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Decarbonization: China from past track to future leapfrogging

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Abstract: Human behaviors lead to environmental change. If that premise stands true, then to put global warming under control is to restrict human behaviors in order to lessen their impact. For carbon emission specifically, the idea is to transform the global economy through a process of decarbonization. This paper focuses on China, both the largest carbon emitter and the largest of emerging economies leading the global CO2 emissions with rapid growth on both energy consumption and carbon emissions. In order to shed some light on how China and other developing countries participate in the global decarbonization, this paper tries to compare its past track with some higher-income countries as Sweden and United Kingdom, sophisticated enough to use more than one single decomposition tool to break down CO2 emissions into driving sources that could be analyzed and measured. For the purpose of a leapfrogging of decarbonization, from the past comparison experience and lessons are expected to draw and applied to future efforts.

Key words: Decarbonization, leapfrogging, energy intensity, carbon intensiy

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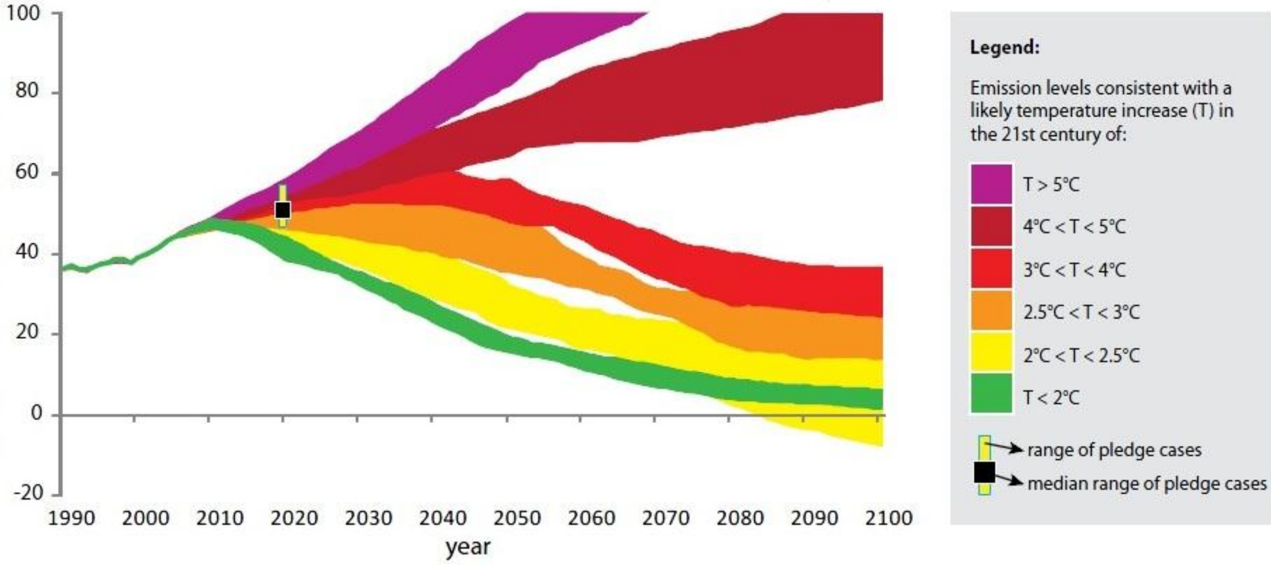
1. Introduction

Global warming, led by the emissions of greenhouse gases (GHGs), has been drawing global attention for decades. From the Kyoto Protocol to the Copenhagen Convention, multilateral endeavors had been practised to unite on reducing human behavior impact on environment. Below the graphs shows the emissions from not only 1990, but more importantly, the future predictions of possible temperature increase based on several potential scenarios of global carbon emissions by United Nations Environment Program (UNEP).

Fig. 1 Global total emissions, in GtCO2 equivalent annually



Different colors demonstrate the likely avoided temperature increase of Integrated Assessment Models (IAM) scenarios and bar super imposed in 2020 shows expected emissions from the pledges.

Source: UNEP (2010) the Emission Gap Report

Human behaviors lead to environmental change. If that premise stands true, then to put global warming under control is to restrict human behaviors in order to lessen their impact. For carbon emission specifically, the idea is to transform the global economy through a process of decarbonization. This paper focuses on China, both the largest carbon emitter and the largest of emerging economies leading the global CO_2 emissions with rapid growth on both energy consumption and carbon emissions. In order to shed some light on how China and other developing countries participate in the global decarbonization, this paper tries to compare its past track with some higher-income countries as Sweden and United Kingdom. For the purpose of a leapfrogging of decarbonization, from the past comparison experience and lessons are expected to draw and applied to future efforts.

The potential contribution of this study should be largely related to its feature of being comprehensive. Some major past studies are stated below in which massive literature reviews and carbon decomposition have been done and are referred to in this paper. However, there are very few studies that combine a history of theoretical progress of both the concept and multilateral actions of decarbonization, and a sophisticated comparison using more than one single decomposition tool to break down CO_2 emissions into driving sources that could be analyzed and measured. Above all, for the purpose of drawing lessons from past track so as to increase the possibility of future leapfrogging, this paper tries to make it through for the path from the past decarbonization history to the better actions of China and other developing countries. That is the logic behind the way it is organized. The study starts with the definition evolution of the concept "decarbonization". Many endeavors are classified and presented in which some had already tried to decompose the aggregate emission into certain variables. The second section is a combination of a thorough literature review of past studies on the issue and a presentation of historical change of fossil fuels shares of some major regions within OECD. Of the former part, five interdependent parts are structured, each to focus on real decarbonization in history, role of fossil fuels in the trend, the related cost of the Kyoto Protocol, the participation of developing countries in the multilateral endeavors and China's potential leapfrogging respectively. The next section is the major framework of the study and data from various sources are used in the historical record of fossil fuels, the Kaya Identity and the LMDI decomposition method, hoping to result in a detailed analysis in depth leading to convincing policy suggestions. The final part is the conclusive analysis and a summary to conclude the whole paper from theories to practices.

Undoubtedly flaws and shortages are unavoidable in this paper. The literature review could be subjective and data from different sources could have a few inconsistencies in the calculation. The carbon trade is not referred to and the latest progress of Copenhagen Convention is not included. However, due to the length of the study, the shortage of knowledge background and the limited historical data, a lot more could be left for future and further studies.

2. Definition of decabonisation

Grubler, A. and N. Nakicenovic (1996) stated that the concept 'decarbonization' was first proposed by Yoichi Kaya and Kenji Yamaji (1989, 1991) describing short-term structural change trends in OECD energy systems and longer term and global analysis of decarbonization were first performed at IIASA (1991, 1992). However at that early a time when the concept started to surface, its real meaning had not been debated and efforts not practiced until later. So as to start dealing with the decarbonisation issue, it is better to first focus on its concept since various definitions have been proposed from different perspectives. To grasp a whole picture of its development, they could be briefly classified as below rather than a simple understanding of the decline of total carbon emission.

Sun (2005) classified different kinds of definitions systematically in *The decrease of CO2 emission intensity is decarbonization at national and global levels* and the sorting work here is largely based on his work. He concluded that Decarbonization should refer to decreases in CO2 emissions from fuel generated or consumed. However, such statement is too rough and broad to understand and measure. Grubler, A. and N. Nakicenovic (1996) argued that it is the amount of total energy demand and structure of energy mixture that are two major factors determining the level of energy-related CO2 emission. And they referred to decarbonisation as the decrease in the amount of CO emission per unit of primary energy consumption. From then on, decarbonization started to be widely accepted as a ratio. For Martin, I. H., C. Ken, et al. (1998), decarbonisation was understood as the decrease of carbon intensity of the global energy mix. Such understanding introduced the energy consumption structure into climate change measurement and gradually directed efforts to the structural change away from fossil fuels. And later Sun, J. W. and T. Meristo (1999) compared the concept of dematerialization and decarbonization and based on the description made by Nakicenovic (1996) that decarbonization is one kind of dematerialization in the form of energy use gave out their own definition of dematerialization, which is "the real change of material and energy use (or carbon emissions) in an observation year if that is less or more than the trend based on the levels of a given base year, and if this process occurred throughout the whole observation period". In this way the issue is regarded from a broader view related to dematerialization so that the experience from the energy use field might be applied to broader areas as whole as all resources. Of the carbonization index definitions, Mielnik and Goldemberg (1999) based on previous researches, in their viewpoint, claimed the "carbonization index” to be a better indicator than energy intensity measuring climate change, in tons of carbon (tC) per tons of oil equivalent (toe). To illustrate their proposal in a mathematical way, if C, E stand for carbon emission and energy consumption respectively, then

$$C/GDP \equiv C/E * E/GDP$$

$$\Delta(C/GDP)/(C/GDP)=\Delta(C/E)/(C/E)+\Delta(E/GDP)/(E/GDP)$$

Rewrite the equation and it would be

$$Y= (\Delta(C/E))/(C/E) = (\Delta(C/GDP))/(C/GDP)-(\Delta (E/GDP))/ (E/GDP).$$

Now Y, as the slope of carbon intensity, is the indicator of energy use change. If carbon intensive energy carriers as fossil fuels especially coal occupy more share of energy mix, Y would be >0 and a “carbonization” take place. If more “clean” and renewable energy sources are introduced, then Y would be <0 and a “decarbonization” come into being.

Various definitions stated above also inferred the development of both concept and practice of decarbonization throughout decades. Based on the principles of easy access to understanding and measurement, the definition of decarbonization as the decline in carbon intensity of energy mixture, in other words, the ratio of carbon emission divided by energy consumption, or C/E, should be preferred as a better indicator. However, when taking use of various analysis tools, it could be still relevant to take CO2 emission as a whole or in other forms into consideration and calculation, just as the researches and history records that shall be stated below in the following sections.

