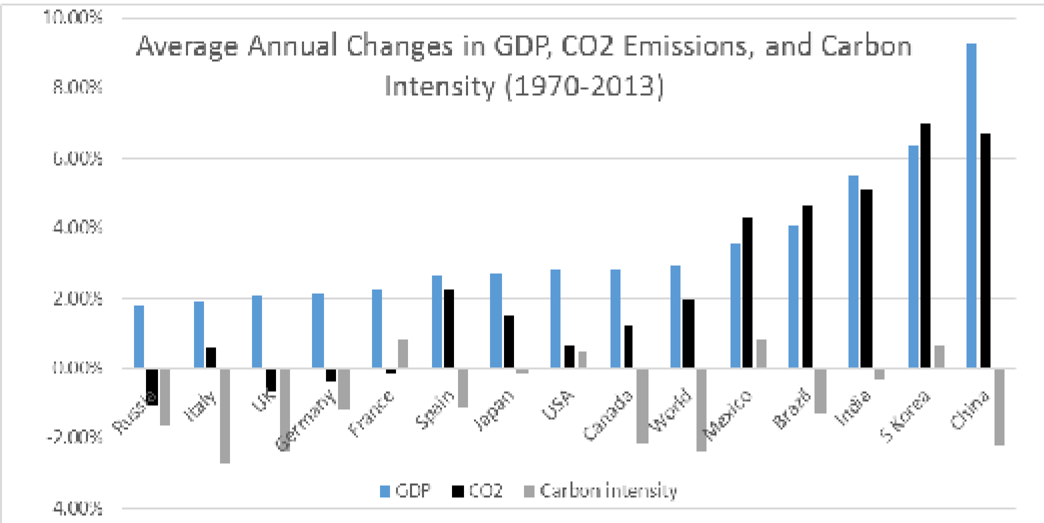

Figure 16. Annual Average Growth Rates in GDP and CO_2, Reduction in Carbon Intensity of Major Economies (1970-2013), Sources: BP 2014, IMF 2012, USDA 2014, World Bank 2012

The results revealed interesting common trends in annual average GDP growth rates and annual average changes in CO_2 emissions that differentiated the developed economies from the developing economies.

On the one hand, most developed economies' annual average GDP growth rates ranging from Italy's low of 1.89 percent to Canada's high of 2.81 percent were lower than the world average GDP growth rate of 2.93 percent, and most developed economies' annual average increase rates in CO_2 emissions were also lower than the world average increase rate of 1.97 percent.

Spain and South Korea represented exceptions to this developed economies' group trend of slower GDP growth rates and slower CO_2 emissions increase rates. While Spain deviated from the developed economies' common feature of low CO_2 emissions increase rates only by presenting an annual average CO_2 emissions increase rate (2.28 percent) higher than the world average rate of 1.97 percent, South Korea decisively rebelled against the developed economies' trends by positioning itself as the only developed economy with both an annual average GDP growth rate and an increase rate in CO_2 emissions not only higher than the world annual averages, but also higher than most main developing economies'. In fact, with its rate of 6.37 percent, South Korea's annual GDP growth was higher than those of all major economies except for that of China, and with its annual average increase rate of 7 percent, South Korea's CO_2 emissions grew the fastest among all major economies', even higher than its annual GDP growth rate.

On the other hand, developing economies' annual average GDP growth rates ranging from Mexico's low of 3.56 percent to China's high of 9.3 percent were in general higher than the world average GDP growth rate of 2.93 percent and their annual average increase rates in CO_2 emissions ranging from Mexico' low of 4.31 percent to China's 6.69 percent were also much higher than the world average increase rate of 1.97 percent.

With its highest annual average GDP growth rate of 9.3 percent in the 44-year period, China's CO_2 emissions also grew at a high rate of 6.69 percent, second highest increase rate among the major economies', only next to that of South Korea. At the same time, China's annual carbon intensity also dropped by 2.24 percent a year, the third highest carbon intensity reduction after 2.7 percent in Italy and 2.42 percent in the United Kingdom.

