HEINRICH BÖLL STIFTUNG

Turning point: Decoupling Greenhouse Gas Emissions from Economic Growth

A study by DIW Econ

Authors: Lars Handrich, Claudia Kemfert, Anselm Mattes, Ferdinand Pavel, Thure Traber

Colophon

The views expressed in this publication are those of the authors alone.

Editing by Rebecca Bertram and Bastian Hermisson
Coordination by Mackenzie Nelson
Copy editing by Bernd Herrmann

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This publication can be ordered from:

Heinrich Böll Stiftung
Schumannstr. 8 – D-10117 Berlin – Germany

Phone: +49 (0)30 - 285 34 - 0
Fax: +49 (0)30 - 285 34 - 109
Email: info@boell.de – Website: www.boell.de

Heinrich Böll Stiftung – North America
1432 K Street, NW – Suite 500 – Washington, DC 20005-2540 – USA
Phone: +1 (202) 462-7512
Fax: +1 (202) 462-5230
E-mail: info@us.boell.org – Website: www.us.boell.org

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EXECUTIVE SUMMARY

The transformation of economic growth towards a lower dependency on fossil fuels and related greenhouse gas (GHG) emissions is essential for the feasibility of a successful global climate strategy. The year 2014 was the first in decades that saw worldwide economic growth *and* a reduction of energy-related GHG emissions. This study attempts to explore these developments and illuminate the drivers through descriptive data analysis, a review of empirical research and a regression analysis. The assessment covers data for the period 1990 to 2014 and includes economic growth, energy-related GHG emissions, energy consumption and energy carriers for 34 countries. Particular emphasis is put on the often-cited examples of China, the US and Germany, which are then compared with the OECD aggregate, India and the worldwide picture.

This study distinguishes weak and strong decoupling of energy consumption from economic growth to analyze specific evolutions. Weak decoupling is defined as a reduction of energy intensity, i.e., energy consumption per GDP, while absolute consumption still rises with economic growth. Strong decoupling is present, if total energy consumption falls with economic growth. Furthermore, this concept is applied to the analysis of decoupling from GHG emissions and to decoupling from conventional energy as the sum of nuclear and fossil energy consumption.

Regarding the past decade, it turns out that global growth went along with an increase of energy use, and that despite a steady decrease of conventional energy intensity. This weak decoupling process was facilitated by greater energy efficiency and the roll-out of renewables. Since 2004, solar and wind have been the fastest growing energy sources worldwide, and they saw substantially accelerated growth over the last four years. This is true for China, India and the OECD group of countries. Moreover, our empirical assessment of the causal relationships suggests that renewables may even promote economic growth. For climate policy this presents an optimistic perspective. In particular, the OECD countries show a strong decoupling of conventional energy and of emissions over the last decade. As exemplified by Germany, a successful renewable energy strategy combined with substantial energy savings will result in substantial emissions reductions – and that despite the phasing out of nuclear energy.

China and India are of particular importance for global trends due to their high growth rates. However, their growth follows diverging patterns. While on a continued economic growth path, China succeeded in a weak decoupling from conventional energy requirements and emissions. Moreover, strong decoupling seems possible in the near future. In 2014, China stopped the expansion of coal use and met the modest 3% growth in energy consumption mainly with less emission intensive energy sources such as natural gas, wind and solar power. By contrast, India's renewable energy expansion is more than canceled out by investment in emission-intensive power sources, mainly coal-fired power plants.

For the US, the second largest GHG emitter, the outlook is unclear. Although the US has successfully combined substantial economic growth with a reduction in total emissions, strong decoupling has not continued since 2012. If China succeeds to further reduce its emissions, this will send strong signals towards a global low-carbon transition.

ZUSAMMENFASSUNG

Damit Maßnahmen gegen den Klimawandel weltweit greifen, ist es unerlässlich, Wirtschaftswachstum so umzugestalten, dass es weniger von fossilen Rohstoffen und den damit verbundenen Treibhausgasen (THG) abhängt. Das Jahr 2014 war das erste seit Jahrzehnten, in dem global die Wirtschaftwuchs und die THG-Emissionen der Energiebranche dennoch sanken. In der vorliegenden Studie soll versucht werden, diese Entwicklungen und ihre Ursachen zu erklären, und zwar mittels deskriptiver Analyse der Daten, kritischer Durchsicht der Forschungsliteratur sowie Regressionsanalyse. Ausgewertet werden hierzu Daten für 34 Länder und über ein Vierteljahrhundert (1990-2014), darunter zu Wirtschaftswachstum, energiebezogenen THG-Emissionen, Energieverbrauch sowie Energieträgern. Unser besonderes Augenmerk gilt dabei China, den USA und Deutschland, welche wir anschließend mit den OECD-Staaten, Indien sowie der Welt insgesamt vergleichen.