3. Previous studies and historical data

3.1 literature review

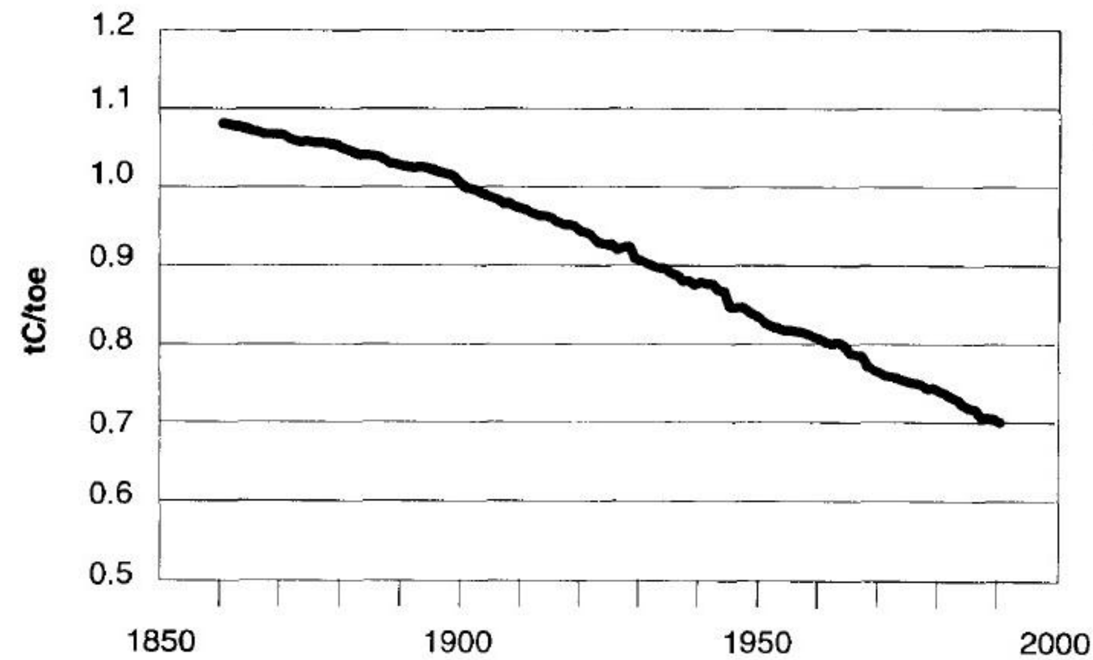
3.1.1 decarbonization in history

Grubler, A. and N. Nakicenovic (1996) regarded decarbonization as a consequence of two ratios, which are carbon emission divided by energy consumption and energy requirement divided by value added, or in symbols, C/E and E/Y. They recorded historical data and found out both ratios have been dropping for decades leading to a real decarbonization in ratio which was CO2 emission per unit of GDP according to their definition, yet was unfortunately offset by the rapid economic growth, and altogether resulted in a global increase in both total energy consumption and carbon dioxide emission. Using the math equation to explain and the process is rather clear. If C stands for absolute amount of carbon emission, E and Y for energy consumption and GDP respectively, then

$C \equiv C/E * E/Y * Y$

So the fact is that both C/E and E/Y did decline but the extent Y grew much more rapidly and eventually the world consumed more energy and released more carbon and global warming got even approaching. In this understanding, the focus was still the absolute amount of CO_2 emission rather than relative percentage so the researchers continued to argue that the real decarbonization did exist in the form of carbon emission increasing slower than primary energy use, as the graph shown below.

Fig. 2 Global decarbonization: carbon emission per unit energy consumed from 1860 to 1980, measured in tons of carbon per ton of oil equivalent (tC/toe).



Source: Grubler, A. and N. Nakicenovic (1996)

According to their data analysis, the global decarbonization, measured in reduction in carbon emission per unit of primary energy consumed, had been “continuous and persistent” yet at a very slow rate of 0.3% annually. And it was predicted based on this trend without effective interrupts that the fossil fuel age was only half way passed and will keep on dominating the energy consumption till the late 22nd century. To give explanations for such slow progress, which might lead to extreme consequences of mass pollution and global climate change, Nakićenović, N., N.

Victor, et al. (1998) argued that it was the annual growth rate of over two percent of primary energy consumption, or more precisely, the almost three percent annual growth of fossil fuels since 1900 that led to the slow progress. And it is the role played by fossil fuels that relates that to the slow annual 0.3% decline rate of carbon intensity.

3.1.2 Role of fossil fuels in the trend

Fossil fuels have an overall important role in the trend of decarbonization in the sense that the whole process toward lower CO2 intensity is a product of continuous substitution of high-carbon-content fuels by low-carbon-content fuels while as a matter of fact that was against facts in some emerging economies. (Nakićenović, N., N. Victor, et al. 1998) So here the analysis involves the issue that different energy carriers contain different carbon intensities. As widely accepted, the carbon emission basically comes from the combustion of fossil fuels, since in the modern case fossil fuels share much higher carbon intensity than any other energy source, as shown in the table below. As for traditional fuels as burning wood, its carbon intensity may reach the same level as fossil fuels only if burned in unsustainable way or else its life cycle value are close to zero if forests are able to regrow (Henriques & Kander 2010). As for renewable energies as geothermal, nuclear, hydro power, solar power, wind energy and photovoltaic, this number is basically zero as well.

Tab. 1 Carbon intensity in different energy carriers

Fuel	(g CO_2/MJ)
coal	92
coke	103
oil	74
natural gas	56
firewood	0*
geothermal	0
nuclear	0
hydroelectricity	0
solar power	0
wind power	0
photovoltaic	0

** Only in the case of forests able to regrow*

Source: partly from Kander 2002

Based on the facts listed above, it is clear that a shift from fossil fuels to non-fossil fuels, or from high carbon density fuel as coal to low carbon density fuel as natural gas, would lead to decarbonization. And that is also the conclusion from Nakićenović, N., N. Victor, et al. (1998). They compared the impacts between carbon intensity and energy intensity in reducing CO2 emission and got the results that opposed to existed consensus that energy efficiency improvements leading to energy intensity decline was usually viewed as the most important single method to reduce carbon emission, their sensitivity analysis only confirmed its top importance in the short term, and decline of carbon intensity from energy consumption structural change should beat it in the medium term and eventually the most effective contributor in the long run would be the global production per capita in the scenarios. To understand their conclusion in a simpler way, all the way from short, medium to long term, they argued that the most important contributor of decarbonization was actually energy per unit of GDP, carbon per unit energy use and economic growth per capita.

The analysis above may eventually lead to a sort of blueprint of how to adjust human behavior especially economic growth pattern to a certain scenario which could be sustainable with the earth. Nakicenovic, N. (1999) finally concluded that decarbonization, from the perspective of relation between human society and environment, was based on the dynamics of structural change in order to provide a certain environmental friendly energy service to a growing and modernizing world population in the new century. Compared to the traditional uncertain future predictions, decarbonization was more like a road map for a necessary sound and stable future development.

3.1.3 Kyoto Protocol: related costs from decarbonization

Among various endeavors to realize and accelerate the global decarbonization, the Kyoto Protocol has been viewed as a milestone in history of international multilateral cooperation bringing about some real achievement. Of this event, a lot of research has been done, particularly focusing on the potential decarbonization cost if not in the Business-As-Usual (BAU) scenario and the actions of the numerous developing countries, which have in recent decades become the major CO2 emitters. Golub, A., A. Markandya, et al. (2006) regarded the first issue as a crucial point in the considerations of those developing countries when they take into account the potential risk of the cost of decarbonization in the growing economies stating that despite the non-stopped concerns about the possible high costs of implementation from politicians, economists, industries and so on, the Protocol had been ratified by various counties including some giant economies as European Union, Japan and Russia when it had come into force in February 2005. However, it was also mentioned that the Bush administration chose not to ratify and to proceed on its own path for US, roused concerns about the purported high economic costs of implementing the Protocol. Therefore they examined lots of literature estimating the costs brought by global warming abatement, hoping to find out whether the Kyoto Protocol really cost too much and set “unbreakable barriers” on economic growth. Instead of a literature review, they insisted their study was using the results of those literatures, in order to inform the political debate.

According to their classification, traditionally there were two ways in which the studies are conducted. One is the “top-down” way, in which studies tried to model the whole economy as an interconnected structure and compare the reduced GDP because of the decarbonization policy to the case without any greenhouse gas (GHG) constraint policy. The other method adopted by some studies is the “bottom-up”, which intended to identify the specific measures at the sector level required to achieve a given reduction target. Apart from the traditional two ways, it is also mentioned that there are also some hybrid models attempting to bring together the two approaches. Of the numerous studies they examined, they concluded though still not consensus; those recent models tend to lead to the lower costs of achieving the long term targets. And reasons for this might very well be the introduction of endogenous growth and ITC that helped towards this general direction. As for the earlier studies, they argued, those coming up with too high costs were mainly because of the assumptions for the models. With sinks, market reforms and market mechanisms as international permit trading taken into consideration as measures to perform GHGs reduction, the costs would come down substantially, they concluded the major issues missed by the early time studies. Also, they argued that collateral benefits could be generated from reduction of carbon emission, which has been commonly neglected when considering the variables in the model. And that could make it even clearer that the costs of emission reduction had been overstated in the earlier studies.

After lessening the concerns of costs brought by reduction of carbon emissions, they also came up with something related to the practical efforts necessary to emission control. They mentioned that in order to achieve climate stabilization with CO2 emission, the reduction rate would has to be accelerated— at least doubled by calculation compared to the historical speed, which was 1.3% annually according the existing information.

3.1.4 Kyoto Protocol: participation of developing countries

The reason why the decarbonization cost is of so much important is to a large extent of its priority in the considerations of those developing countries to make a decision. Of some most recent practical development, Goldemberg, J. and L. Tadeo Prado (2010) reported that most significant contributors to emissions, including United States, European Union and some BRICs countries, had announced their efforts and commitment in different ways. Among all, the European Union, definitely already ahead of world in preventing globe climate change, pledged a reduction of their CO2 emission 20 percent below the 1990 level by 2020. The United States, which used to be the biggest carbon emission source in a long period of time and even refused to join the commitment in Kyoto Protocol, also announced a 17 percent reduction below the 2005 level. As for China and India, the two largest industrializing and carbon emission expanding countries, according to their description, in contrast to pledge a reduction of absolute amount of CO2 emission, informed the Secretariat of the Copenhagen Convention that they endeavor to reduce their carbon intensity, as analyzed above defined as carbon emission per unit of GDP, or C/GDP. China promised to a reduction by 2020 by 40- 50 percent below the 2005 level and India 20-25 percent same time same comparison standard. So what exactly are the roles of those rapidly industrializing countries in the global decarbonization trend? China, as the biggest fast emerging economy, is drawing more and more attention worldwide on the issue. So in prior to more detailed analysis in the comparison and historical data calculation, it should be necessary and appropriate to have a brief review of what studies have been done on those growing giants theoretically and what they themselves have behaved on this practically.