The data also showed that other major economies under investigation also experienced decreases in annual carbon intensities, except for France, Mexico, and South Korea, whose annual average carbon intensity increased instead by 0.86 percent, 0.86 percent and 0.64 percent respectively.

The only exception to this developing economies' trend of higher economic growth rate and higher increase in carbon emissions was Russia, whose annual average GDP growth of 1.78 percent and its annual average change in CO_2 emissions of -1.07 percent were both below the world averages. Russia's low economic growth and carbon reduction, which made it looking more like most developed economies rather than developing economies, were however caused by the economic collapse of its predecessor, the former Soviet Union after its political disintegration.

The comparison of the two groups' diverging trends of GDP and CO_2 emissions showed that the increase in CO_2 emissions significantly was correlated with the economic growth; i.e. high economic growth was correlated with higher CO_2 emissions, and vice versa.

4. Nuclear Dependence

The term of nuclear dependence used in this study was defined as the share of an economy's nuclear energy consumption in its total black energy consumption. Although nuclear power is considered carbon-free and does not, like carbon-based fossil fuels, emit huge amounts of CO_2 and other pollutants that cause climate change and environmental degradation, its generation process is far from being clean. It requires uranium that must be mined and transported to nuclear power plants. In addition, nuclear power generation produces radioactive nuclear waste, which is non-biodegradable and remains highly radioactive and therefore dangerous for lives and environment for thousands of years. Therefore, the investigation of nuclear dependence is of utmost importance.

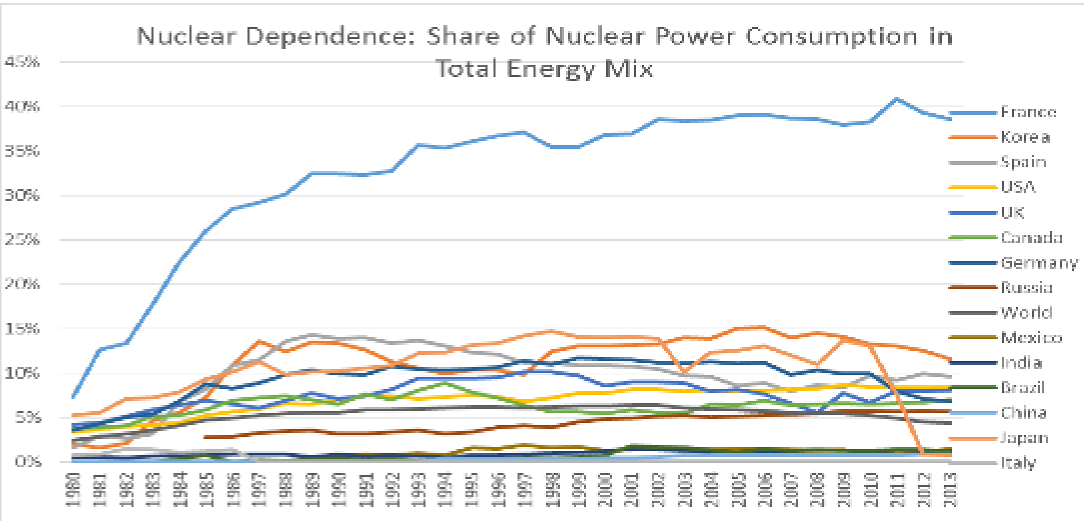

Figure 17. Nuclear Dependence: Shares of Nuclear Power Consumption in Total Energy Consumptions in Major Economies (1980-2013)

The results of the investigation of major economies' nuclear shares in their respective total energy mixes indicated that the nuclear dependence was a phenomenon associated with developed economies. While the major developing economies China and India only had very low nuclear shares of 0.9 percent and 1.3 percent respectively in 2013, the developed economies had much higher nuclear shares in the investigated period between 1969 and 2013.