Um auf spezifische Entwicklungen eingehen zu können, unterscheidet die Studie zwischen einer schwachen und einer starken Entkopplung von Energieverbrauch und Wirtschaftswachstum. Schwache Entkopplung liegt vor, wenn die Energieintensität gemessen als Energieverbrauch im Verhältnis zur Bruttoinlandsprodukt (BIP) rückläufig ist, der absolute Verbrauch aber analog zum Wirtschaftswachstum weiter steigt. Von starker Entkopplung sprechen wir, wenn der absolute Verbrauch bei gleichzeitigem Wirtschaftswachstum sinkt. Dasselbe Prinzip wenden wir auch an für die Untersuchung der Entkopplung von THG-Emissionen und von konventioneller Energie, d.h. der Summe von nuklearem und fossilem Energieverbrauch.

Im vergangenen Jahrzehnt ging das globale Wachstum einher mit einem steten Anstieg des Energieverbrauchs – und das, obgleich die konventionelle Energieintensität sank. Zu dieser schwachen Entkopplung kam es durch verbesserte Energieeffizienz und den Ausbau erneuerbarer Energien. Seit 2004 sind Wind- und Sonnenenergie global die am schnellsten wachsenden Energiequellen, und dieser Anstieg beschleunigte sich in den vergangenen vier Jahren noch einmal deutlich. Dies gilt insbesondere auch für China, Indien und die OECD-Staaten. Unsere empirische Wirkungsanalyse zeigt zudem, dass Wirtschaftswachstum durch den Ausbau erneuerbarer Energien möglich ist. Dies macht Hoffnung für die Chancen von Klimapolitik. In den letzten zehn Jahren kam es besonders in den OECD-Ländern zu einer starken Entkopplung von konventioneller Energieerzeugung und Emissionen. Das Beispiel Deutschland zeigt, durch eine gelungene Strategie für erneuerbare Energien und erhebliche Energieeinsparungen lassen sich trotz Atomausstiegs Emissionen deutlich absenken.

Wegen ihres starken Wachstums spielen China und Indien für globale Trends eine besonders wichtige Rolle. Allerdings wachsen die beiden Länder sehr unterschiedlich. China gelang, trotz anhaltenden Wachstums, eine schwache Entkopplung von konventioneller Energie und Emissionen, und bald schon könnte auch eine starke Entkopplung möglich sein. Im Jahr 2014 stieg Chinas Kohleverbrauch nicht weiter an, und die mit 3 Prozent vergleichsweise geringe Zunahme des Energieverbrauchs wurde vor allem mit emissionsarmen Energieträgern wie Wind und Sonne gedeckt. In Indien hingegen wird der Ausbau der erneuerbaren Energien durch Investitionen in Energieträger, die hohe THG-Emissionen verursachen – vor allem in die Kohleverstromung –, mehr als neutralisiert.

Wie es in den USA, dem weltweit zweitgrößten Verursacher von THG-Emissionen, weitergeht, ist nicht klar. Zwar gelang es den USA, solides Wirtschaftswachstum zu verbinden mit sinkenden Emissionen, seit 2012 ist jedoch keine starke Entkopplung mehr festzustellen. Sollte China seine Emissionen weiter senken, würde dies starke Signale in Richtung einer progressiven internationalen Klimapolitik senden.