Kim and Baumert (2002) argued that it is the emphasis put on mechanisms designed to facilitate the participation of developing countries in climate change mitigation that reflects the fact without their efforts and contributions, it would be barely feasible and definitely not cost effective to avoid global climate change. But the fact is that the important developing countries have so far still remained doubtful and hesitant about the issue, fearing the policy restrictions adopting emission reduction would be obstacles on the way of their economic development.

As a result of this very concern, some countries proposed unique reduction targets, intensity reduction instead of total amount reduction, hoping to reduce the relative costs to the very limit. Marschinski, R. and O. Edenhofer (2010) analyzed that in the debate of post-Kyoto climate policy, intensity targets instead of absolute amount targets, which sets a maximum ratio of emissions per GDP, worked as an important option, especially to those developing countries most afraid of possible harm to economic growth. They continued to state that on one hand are absolute reduction targets, requiring future emissions less than a certain amount of CO2 or CO2 equivalents, also referred to as caps, being adopted by most industrialized countries under the Kyoto Protocol. One the other hand are the intensity targets setting an upper limit on the ratio of emissions to output, expressed in CO2 per unit GDP.

In order to find out the essence of the latter, Marschinski, R. and O. Edenhofer (2010) re-examined the cases of intensity targets, critically assessing several properties. They listed five, which were (i) reduction of cost-uncertainty, (ii) reduction of ‘hot air’ (which could very possibly mean the air emissions from combustion, i.e. CO2, CH4 and so on), (iii) compatibility with international emissions trading, (iv) incentive to decouple carbon emissions and economic output (decrease in ration of C/Y), and, (v) use as a substitute for banking/borrowing and what they got from the assessment is as below.

Out of five parameters, three were labeled uncertain and found contingent on correlation r between future emission stocks and future economic output. It is summarized that there should not be any doubt about the stability and predictability of reduction commitments greatly influencing the developing countries on whether to accept the proposed emission reduction targets. And that is the essential logic behind the BAU scenario if the whole thing is without uncertainty. However, even in the model uncertainty is considered crucial to results. Through their analysis, they showed even though the intensity targets can reduce some uncertainty under certain conditions but they are also capable of introducing new uncertainties. And that is a model result. They warned that in the real world practice, this might turn into concealed consequence that eventually those potential benefits might turn out liabilities. So based on the model conducted all the way from assumptions to results, it is argued the incentives for an energy system transformation through low carbon emission technology, i.e. decarbonization, is not necessarily stronger under the targets of intensity than the absolute goals. However, it is still an unsettled question and further studies are required on it.

3.1.5 Leapfrogging for China

Goldemberg, J. (1998) described leapfrog as an option for developing countries as skipping certain steps already followed by industrialized countries and accompanying development processes with modern technologies instead of duplicate the same path already taken. And the advantages would be low pollution, low adoption costs and low environmental costs due to the less usage of those heavy polluting and energy intensive technologies. Then several potential opportunities were listed to prove the possibility and modernized usage of biomass, Brazil ethanol program, photovoltaics, electric vehicles and wind energies were included.

Geng, Y & Doberstein, B (2008) analyzed one of China's policy target of “circular economy”, a realization of a nearly closed circle in which materials or resources flow, and treated it as a possible way for China to realize its leapfrog on environmental impact issues without experiencing similar environmental damages as side effects of industrialization. Despite the barriers and challenges of policy, technology and public participation, the circular economy was considered a feasible way of sustainable development of increasing eco efficiency if adoptions were achieved and realized. Tønnesson, S (2007) also considered improvements in energy efficiency and alternative energies to be the major possibilities in the leapfrog growth strategy for developing countries.

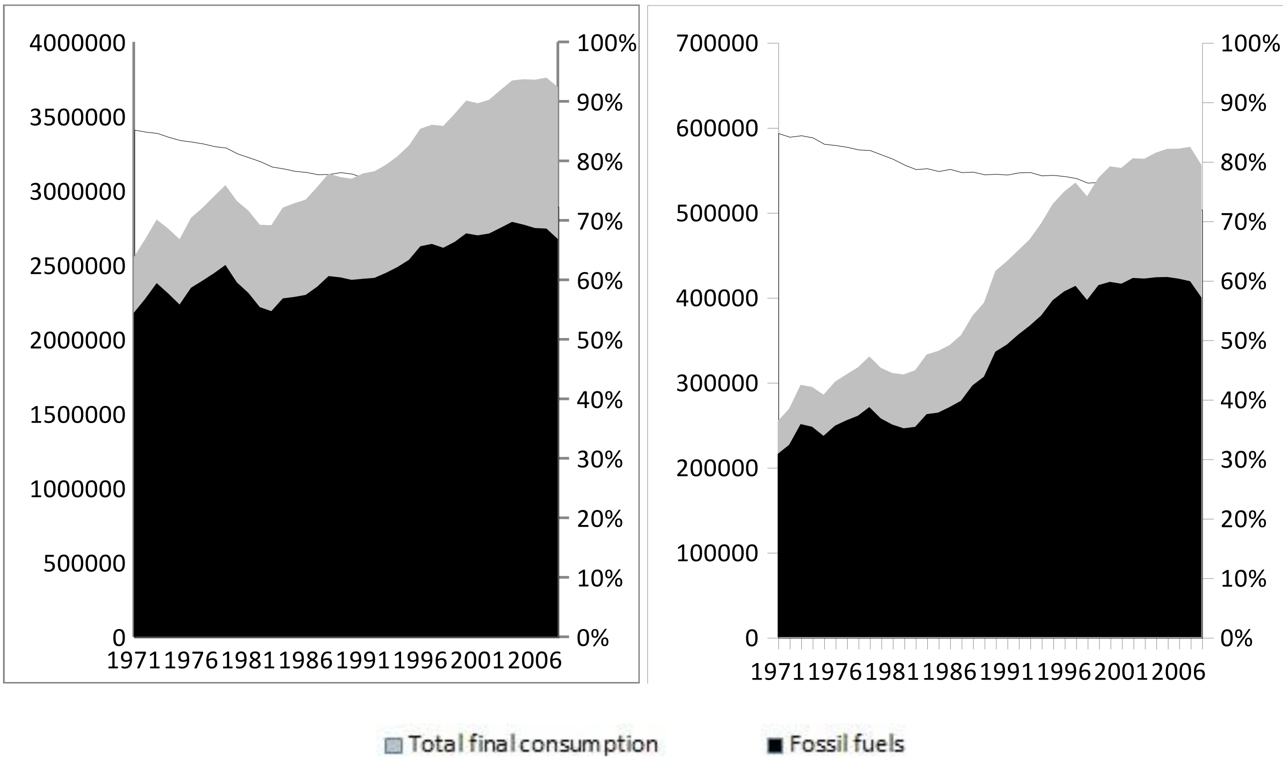
3.2 Historical records

From the literature review, one can tell that the decarbonization is basically the energy mixture shifting from fossil fuels. And here is the change of relative share of fossil fuels in the energy mix in the almost latest 40 years for OECD total, and OECD Europe, OECD pacific and United States each as an important consumer of world energy. All the data are collected from the IEA database for

OECD energy balances[1], properly classified. All OECD countries can be sort into three groups of OECD Europe, OECD North American and OECD pacific. For OECD pacific, it is a combination of Australia, Japan, South Korea and New Zealand. And for OECD North America, only the United States is chosen as a major representative since Canada and Mexico as a whole only consumed 20% of US total energy consumption.

To understand the graphs below, there are three indicators and two corresponding Y axises from the year 1971 to 2008. The first indicator is the annual consumption amount (k toe) of all fossil fuels including coal and coal products, peat, crude, natural gas liquid and feedstocks, and oil products and gas, shown in horizontal lines. The other two indicators are the annual amount of total energy consumption and share of fossil fuels, shown in boxes and black curve respectively. The Y axises are the absolute amount on the left for fossil fuel and total consumption, and relative share of fossil fuels in the energy mix in percentage form on the right.

Fig. 3 Changes of fossil fuel of OECD total and OECD pacific, 1971-2008



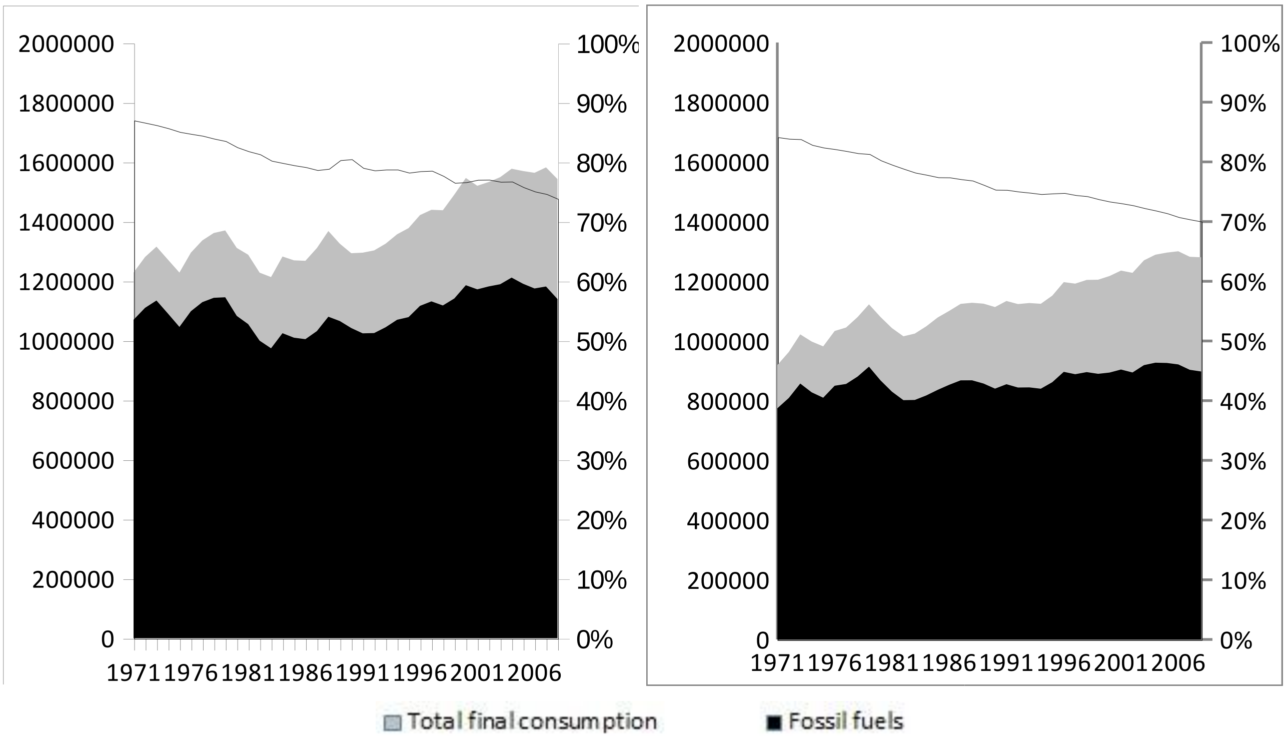
Source: IEA energy balances for OECD countries