France was the world's top nuclear dependent economy, whose average annual nuclear share was already 22 percent in the 1980's, 35 percent in the 1990's, and 38 percent since 2000. However, its nuclear share started to decline slightly after it had reached 41 percent in 2011. Japan's nuclear share reached its peak of 15 percent in 1998, and then started to decline to 8 percent before the Fukushima nuclear disaster.

Spain had its highest nuclear share of 14 percent in 1993, which declined to 9 percent in 2011 and recovered to 9.6 percent in 2013. South Korea experienced its top nuclear share of 15 percent in 2005 and 2006, which dropped to 11.6 percent in 2013. Other developed economies also reduced their nuclear dependences.

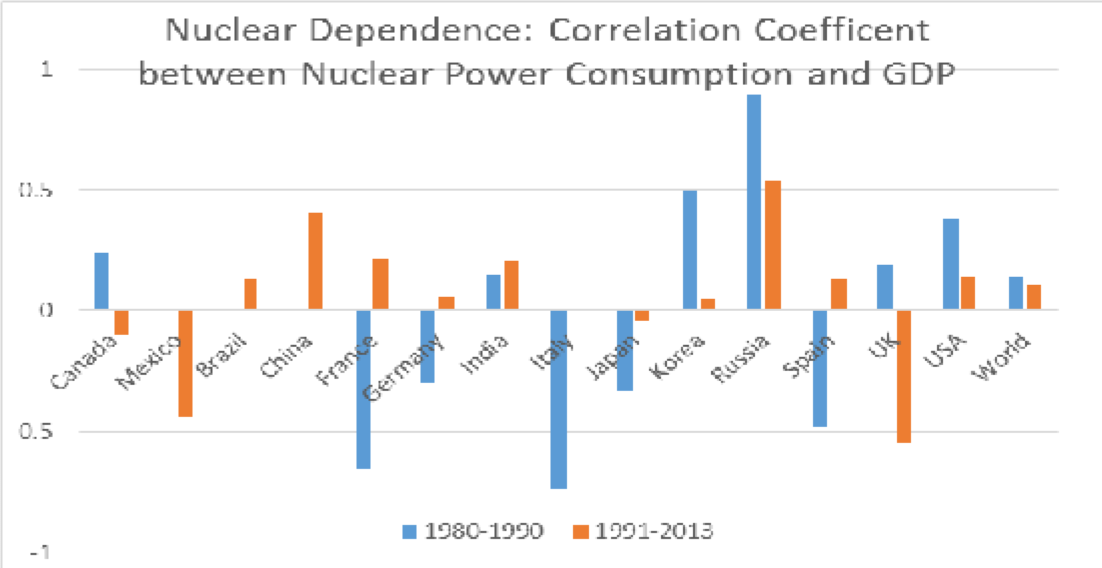

Figure 18. Nuclear Dependence: Correlation Coefficient between Nuclear Power Consumption and Real GDP of Major Economies in 1980-1990 vs. 1991-2013, Sources: BP 2014, USDA 2014