1. Introduction

1.1 Background and research question

The transition of economies towards a lower dependency on fossil fuels and related carbon emissions is essential for the feasibility of a successful global climate strategy. The fast pace at which the cost of renewable energies is dropping, opens up promising prospects for both economic growth and climate mitigation. The growing rate at which wind and photovoltaic plants are deployed in both developed and emerging countries underlines this opportunity. In particular, after the financial crisis of 2008 and 2009, highly developed countries like Austria, Belgium, Germany and the United Kingdom followed a trajectory that combines growth with reductions in fossil fuel consumption and respective emissions. This constitutes a great success for climate policy, a success also driven by the fact that these countries adopted policies to promote energy savings and renewable energies. Such examples of successful energy policies attest to the economic potentials of an accelerated reduction of carbon dioxide emissions, which, in turn, may lead to a shift of public perceptions. In the same vein, the International Energy Agency reports that, for the first time in 40 years and despite economic growth, annual global CO_2 emissions did not rise in 2014. Previously, stagnating emissions had always corresponded to economic stagnation.

In the early 1990s, emissions stagnated because of the collapse of Eastern European economies, while in 2008 the financial crisis and the shrinking of global industrial production brought down emissions. The latest developments, however, are attributed by the IEA to changing patterns of energy consumption in China and the OECD countries. China in particular generated more electricity from renewable sources and reversed coal-based power generation, while in OECD countries efforts to increase renewable energy use went along with energy-saving policies, resulting in the decoupling of economic growth from CO_2 emissions.

This study attempts to shed light on these developments and their drivers. In the following, we first define a concept of decoupling that facilitates a distinction between strong and weak decoupling and formulate our working hypothesis. In section 2 we provide an in-depth descriptive assessment of trends in conventional energy consumption and growth for the OECD aggregate, as well as for China, Germany, the US and India – countries that are considered to be of major importance for worldwide climate policy. In addition to trends that characterize the past decade as a whole, we also highlight annual developments. Moreover, we show corresponding changes in energy-related GHG emissions and assess major impacts effected by switching energy carriers. We further present changes in respective energy mixes, i.e., shifts in coal, gas and renewable energy consumption and their impact on the emission intensity of energy production.

Our descriptive assessment shows the outstanding role played by China and India as well as the effects of the US gas boom. Moreover, we highlight the exceptional German mix consisting of a renewable rollout, energy savings and a nuclear phase-out.

In section 3, we review the latest research on possible drivers and interdependencies between energy and growth (up until 2010). Based on a widely used approach, we investigate the relationship between the economy, the consumption of renewables and conventional energies for different country groups and on different time scales. Finally, we review the latest data (up to 2014), which provide us with new evidence supporting the hypothesis that growth can be triggered by renewable energy policies.

1.2 Definition of Decoupling

In this study, decoupling is defined as two distinct processes:

Weak decoupling: Weak decoupling refers to the reduction of energy intensity (ratio between energy consumption and GDP) with growing GDP.

Strong decoupling: Strong decoupling refers to the reduction of total energy consumption with growing GDP.

These concepts may be applied to either total energy consumption, fossil energy consumption or conventional energy consumption (including fossil and nuclear energy).

Furthermore, the decoupling of conventional energy consumption and economic growth can be facilitated by four approaches that change the relation of economic activity to energy consumption.

- **Structural change** of the economy (displacement of energy intensive by less energy intensive sectors, e.g., the tertiary sector)

- Increased **energy efficiency on the supply side** (more efficient energy transformation processes, power plants etc., switch to other fossil fuels)

- Increased **energy efficiency on the demand side** (appliances with lower energy consumption per delivered service)

- **Substitution of low-carbon energy sources for fossil energy sources,** e.g. renewables for coal.

The focus of this study is on the substitution of renewable energy for conventional energy sources and on energy efficiency on the demand side. However, other possible methods for decoupling will be considered as well.

1.3 Working hypotheses

This study investigates the following hypotheses:

1. Renewable energy expansion **decreases** the **conventional energy intensity (CEI)** of economies (CEI=Conventional Energy/GDP). In other words, renewable energy roll-out displaces conventional fuel consumption more than it potentially depresses GDP. If we find that renewable energies do not reduce economic growth and, at the same time, substitute for conventional resources rather than complement them, the hypothesis holds.

2. An effective **energy efficiency policy** decreases **energy intensity**. If we find that, in the group of countries with rigorous energy efficiency policies, energy intensity falls faster, than in the group where no or less substantial energy efficiency measures are implemented, we have evidence in favor of the hypothesis.

3. Developed countries show a strong decoupling from conventional energy consumption, while developing countries show a weak decoupling. If we find that growth coincides with a less pronounced increase in non-renewable energy consumption in the developed countries compared with the less developed or emerging countries, the hypothesis holds.