Looking at the graphs above for OECD total and OECD pacific, there are some certain obvious features in the comparison. Both the total and the Pacific region expanded their energy consumption in the 40 years but apparently the latter had steeper rising border between the blank

1 website: http://data.iea.org, more to see acknowledgment

and the black part, indicating a more rapid growth in both total energy and fossil fuel consumption, though still not the biggest part of the whole but in fact a rise from around one tenth of the total to about one seventh of the total in less than 40 years, which should be largely attributed to the booming industrialization of Japan and South Korea. The second feature would be that though the borders of fossil fuels and total energy consumed are to a large extent parallel, the curves indicating the shares of fossil fuels are even more parallel falling, both from a bit less than 90% down to over 70%. Actually that feature could be observed globally for other parts of the world as well, and will be revealed again in this paper later.

Fig. 4 Changes of fossil fuel of the United States and OECD Europe, 1971-2008



Source: see Fig 3

Of US and OECD Europe, the two had very similar change patterns. Despite of the difference of the absolute amount that US consumed about 20% more than Europe did, they had almost the same growing speed and fossil share decline curve. However, if taken more seriously, it can be observed that Europe did have 3% - 4% less share of fossil fuel than the US.

Now if different regions are put together, it would be like this.

Tab. 2 Energy consumption change of various regions in OECD, 1971-2008

	Regions	1971	2008	Change
Total energy consumption (k toe)	OECD total	2552760	3695879	45%
	OECD Pacific	254052	555475	119%
	OECD Europe	919171	1280492	39%
	US	1228606	1542245	26%
Fossil fuel consumption (k toe)	OECD total	2178184	2674125	23%
	OECD Pacific	215460	399451	85%
	OECD Europe	774284	897624	16%
	US	1069720	1139429	7%
Fossil fuel share	OECD total	85%	72%	-13%
	OECD Pacific	85%	72%	-13%
	OECD Europe	84%	70%	-14%
	US	87%	74%	-13%

Source: see Fig 3

In the form of numbers in change, some features are clearer to recognize. For example, though the absolute numbers of different regions varied throughout decades, the percentage of fossil fuel share decline was shared by all very much similarly. What is more, comparatively speaking, United States and OECD Europe are still the biggest energy consumers with largest number of absolute figures, yet the globe energy scenario is now mainly driven by the new industrialized and industrializing economies, in the table above, early Japan and South Korea. And that is even the case in which BRIC countries excluded. China has already exceeded the US in carbon emission and has become the second largest energy consumer all over the world. (IEA CO2 Emission Highlights) So if adding China, India and other emerging economies to the calculation, the whole picture would be completely different. And that is part of the reason of the focus of this paper and what to be more detailed analyzed in next section. As for the more than 10% decline of fossil fuels, nuclear power and renewable energies have taken the share resulting in a large part of CO2 reduction, which would be analyzed in the example of Sweden in the final part.

4. Methodology

4.1 methods and data sources

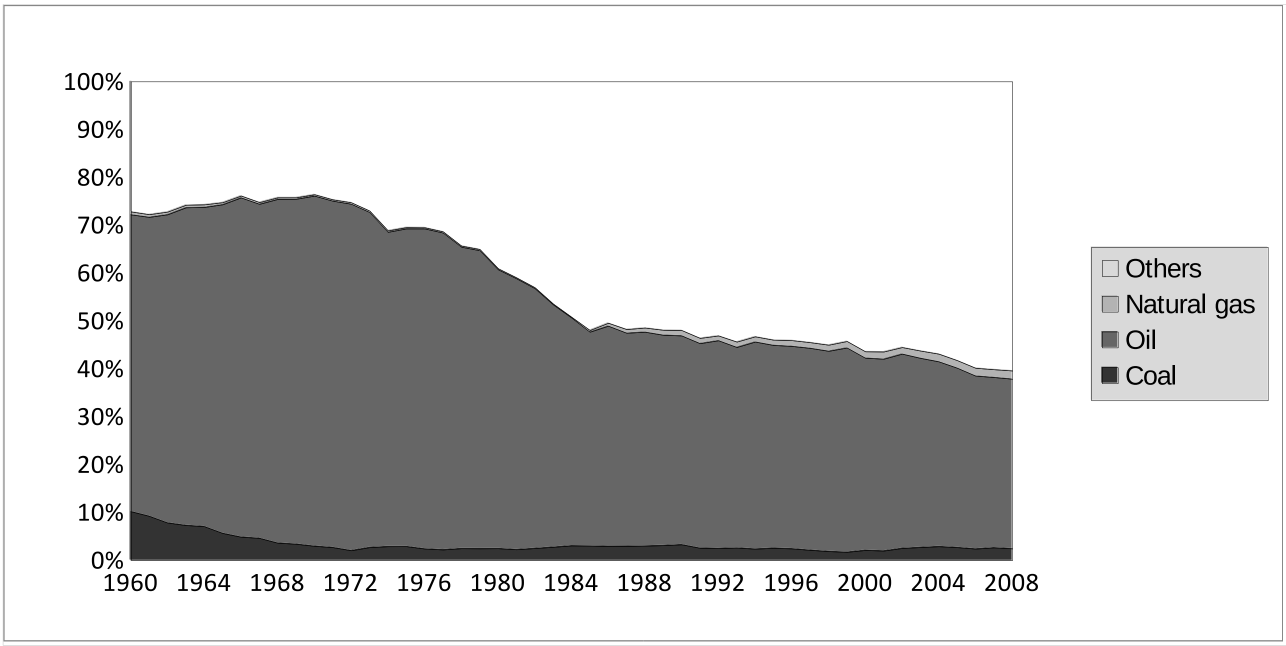
The whole section would be a grand and sophisticated carbon decomposition of Sweden, United Kingdom and China, some of almost the latest 50 years all the way from the year 1960 to 2008, some due to the lack of data of the period 1971 to 2008. As has mentioned and analyzed above, the fossil fuels played a crucial role in the trend of decarbonization. So first of all, a detailed and thorough division of energy mixture of individual countries is necessary to demonstrate the changes in history, and at the same time to raise questions. Since it could be accepted that a shift from fossil fuels is related to the reduction of carbon emission, then it is the time to come to the quantitative analysis of to what degree the correlation really is. To give an answer to that, two methods are applied. The Kaya Identity (Kaya 1990) is to help decompose the carbon emissions of individual countries, into the sources of carbon intensity change, energy intensity change, per capita economic growth and population growth, which would be demonstrated in mathematical form step by step later. From the process, it would be extremely clear of the existence of the decarbonization trend and its driving sources and how much they each actually contributed to the whole from the results.

The other method used for decomposition is the logarithmic mean divisia index (LMDI) decomposition, first presented by Ang & Zhang (2000). The clear advantage of LMDI is that it is able to distinguish between effects of structural change and intensity change caused by technological innovation within single sector. After the decomposition, the carbon emissions would be decomposed into the two sources and it should be clear what the major driving force behind the historical record was and what the main contributor could be in the future.

As for the data, all of Sweden and United Kingdom are collected from the IEA “2010 CO2 Emission from Fuel Combustion highlights” and IEA energy balances for OECD countries. As for China, the data after year 1971 is accessed from World Development Indicators (WDI) from World Bank and some from “China Energy Statistical Yearbook 2010” and data before the year 1978 comes from “China Compendium of Statistics 1949-2004”. For specific data units and approach, those would be explained in details in each specific method. As for the choices of individual countries, more would be revealed through the calculation results, demonstrations and analysis but still some could be stated here. China is chosen as the focus because of its position among the largest amount countries of total primary energy consumption and carbon emission in the world, and more importantly its explosive growing speed for the both as well as its economic performance. As the so-called "world factory", together with its dramatic explosion of manufacture industry, its already unspeakable and still rapidly growing impact on global climate change is drawing attention from all over the world. The world would not risk its economic engine, mainly the BRICs countries, for anything while China as a representative the side effect of its fast growth could not be underestimated anymore. Therefore what could be done to most effectively reduce human impact on environment especially greenhouse gases on climate change, without challenging the economic growth to an unacceptable extent, has long been an issue with global attention and efforts. So China could be a focus undoubtedly. Then what is special about Sweden and United Kingdom? Why not other countries? The first question would better be left to the second part of this chapter to answer with more solid proof and analysis to show how they stand representative for later comers. As for the second question, definitely US and Japan would have been included in the calculation and analysis if this study being conducted ten or twenty years ago when they ranked higher than now in the list of world's largest energy consumers. Even now, there are still not absolutely solid excuses to exclude them in the study. The same statement goes for India as well. But the point is, this paper is based on a comparison between China, as a representative of the major emerging economies and some countries far away from the same stage of industrialization and dematerialization, in the hope of revealing some deep reasons behind the historical change and potential policy implications for future endeavors. Under this premise, the potential advantages for comparison and over sophistication of US could to a large extent be replaced by those characteristics of UK, an industrialized case in Europe Union ,with many similarities in the decarbonization stage for comparison and distinction, and much less complexity to overcome. Germany would have been an ideal choice, if not for its data uncertainty during the period in which both East and West Germany existed. The same feature for US goes for Japan and India as well. Japan is the world's third largest economy (2011), yet its energy consumption is incredibly low according to its huge economic scale thus limited carbon emission as well. Though it relies on mainly fossil fuels so unavoidably high carbon intensity but its extremely high energy efficiency, i.e. energy intensity, had helped to limit its total CO_2 emissions. And that is what could be regarded as most helpful in comparison with China with almost same large economic scale but a lot more energy consumption. However on this point, Sweden can to some extent replace its role. As a typical Nordic country, Sweden can be viewed as an example of early actions toward reducing energy consumption and carbon emissions. Although the strength of Sweden lies in its low carbon intensity according to its low share of fossil fuels in the energy mixture, not so much similar to Japan, yet they each stands as a path toward carbon control for future options. And what is unique for Sweden is that, its low fossil energy mixture is mainly the result of no fossil domination tradition in the history, which might be attributed to policy implication on technology innovation and natural endowment, and that is exactly key points for China as a centralized bureaucratic country with weak technological advantage on the issue of energy use. As for India, China shares many of its energy characteristics as fossil fuel dependence, a dominant role of coal in energy mixture and relatively high carbon intensity as well as energy intensity so only one standing for the two or even other emerging economies would be acceptable.