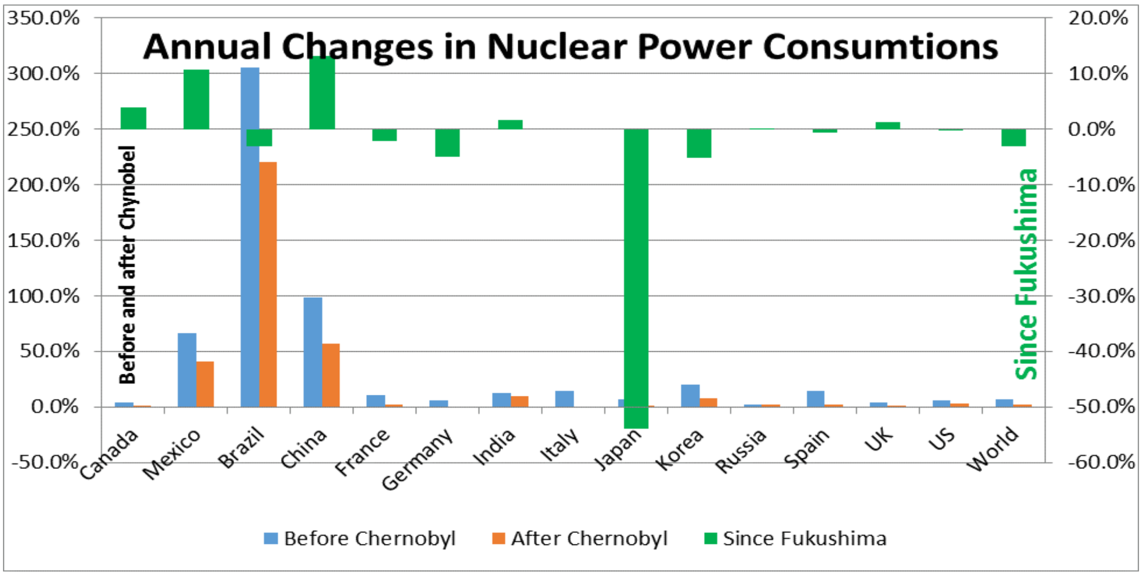

Figure 19. Impacts of Nuclear Disasters on Nuclear Power Consumption, Sources: BP 2014

To gauge the impacts of the nuclear disasters in Chernobyl and Fukushima on nuclear power consumptions of the major economies, this study examined the annual changes in nuclear power consumptions before and after the Chernobyl disaster and since the Fukushima disaster. The results of the investigation, as displayed in Figure 19, indicated that the Chernobyl disaster had affected all major economies' nuclear power consumptions to different extents, from Italy's elimination of nuclear power consumption and Germany's reduction of nuclear power to other major economies' reduced growth rates of nuclear power consumptions. The investigation also showed that the Fukushima nuclear disaster more negatively impacted major economies' nuclear power consumptions. For example, the nuclear power consumptions in China, Mexico, and India significantly reduced their growth rates from around 57 percent, 41 percent and 9.8 percent to around 13 percent, 11 percent and 2 percent respectively; those in Russia and the United States reached a standstill; and those in Japan, South Korea, German, Brazil, France and Spain presented negative growths of around 54 percent, 5 percent, 5 percent, 2 percent and 1 percent respectively. With its higher growth rate of 3.8 percent since the Fukushima nuclear disaster versus that of 1.5 percent after Chernobyl disaster, Canada became the only economy whose nuclear power consumption was less impacted after the recent nuclear disaster than the previous one.

Furthermore, the large-scale ceasing of operation of nuclear power plants in the wake of the Fukushima nuclear disaster in Japan led to sharp decline in Japan's nuclear share from 8 percent in 2011 to less than 1 percent in 2013 and Germany's nuclear share from 8 percent in 2011 to 6.77 percent in 2013. The related fundamental shift in public perception of nuclear safety and security related to reactor accidents, radioactive waste, and other potential problems, prompted Germany to decide to close all its reactors by 2022, Italy to ban new reactors (Westall and Dahl 2013), and the IEA (2012) to halve its estimate of additional nuclear generating capacity to be built by 2035.

Therefore, although nuclear power as a non-carbon energy presents an attractive solution to reducing CO_2 emissions and related global warming for highly carbon dependent major economies, the past pitfalls and future potential concerns related to nuclear safety and security require that considerable improvements in secure and economic technologies be achieved before it can be accepted as a safe, secure and reliable replacement of carbon-based fossil fuels.