2. The empirical picture: Developments of energy consumption and CO_2 emissions by 2014

2.1 Data sources and energy aggregates

To analyze the relationship between energy consumption and economic activity we use data for the following EU countries: Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Slovak Republic, Spain, Sweden and the United Kingdom. In addition, we use data from Norway and Switzerland and from the following non-European OECD countries: Australia, Canada, Chile, Israel, Japan, New Zealand, South Korea, Mexico, Turkey and the United States. We also include China, India, Malaysia and Vietnam in the data set as examples of developing and emerging countries.

The source of our empirical information is the *BP Statistical Review of World Energy* (2015), which provides primary energy consumption data for the selected countries for the time period between 1990 and 2014. In this source *Conventional Energy* includes and distinguishes between oil, coal, gas and nuclear, whereas *Renewables* is the aggregate of hydro, solar, wind and biomass. Moreover, the BP data tracks GHG emissions from energy-related fossil fuel combustion. To measure economic development, we use the gross domestic product in USD (at purchasing power parity) as collected by the World Bank.[1]

2.2 World

The composition of world-wide primary energy consumption as reported by BP (2015) and disaggregated into the main fuel carriers is shown in the central pie chart in **Figure 1**. In 2014, the global primary energy consumption mix consisted of 91% conventional and 9% renewable energy.[2] Coal (30%) and oil (33%) are the main contributors, while renewable sources are dominated by hydro power (7% of total energy supply) and wind (1.2%). Solar-based energy contributes 0.3% to total primary energy.

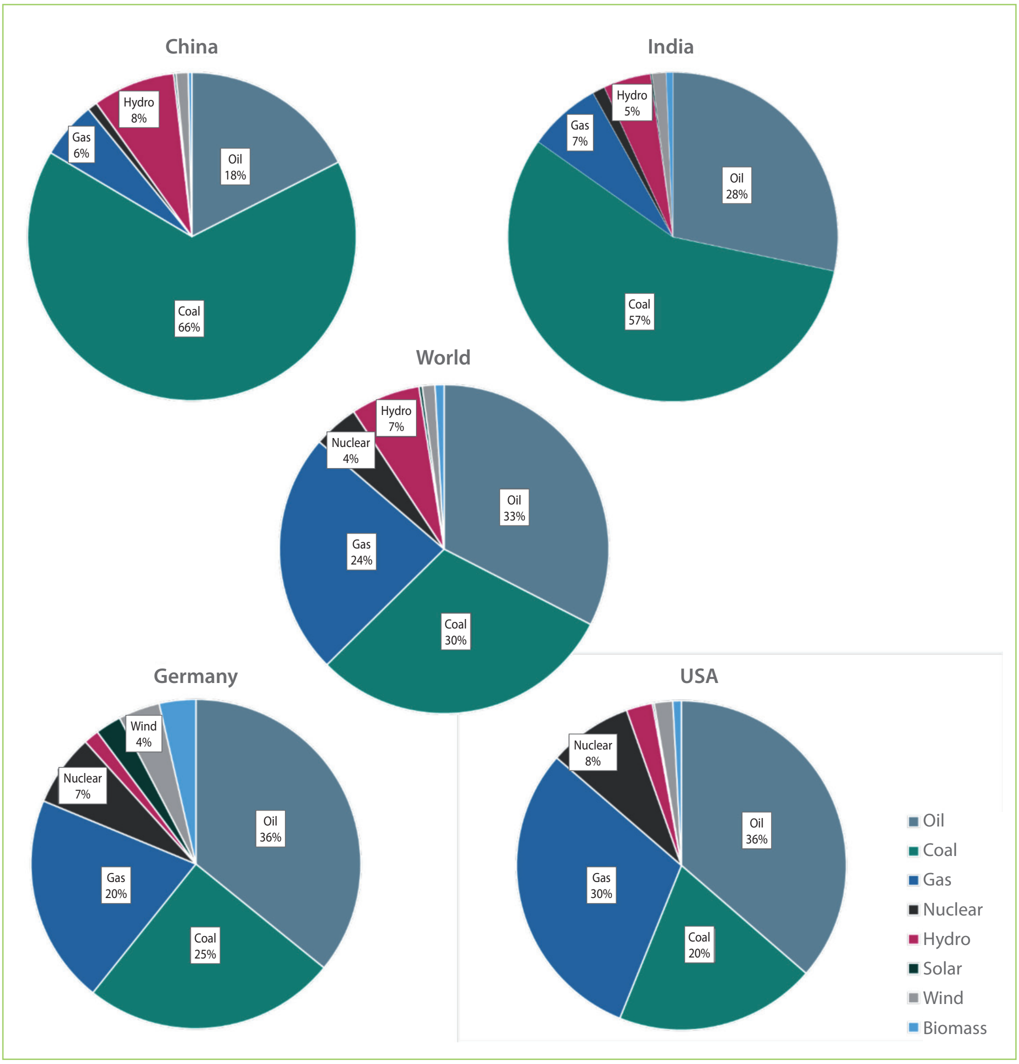
In our sample of countries, we find that the composition of energy sources often diverges from the world aggregate. China, for example, derives about two thirds of its energy from coal, while nuclear power is negligible and natural gas has a marginal share of less than 6% **(see Figure 1)**. Moreover, oil accounts for 18% of China's primary energy consumption. By comparison: In 2014, the share of oil in Germany and the USA stood at 36% – twice as high as in China.