4.2 trend in energy mixture change

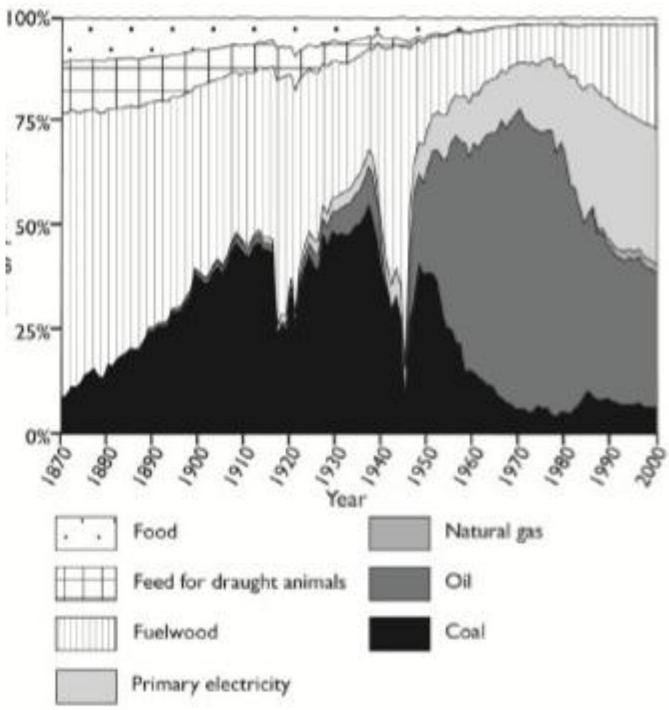
Fig. 5 Sweden History of Energy Mixture, 1960-2008



Source: IEA energy balances

As the Fig. 5 shows, Sweden is a typical example of decarbonization due to early efforts. Not like other countries, its energy mix transformation was smooth and incremental. Its fossil fuel climax was in the late 60s and early 70s. Yet in the next almost 40 years, around 30% of its oil consumption had been gradually turned into non fossil energy use, mainly renewable bio fuels and nuclear power and now the share of fossil energies in its whole energy mix is merely over 40% with extremely low coal and natural gas, the latter had barely increased significantly in history.

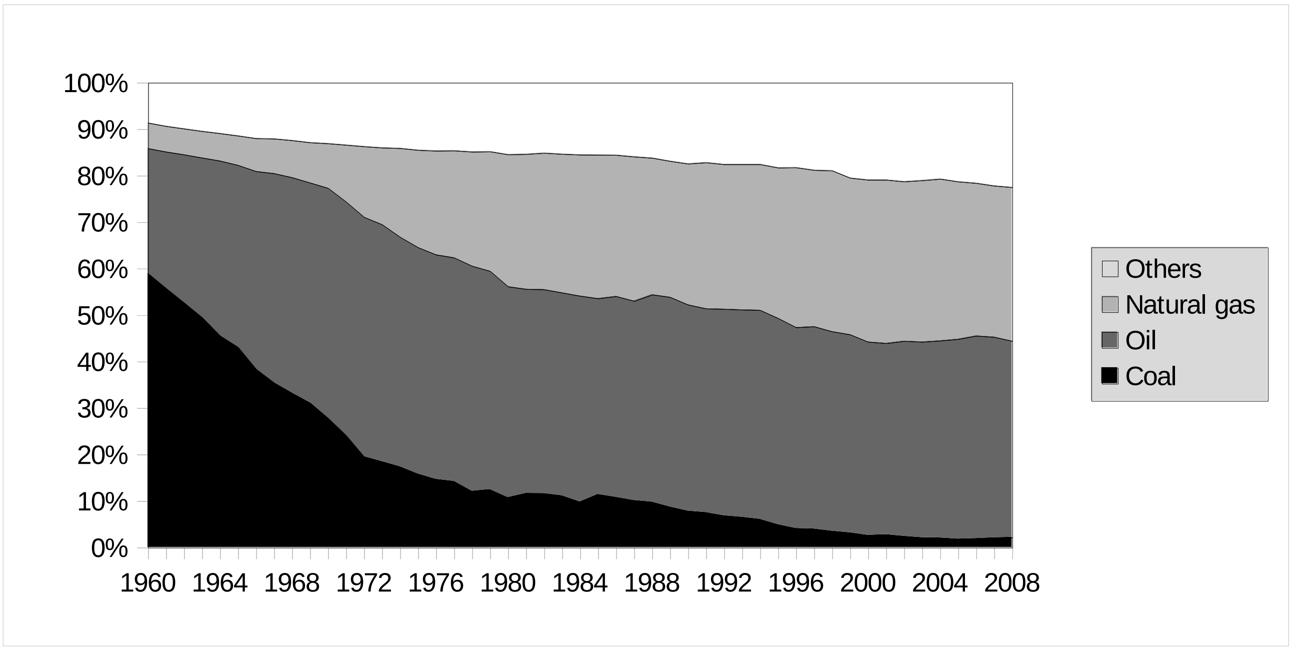
Fig. 6 Sweden History of Energy Mixture, 1870-2000



Source: Gales et al 2007

Despite the analysis above, with the help of data showing a much longer period of time in history, it might be able to give a different view of the whole transformation of Sweden energy consumption in the history. As a Nordic country, coal barely exceeded 50% in total energy supply in Sweden. Oil consumption took off in the middle 1940s and started to go down in the late 1960s, when bio fuels and primary electricity, mainly consisting nuclear and wind power began to take over. So as a result of observation of longer time in history, the horizon gets broader and the picture clearer, and instead of insignificant shifting from fossil energies, Sweden performed its transformation earlier than previous observation time period.

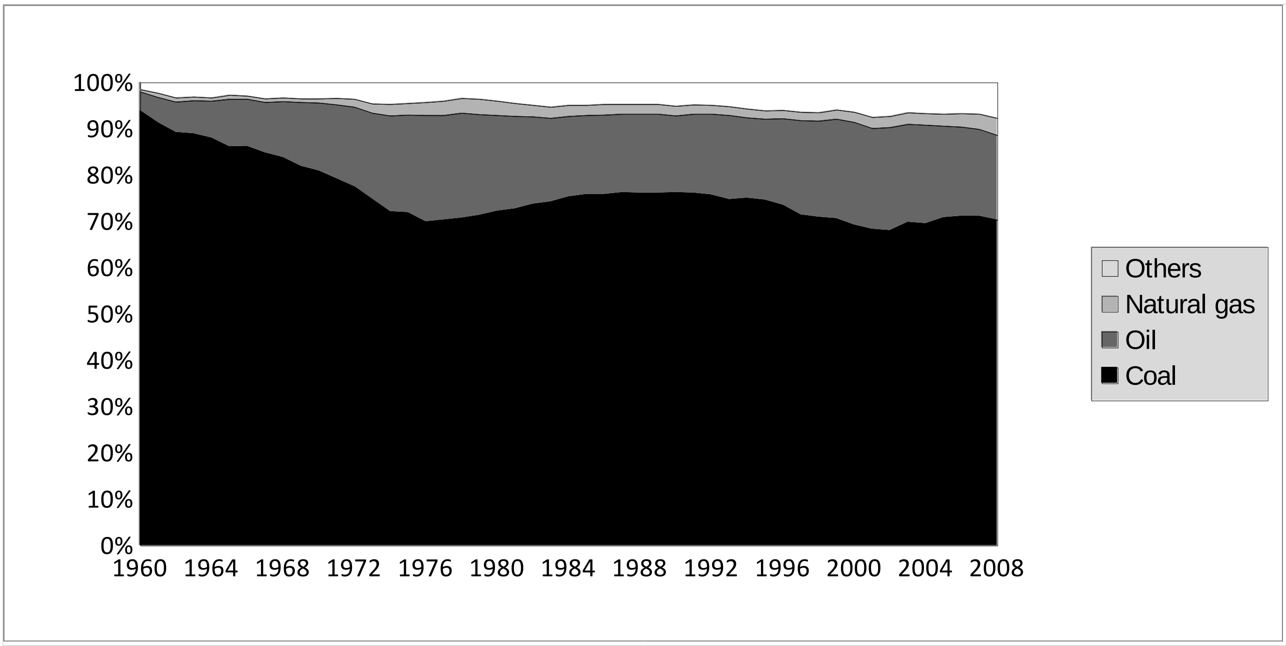
Fig. 7 United Kingdom History of Energy Mixture, 1960-2008



Source: See Fig 5

Unlike Sweden, the United Kingdom has got a totally different history of energy mix change though both are European countries. Its fossil fuel climax was before 1960 and the share in total energy consumption has declined all the way till now but still, fossil energies occupy its total energy use by almost 80%. However, its decarbonization trend still existed, just demonstrated in another way. Instead of cutting down the shares of total fossil energies within the half century, UK succeeded in a huge transformation with the fossil part, shifting all the way from coal to oil and then natural gas. From 1960 to 2008, its coal consumption from almost 60% of the whole dropped to a level so low that was almost able to be neglected. In the meantime, the share loss of coal was attributed quite evenly to the growth of oil, natural gas and non-fossil fuels. So by now, UK is using energies still with large share of fossil fuels but almost of which are in the lower carbon intensity carriers of oil and natural gas.