In this regard, research and experiments on thorium with molten salt fast reactors as an alternative nuclear fuel to uranium seems to indicate an attractive alternative solution of nuclear energy. Its abundant availability might help meet the energy needs to both support further economic growth and displace fossil fuels on the one hand and its lower radioactivity might help resolve the existing uranium-based nuclear power's environmental and security concerns in terms of nuclear waste disposal and nuclear weapon proliferation (Elsheikh 2013, Heuer et al. 2014, Lin et al. 2013, Ritsuo 2013, Rouch et al. 2014, Schaffer 2013, Serp et al. 2014).

5. Conclusions

Based on an analysis of the major economies' energy consumption, this study reviewed the data of their fossil fuel consumption in the past and examined their carbon dependences, carbon emissions, and the trends of their energy consumption in terms of reducing carbon dependences and carbon emissions. The exploration in the historical carbon-dependent economies provided insights into their strengths and weaknesses in dealing with the carbon challenges, and provides potential keys to understanding the needs of the energy transformation in the major economies.

More specifically, the study examined fossil fuel and nuclear power consumptions of major economies. The ten-year time series data of the oil consumption of the world's four largest economies—the United States, China, Japan and Germany—and the rest of the world and the 46-year time series data of the coal consumption of the world's five largest economies—the United States, China, Japan, Germany and India, were investigated. In addition, the study explored these major economies' natural gas shares, nuclear dependences, energy intensities and carbon intensities in relation to their respective populations and GDPs.

Through this data analysis, the study found common group patterns of oil and coal dependences for both the developed countries and the developed countries as well as exceptions to these common group patterns. While developed countries moved away from coal dependence to oil, gas, and nuclear dependences, the developing countries were still largely stuck with heavy coal dependences. Exceptions to these general group patterns included Germany, which certainly like the other developed economies moved away from its coal dependence, but also decoupled its economy from its original oil dependence and planned determinedly to move away from its nuclear dependence. These findings illuminate different economic, environmental, and ecological challenges of the respective fossil fuel dependences for different development groups on one hand, and on the other hand policy implications of the exceptions to the fossil fuel dependence. Because the developed economies, especially the United States, consumed much more energy, especially oil, per capita, their high oil dependences made them, as existing studies observed (Blanchard and Gali 2007, Anderson 2009, Blinder and Rudd 2009, Hamilton 2009, Theramus 2009, Glaeser et al. 2010, Sexton et al. 2012), extremely vulnerable to soaring oil prices and oil crises which posed high risks to their economic performances. Since the major developing and transitional economies, especially China, were stuck with cheap yet much more polluting coal, their high coal dependences, high energy intensities and high carbon intensities made them extremely susceptible to environmental pollution and related health challenges, which posed high risks to their economic, social, and political development.

These insights have significant contrasting policy implications. The developed countries need to focus their energy policies on reducing energy consumptions per capita, carbon emissions per capita, and oil dependences by accelerating energy transformation ("Energiewende") and further improving energy efficiency. The developing and transitional countries need to focus their energy policies on reducing environmental pollution, coal dependences, energy intensity, and carbon intensity by significantly improving energy efficiency and meeting their increased energy needs through renewable energy.

In this regard, the exception Germany represented to the developed country pattern have positive policy implications for the world economy. The achievements of Germany in economic development with relatively low fossil fuel dependence, low coal dependence, and reduced carbon emissions set good examples for both the developed countries in terms of reducing oil dependence and the developing countries in terms of reducing coal dependence.

The exploration into the major economies' development of unconventional natural gas and nuclear energy production provide some interesting revelations. It showed on the one hand that the deployment of these technologies was still a dividing line between the developed economies and the developing economies. On the other, it indicated while both shale gas and nuclear energy could be developed as alternative energy sources to displace more carbon-intensive fossil fuels such as coal or oil, their past, present and future environmental risks caused and will further cause substantial concerns in affected economies, which prevented and will further prevent them from being developed in large scale as environmentally reliable, trustworthy and sustainable "transitional" alternative energy sources.

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