Fig. 8 China History of Energy Mixture, 1960-2008



Source: China Compendium of Statistics 1949-2004 and China Energy Statistical Yearbook 2010, private domestic use excluded.

Fairly clear from the figure above, China has an energy use history to another extreme compared to Sweden and United Kingdom. Throughout the period from 1960 to 2008, both its fossil energy share and structure within the fossil part only had an insignificant change. More precisely, the most obvious observable one would be that its coal consumption did decline, by about 25%. Within this transfer, most came to the growth of oil consumption, a little less than 10% due to the insignificant growth of natural gas and non-fossil fuels. So in 2008, China reached an energy mix dominated by fossil fuels and within all fossil carriers coal had a dominant position, which in fact was even definitely better though not to a large extent than the situation in 1960.

Now it should be reasonable to put the three countries together and see what could be observed out of them. Obviously China is far from decarbonization compared with Sweden and the United Kingdom both of which had performed a grand structural change in energy consumption mixture in history. So undoubtedly there are gaps. Yet the questions still remained. How did the differences emerge? In other words, what led to the diverse results or outcomes? And more importantly, what could be the key contributors playing important roles in the Sweden case and the UK case of decarbonization that might also be applied by China's future development?

The fact that the three countries are at different stages or periods of decarbonization should be very much related to their different levels of industrialization and economic growth, or perhaps natural resource endowment or even policy influence. So the following Kaya Identity would try to "break down" their carbon emissions into different sources, in order to answer the questions proposed above.

4.3 Kaya Identity

Albrecht, J., D. Francois, et al. (2002) classified two broad categories of decomposition techniques. One is the input-output technique and the other is disaggregation technique. They argued that despite different data requirements, the disaggregation technique suits better in international comparison. And that should be able to explain its popularity and wide usage.

The Kaya Identity could be used to decompose total national carbon emission as below:

$C \equiv C/E * E/Y * Y/P * P$

which is very much like the equation proposed by Grubler, A. and N. Nakicenovic (1996), which used one single variable of Y instead Y/P*P

In the equation

C=CO_2 emissions

C/E= Carbon factor for energy

E/Y=Energy intensity

Y/P=Income per capital

P=Population

Rewrite in the version of annual growth rates

$c=c/e+e/y+y/p+p$

Albrecht, J., D. Francois, et al. (2002) explained the equation above as a useful tool linking energy-related carbon emission to total energy consumption, aggregate economic production and population. C/E, carbon intensity, is the major indicator of decarbonization. E/Y, energy intensity, in the same way is the indicator for energy efficiency. Y/P, GDP per capita, similarly indicates the national economic level according to its scale and P refers to total population. They explained that at any given time, the level of CO_2 emission can be seen as the product of those four components.

Tab. 3 Kaya Identity of CO2 emissions of Sweden, 1960-2008

Sweden	Unit	1960	2008	%
C	thousand tonnes	49181.87	45900	-0.14%
C/E	thousand tonnes per one thousand tonnes oil equivalent	2.43	0.93	-2.02%
E/Y	thousand tonnes oil equivalent per one million 2000 US dollars	0.24	0.16	-0.78%
Y/P	million 2000 US dollars per one thousand	11.34	32.87	2.22%
P	thousands	7480	9219.64	0.44%

Source: WDI

i.e.: -0.14%=-2.02%-0.78%+2.22%+0.44%

As the table demonstrates above, the results of the Kaya Identity is able to distinguish the contributors and back holders to the decarbonization trend within the components. In Sweden case, its total carbon emission decreased from 49.2 million tonnes in 1960 to 45.9 million tonnes in 2008, at an annual change rate of -0.14%. And that result is the product of carbon intensity change, energy intensity change, per capita GDP change and total population change. The former two elements each contributed respectively a -0.202% and a -0.78% annual rate toward decarbonization, while the latter two factors held back the trend by 2.22% and 0.44% annually. That is how the number -0.14% as the rate for annual CO2 emission change is achieved. To examine the figures closely, it would be easy to tell though its energy intensity did decline throughout the time; the carbon intensity indicating the rapid shifts from fossil fuels to non-carbon energies was the major accelerator, contributing more than the double of the former. As for the factors driving the increase of total CO2 emission, growth of total population and per capita GDP on one hand drive CO2 increase, on the other hand they may also lead to technological innovation for decarbonization.

Tab. 4 Kaya Identity of CO2 emissions of United Kingdom, 1960-2008

UK	Unit	1960	2008	%
C	thousand tonnes	583822	510600	-0.28%
C/E	thousand tonnes per one thousand tonne of oil equivalent	3.67	2.45	-0.84%
E/Y	thousand tonnes of oil equivalent per one million 2000 US dollars	0.29	0.12	-1.88%
Y/P	million 2000 US dollars per one thousand	10.48	28.87	2.11%
P	thousands	52373	61406.93	0.33%

Source: WDI

In the United Kingdom case, things were different. The decline of both carbon intensity and energy intensity were important in helping reducing carbon emissions, yet UK decarbonization was more driven by the latter rather than the former factor, indicating a substantial improvement on energy efficiency.

Tab. 5 Kaya identity of CO2 emissions of China, 1960-2008

China	Unit	1960*	2008	%
C	thousand tonnes	780087.58	6550500	4.43%
C/E	thousand tonnes per one thousand tonne of oil equivalent	2.37	3.10	0.55%
E/Y	thousand tonnes of oil equivalent per one million 2000 US dollars	4.7	0.8	-3.72%
Y/P	million 2000 US dollars per one thousand	0.11	2.03	6.16%
P	thousands	667070	1324655	1.43%

** Data for energy consumption in 1960 is calculated through coal to oil unit conversion in the reference to other years.*

Source: WDI

As for China's decarbonization history, or more precisely “carbonization” history, its differences in industrialization level and economic development have been clearly demonstrated by the figures. Rather than a minus rate, China had got an amazingly high plus annual rate of 4.53% of total CO2 emission. But in fact though its carbon intensity increased at a rate of 0.55%, China had a fairly good annual decline rate of -3.72% for energy intensity indicating a much less consumption of energy per unit GDP nowadays than half a century ago. So what were the key players “manipulating” the rapid growth of CO2 emissions? The answer surely lied in the latter two indicators. China had a 6.16% for annual per capita GDP growth rate and 1.43% for annual population growth rate, both of which were around three to four times of those for Sweden and UK. Those two adding together almost 8% of total GDP growth rate annually, was the key characteristic of China representing the rapid growth of emerging economies. So it seems to a large extent that China's CO2 explosion in the last decades might be regarded as a pattern of growth driven.

To compare and assess the three chosen countries more, a common standard would be necessary to work as a starting point in order to show the deviation. So the table below is a combination of the three countries in a comparison based on the average level and annual change rate of various indicators throughout time.

Tab. 6 Comparison of Sweden, UK and China through Kaya identity, 1960-2008

Variables	Unit	Sweden		United Kingdom		China	
		average of 1960 & 2008*	annual change rate	average of 1960 & 2008	annual change rate	average of 1960 & 2008	annual change rate
C	million tonnes	47540.9	-0.14%	547210.9	-0.28%	3665293.8	4.43%
C/E	million tonnes per one million tonne of oil equivalent	1.7	-2.02%	3.1	-0.84%	2.7	0.55%
E/Y	million tonnes of oil equivalent per one billion 2000 US dollars	0.2	-0.78%	0.2	-1.88%	2.7	-3.72%
Y/P	Billion 2000 US dollars per one million	22.1	2.22%	19.7	2.11%	1.1	6.16%
P	millions	8349.8	0.44%	56881	0.33%	995862.5	1.43%

** See Tab. 5.*

Source: see Tab 3, Tab 4 and Tab 5

It should be much clearer with the tab. 6, to discover something about where the three countries are in the decarbonization trend. Among four indicators, C/E or carbon intensity is a crucial one for national level of decarbonization as analyzed earlier in the paper. So on this one, Sweden clearly outpaced the other two, not only growing at a highest annual rate, but also on the lowest absolute base. The reason for this leading advantage could be largely related to its large share of non-fossil fuels. In the equation calculating carbon intensity through weighted sum of all the products of carbon intensity of each energy carrier and its share in total energy consumption, for Sweden, more than half of the components are zero due to almost none extra carbon emissions being produced by its non-fossil energies, and that results in its leading place among three, and also in the world. In fact in 2008, Sweden ranked 2nd lowest among all OECD countries, next to Ireland. (WDI 2010) As for the second indicator of energy intensity, China outpaced Sweden and United Kingdom in annual decline rate which obviously did not come from nowhere. China had got much larger an absolute carbon intensity as a starting level, and that actually refers to the fact that for every unit of value added, China had got to consume 13 to 14 times of energy consumed by Sweden or United Kingdom. So for the ambiguously okay rapid decline rate, there is still long distance from European countries ahead, which might very possibly take several decades of time, equaling in the meantime incredibly huge amount of energy to be consumed. However, every coin has two sides. The huge disadvantage could sometimes be turned into opportunities and driving sources to moving ahead. With the already lowered-down energy intensity of those industrialized countries, much experience and technology might be able to be applied. So is there a possibility to achieve energy leapfrogging for emerging economies as China? That probablility would be further analyzed in the last section of the paper.

Per capita value added, or GDP per capita, is an indicator showing the national economic power for one country. On this one, Sweden and United Kingdom are more or less the same. As for China, this factor is the major driving source for historical carbon emission increase, at a 6.16% rate annually. The problem is that, China had got a three times the growth rate of Sweden and United Kingdom for half a century, yet its per capita GDP in 2008 was still less than one tenth of any of them. From the statement, two things could be revealed. One is that, the leading advantages in both economic performance and energy consumption efficiency for Sweden and United Kingdom are much related to their economic growth history of hundreds of years, which means that even for the industrialized countries at the very least achieving decarbonization was also a time consuming process in history in the sense that it was to certain extents a product of highly development economic and technological strength. The other one might be that with so low a level of economic development, China could very possibly maintain its high growth rate for a certain long period of years, and that together with its continuing driving CO2 emissions could definitely be a challenge on the basis of global climate change situation now.

The population growth indicator was similar in the past and different in the future. Within the period from 1960 to 2008, China's total population grew at a relatively high rate of 1.43%, which also drove the CO_2 emission increase, though to a smaller extent than per capita GDP growth. However, according to “World Development Indicators” from World Bank, this rate of China had dropped to o.5%, even lower than Sweden and United Kingdom. So this could be excluded from further efforts.

To give a brief conclusion, Sweden is ahead among three in the decarbonization process with both two low intensity indicators. Due to a grand transformation in energy carrier mix, Sweden achieved quite low carbon intensity through large shares of zero carbon intensity energies and at the same time maintained its strength in energy use efficiency. The United Kingdom conducted its process in a different way. Despite a fair reduction rate yet still relatively high absolute figure of carbon intensity, the United Kingdom focused on its energy intensity, leading to a same level of Sweden. As for China, its rapid growing economic productivity acted as the major cause of the carbon explosion in the past decades, which made it a side effect of fast development. However, the real problem lies in the amazingly high energy intensity. As a so called “world factory”, China falsely based its fast growing economy on intensive energy consumption, resulting in huge amounts of CO_2 emissions. This was the number one disadvantage on energy use, yet the possibility to draw experience from past history and technologies from leading countries as Sweden, and achieve leapfrogging remains.

However there are still questions remained after the Kaya Identity. What were the actual reasons between the structural changes? The reason could only be within the economic transformation. For Sweden and United Kingdom, an annual growth rate of 2% was enough to double their per capita production in less than 40 years, not to mention China with more than 6%. Same as energy structural change, the economies were also witnessed to be holding structural changes among its sectors. Different sectors develop at different paces, with different energy consumption patterns leading to different CO_2 intensities also in change. So the changes in different sector share would lead to total intensity change, and the changes of energy consumption structure within single sector driven by technological progress had similar impacts. How to indicate and measure those through economic structural change could be a more specific issue on lowering CO_2 level.

Therefore to clearly distinguish between intensity change within single economic sector led by technological innovation and structure change with the whole energy mixture, which could be argued the answer to the question above, the third method of LMDI decomposition is applied to demonstrate the trend of three countries. Due to the inaccessibility of data for earlier time, this decomposition consists of data only in the period of 1971 to 2008.

4.4 Energy source decomposition

Here applies the adjusted LMDI decomposition originally present by Ang, B. W. and F. Q. Zhang (2000). Since almost all CO_2 emissions come from fossil fuels of coal/coke, oil and natural gas, the aggregate economy is divided into four sectors of agriculture, industry, service and transport. More specifically, agriculture includes forestry and fishing. Industry sector involves various industries led by steel & iron and cement production. The service sector also includes some unspecific factors classified into the column of nonspecific others and the transport division also include some non-energy causes. Other sources influencing, are all put into the residentials. All the five components adding up and the total final consumption is reached.

Henriques, S. (2010a) described the LMDI decomposition as below. (Adjusted to own usage)

The starting equation is:

$I_t=\sum S_{i,t} * I_{i,t}$

in which I_t= Total CO_2 intensity at time t

$S_{i,t}$=Share of sector/carrier I at time t

$I_{i,t}$= Intensity of sector/carrier I at time t

Then treat the variables as continuous and apply the instantaneous growth rate theorem and it turns into:

$d\ln(I)/dt=\sum w_i[d\ln(y_i)/dt+d\ln(I_i)/dt]$, in which $w_i=E_i/Y$

And that is to say the share of CO_2 emission in total energy consumption is viewed as the weight for carriers in summation. Adding the time change into the equation and it turns into:

$\ln(I_t/I_0) = \int\sum w_i[d\ln(y_i)/dt]dt+\int w_i[d\ln(I_i)/dt]dt$

Basically, it is the exponential form of

$D_{tot}=D_{str} * D_{int} * D_{res}$ (2)

in which

D_{tot}= total CO_2 intensity change

Dstr= structural change

Dint= intensity change

Dres= non fossil energies change

To decompose, they would be as below:

$Dstr=exp[\sum w'_i * ln(S_{i,t}/S_{i,0})]$

$Dint=exp[\sum w'_t * ln(I_{i,t}/I_{i,0})]$

$Doth=exp\{\sum w'_k * ln[(E_{k,t}/Y_t)/(E_{k,0}/Y_0)]\}$

in which

$w'_{i(k)}=L\{[(E_{i(k),t})/Y_t)], [(E_{i(k),0})/Y_0]\}/L(I_t, I_0)$

and in which $L(x,y)=(x-y)/ln(x/y)$

and then (2) is reached.

And here are the calculations and tables of results. All the data are collected from IEA energy balances and WDI. The CO_2 emission data from single sectors are calculated by summing up its consumption of different fuels, timed by the CO_2 intensity of each carrier from Tab 1, which should be a convincing calculation.

Tab.7 LDMI decomposition for United Kingdom, 1971-2008

		Agriculture	Industry	Service	Transport	Residential	Total
E	1971	1782	49831	14688	35571	32559	134431
	2008	866	29651	17977	52290	42063	142847
C	1971	108.602	3346.772	849.42	2617.056	1981.276	8903.13
	2008	30.644	1254.276	525.948	3744.37	1841.168	7396.41
Se	1971	1.3%	37.1%	10.9%	26.5%		76%
	2008	0.6%	20.8%	12.6%	36.6%		71%
I	1971	0.06	0.07	0.06	0.07		0.07
	2008	0.04	0.04	0.03	0.07		0.05
dTotal	=It/I0=	78.2%					
C/E	1971	0	0.03	0.01	0.02	0.02	0.07
	2008	0	0.01	0	0.03	0.01	0.05
L(C/E)	1971	0.000	0.015	0.005	0.023	0.014	
L(It/I0)	2008	0.06					
W	=L(Ct/Et,C0/E0) /L(It,I0)=	0.008	0.263	0.083	0.386	0.235	
dStr	=exp(W*ln(St/S0))=	0.99	0.86	1.01	1.13		98%
dInt	=exp(W*ln(It/I0))=	1.00	0.89	0.94	0.99		82%
dRes	=exp(W*ln((Ct/Et)/(C0/E0)))=					0.97	97.00%
dTotal	dStr*dInt=	0.990	0.760	0.956	1.122		
dTotal	dres=					0.969	78.2%

Source: IEA energy balances and WDI

So the first four major rows show the energy consumption, carbon emission, energy share of total and carbon intensity of each sector, in which the latter two not including residential are of both 1971 level and 2008 level. Then the ratio of dTotal is got by dividing the CO2 intensity of 2008 by 1971 level. The rest of the table is to get the same result through a more sophisticated way so as to calculate out the effects of economic structural change and intensity change within sectors led by technological progress as the mathematical demonstration above.

Simpler presentation could be seen in only results as below.

Tab. 8 Decomposition results of United Kingdom, 1971-2008

	Agriculture	Industry	Service	Transport	Residential	Total
Dstr	0.994	0.858	1.012	1.134		0.979
Dint	0.996	0.885	0.945	0.990		0.824
Dres					0.969	0.969
Dtotal	0.990	0.760	0.956	1.122	0.969	0.782

Source: see Tab 7

The table lists the total intensity change, together with its sources of structural change, intensity change led by technology evolution and residential change from different sectors. The number refers to the ratio of 2008 level per 1971 level for different combinations of change sources and sectors. All numbers range from 0 to 2, indicating the changes were all below 100%.

So from the Tab. 8 above, it could be easily told that the United Kingdom managed to lower its carbon intensity to 78% of the 1971 level by 2008. Throughout the period, energy structural change accelerated and intensity change within individual sectors contributed in the process. Of the former part, a significant shift of energy consumption from industry to transport led to an over 2% decline from structure change. Among the latter part, industrial carbon intensity decreased by a substantial level, however combined with the result of structural change, it could be inferred that industry was actually the highest intensity among all. The point is that, the overall slow pace of CO2 intensity decline, perhaps besides industry, generated a really limited contribution from the first source, especially the increase of CO2 intensity in transport and service largely offsetting the decline in industry. The product of two things, as well as almost unchanged residential, adding together was the limited decline of overall intensity.

Tab.9 LDMI decomposition for Sweden, 1971-2008

		Agriculture	Industry	Service	Transport	Residential	Total
E	1971	485	12175	2846	6867	10162	32535
	2008	717	11673	4133	10606	6637	33766
C	1971	31.598	507.688	143.412	495.818	646.914	1825.43
	2008	18.512	190.21	31.298	742.186	10.146	992.352
S	1971	1.5%	37.4%	8.7%	21.1%		69%
	2008	2.1%	34.6%	12.2%	31.4%		80%
I	1971	0.07	0.04	0.05	0.07		0.06
	2008	0.03	0.02	0.01	0.07		0.03
dTotal	=It/I0=	52.4%					
C/E	1971	0	0.02	0	0.02	0.02	0.06
	2008	0	0.01	0	0.02	0	0.03
L(C/E)	1971	0.001	0.010	0.002	0.018	0.005	
L(It/I0)	2008			0.04			
W	=L(Ct/Et,C0/E0)/L(It,I0)=	0.018	0.237	0.054	0.445	0.113	
dStr	=exp(W*ln(St/S0))=	1.01	0.98	1.02	1.19		120%
dInt	=exp(W*ln(It/I0))=	0.98	0.80	0.90	0.99		70%
dRes	=exp(W*ln((Ct/Et)/(C0/E0)))=					0.62	62%
dTotal	dStr*dInt=	0.990	0.786	0.919	1.177		
	dres=					0.62	52.4%

Source: see Tab 7

Tab. 10 Decomposition results of Sweden, 1971-2008

	Agriculture	Industry	Service	Transport	Residential	Total
Dstr	1.006	0.981	1.018	1.194		1.201
Dint	0.984	0.800	0.903	0.986		0.701
Dres					0.623	0.623
Dtotal	0.990	0.786	0.919	1.177	0.623	0.52

Source: see Tab 7

Compared to the United Kingdom, Sweden was fairly different as Tab.10 shows. With reduction contributions from both individual intensity change and residential change, Sweden cut down its total CO2 intensity by 2008 to almost half of 1971 level. Unlike the United Kingdom, Sweden experienced a strong economic structural transformation from industry to transport. As a result, its structural change even slowed down the decarbonization process by increasing the total intensity. But what distinguished Sweden from the large offsetting of the United Kingdom case was that Sweden managed at the same time to low down its intensities of both industry and service, as well as the residential part. Essentially, the impact from Swedish energy consumption structural change from fossil fuels to non-fossil fuels is much strong than the change for United Kingdom within fossil fuels, i.e. the transition from “yes” to “no” was more thorough than the transition from “more” to “less”.

As for China, it at the very least had its CO2 intensity increased by 40%, if domestic consumption included, which was the definitely against the trend. According to the “CO2 emission highlights 2010” from IEA, global CO2 intensity decreased by 6% in the meantime. However, as for the countries growing at a remarkable rate, the BRIICs, according to the same source, except Russia; all had been on a path towards higher CO2 intensity. Brazil was acceptable partly due to the bio fuel program; China was even slower on the path following India and Indonesia. So what led the emerging economies to a path of carbonization? Take China as an example, due to growing energy demands and unsecured energy supply, the stress of technology innovation and progress was not carbon reduction, on the contrary how to improve combustion efficiency, in other words, how to increase carbon, in the chemical sense. How to cut down large expenditure on energy imports and to avoid potential energy shortage or even crisis were their priority of policy targets, instead of global climate control, in the past decades of catching up.

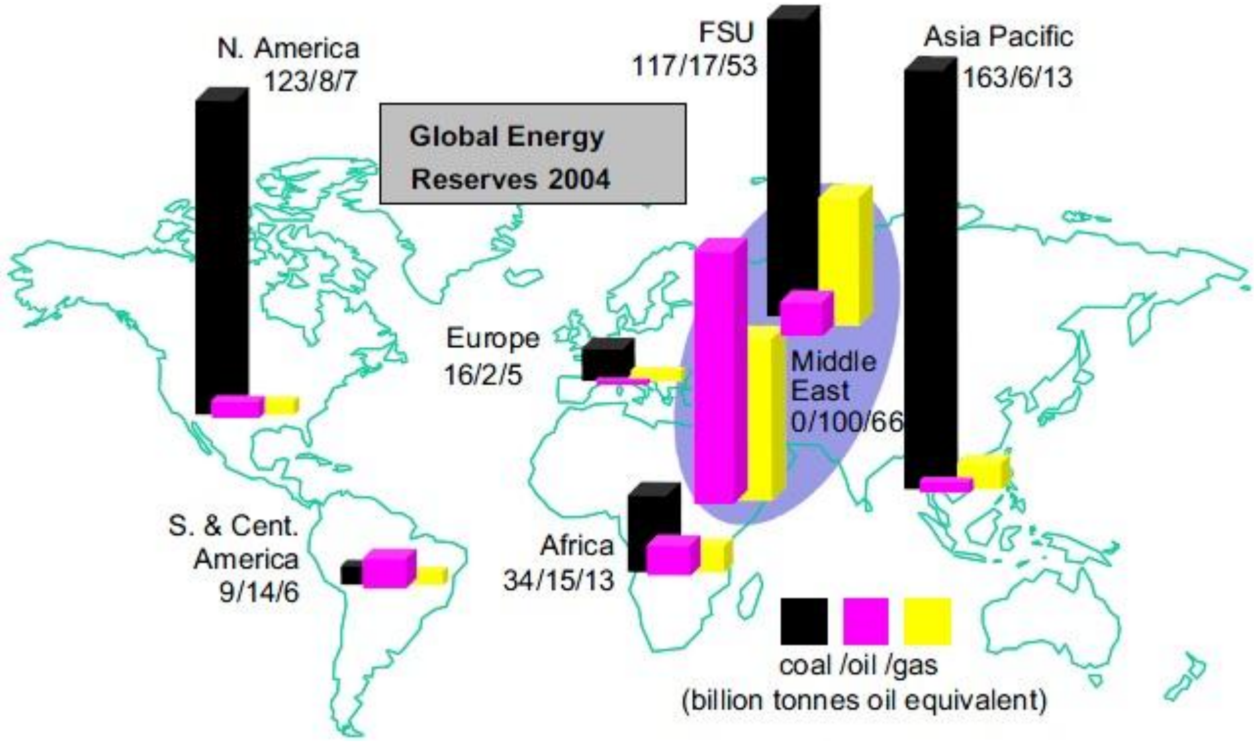
So far, one deep reason behind the data analysis started to surface despite of the contribution by structural change, which is largely the governmental impact, or policy implementation. Take a glance back at the United Kingdom and Sweden, the much wider acceptance of the decarbonization concept could be largely attributed to the government appeal, without which the past structural change might be estimated much weaker and slower depending merely on technological progress. Besides all those analyzed above, another element would be taken into consideration below in the final section of this paper, which has to be the natural resource endowment. It would be definitely inappropriate to ignore environmental or natural factors when considering an energy issue intending to lessen the impact from human behavior on global environmental change. Due to the limitation of research range and shortage of effective quantitative tools, it would be impossible here to actually “calculate out” how much the natural endowment affects the decarbonization trend, instead what would be stated are certain presentations of related data, to help form a rough picture of the correlation. In this way it is hoped that both the past and the future could be pictured into clear connections between specific reasons and decomposed results, in the hope of shedding light on the exploration for the possibility of leapfrogging.

5. Conclusive analysis and summary

Henriques, S. (2010b) illustrated leapfrogging in two ways on the energy issue. The first is to skip the whole or part of fossil age, thus lessening side effects from fossil combustion. The second is similar to the catching up theories that lagging countries share an advantage in catching up through skipping technological evolution stages. As for energy use, technology factor could directly affect the economic structure and energy mix. So acceleration of technological progress should similarly skip some stages of fossil time, as well as improve energy efficiency. For the first possibility according to historical data, China seems to have already been trapped in the coal lock-in, which could block the fossil-skipping path in some way. So what led to such circumstances and could it be adjusted to future development is the reason argued here, China’s natural endowment for energy resources.

5.1 Past: natural endowments of China vs. policy implication of Sweden

Fig. 9 Geographical distribution of fossil fuels reserves world,



Source: BP Statistical Review of World Energy 2005 in Kavouridis, K. and N. Koukouzas (2008)

Fig. 9 shows the proved reserves of fossil fuels according to geographical distribution. Asia has got the largest reserve of coal and Middle East of oil and natural gas. It might not be accurate to view the coal domination in China and India fully as products of their coal reserves, yet their massive coal production has definitely got positions leading to current situation, as well as their lagged positions in technological progress path. To give a more precise picture, China is listed below for its fossil fuel reserves and shares of world total.

Tab. 11 Proved reserve of fossil energies in China, in thousand million tonnes

Energy	Reserve	World share
Coal	80.1	12.60%
Oil	2.3	1.40%
Natural gas	2	1.20%

Source: BP Statistical Review of World Energy 2005

From Tab.11, it should be clear that it was unreasonable to expect cleaner fuel domination than coal in the starting stage of industrialization, since coal could be much more accessible and cheaper than oil and natural gas. A more than 10% of coal total reserve puts China among the largest coal producers in the world. But that does not mean the carbon lock-in, opposed to decarbonization leapfrogging, is unavoidable, at least not necessarily.

Fig.6 shows that Sweden also used to have times when fossil fuels occupied relatively high consumption shares. However, starting from the 1960s when oil began to drop obviously, Sweden managed to increase its nuclear share in electricity production from 0 to 40% to 50% from 1960 to 2008. (IEA energy balances) While that percentage barely exceeded 13% worldwide and stayed less than 2% for China in the half century. (WDI 2010) Along with nuclear, Sweden also increased wind energy share in electricity generating and bio fuel in transport energy supply while United Kingdom, China and other parts of the world were witnessing oil flood in energy use at the same time. Now that CO2 intensity is directly related to the type of fossil energy carrier, then China's huge coal consumption should stand for opportunities for leapfrogging on energy mix transformation. Sweden is a successful example, and China is also taking this path as a possibility according to its grand natural gas pipeline construction and the takeoff of wind turbine manufacture industry.

5.2 Future: path dependence as United Kingdom or leapfrogging?

Fig.7 demonstrates the transformation in energy mix for United Kingdom, step by step leading to a thorough example representing world energy transition from coal to oil and then natural gas. However, that would not be a delighting option for China based on its huge current CO2 emission from rapid economic growth together with both high carbon intensity and high energy intensity. If the United Kingdom case could be viewed as path dependence of energy use on technological progress, then does China stand a chance to leapfrog as a catcher-up? Future predictions should be drawn from past tracks and below is the Kaya Identity results of China in individual decades.

Tab. 12 Kaya Identity of China in decades, 1960-2008

Variables	1960-1970	1971-1980	1981-1990	1991-2000	2001-2008
C	-0.12%	5.72%	5.87%	3.06%	9.02%
C/E	-0.56%	1.01%	1.72%	0.35%	-0.46%
E/Y	-3.08%	-1.24%	-5.15%	-7.32%	-0.94%
Y/P	1.48%	4.24%	7.83%	9.01%	9.84%
P	2.04%	1.71%	1.48%	1.03%	0.58%

Source: see Tab 5

Among the four indicators affecting total CO2 emission level, population growth of China has already declined all the way to an acceptable level compared to other countries thus possible to be excluded from consideration. As for GDP per capita growth, it shows the trend of continuous accelerating, which could in long term greatly affect the total CO2 level. However, potential technological progress driven by per capita productivity is a double bladed sword and its own sustainability of growth is beyond the discussion since huge uncertainty occurs off the energy area.

Therefore to reduce carbon intensity and energy intensity are the only options. In the history, China demonstrated a rather sharp decline of energy intensity but according to the absolute number great potential should be still left to realize. As for the CO2 intensity, no obvious consistency is shown through decades but the same reason for energy intensity could also work. For the future reduction for two types of intensity, one has partly been discussed in 5.2 and the rest together with the other might find the opportunity for potential technological leapfrogging, according to its theoretic constraints. Countries as United Kingdom have left clear footprints in history, so perhaps it is time for another economic reform in China of industry upgrading in structural transformation, along the industrialization process. Anyway, it should be easier to find and take another way if an inappropriate one has already been tried and labeled by early comers.

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