At 30% (2014) the US has a particularly high share of gas usage, whereas, in Germany, renewable energy accounted for 12% of the country's energy mix – and that despite the low level of hydro-electric energy generation (1% of total). Due to less favorable geographic conditions, hydro power represents only 13% of Germany's renewable energy, while continuing to be the dominant source of renewable energy in China (82%) and the US (48%).

1 The World Bank provides GDP data up to 2013. We calculated the 2014 values on the basis of GDP in 2013 and growth rates provided by the OECD, or, in case of Vietnam and Malaysia, by the World Bank.

2 It must be noted that traditional forms of energy use – e.g., biomass for cooking – are difficult to measure and consequently not included.

Figure 1 – Composition of primary energy sources in 2014: World, China, India, Germany and US

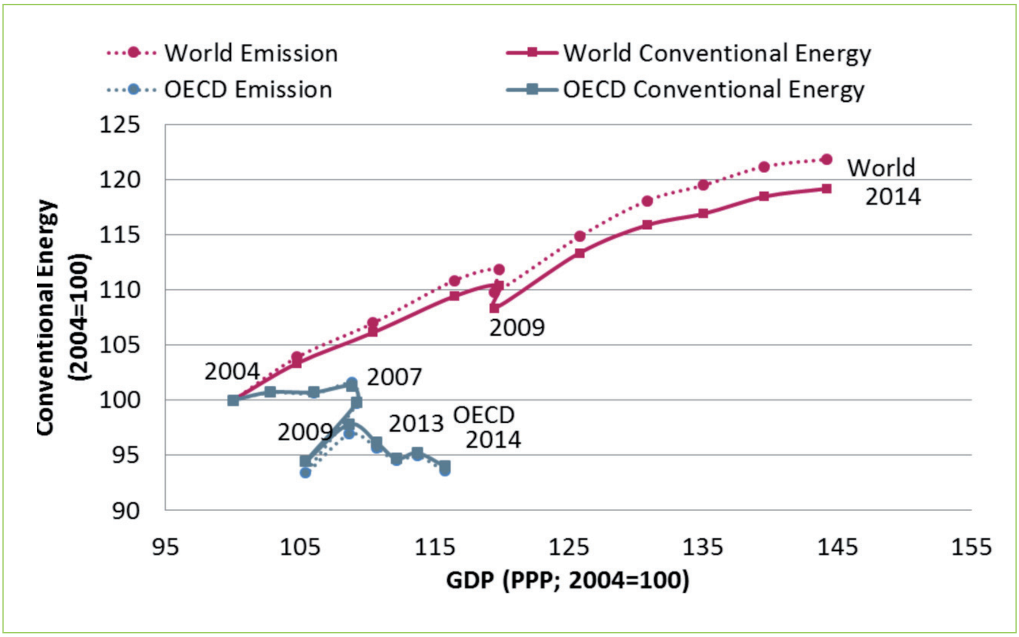


Source: BP Statistical Review of World Energy (2015)

Between 2004 and 2014, global GDP has grown by 44%, while the consumption of conventional fuels has increased by 19%, resulting in a 22% increase of worldwide emissions. During the same period, the OECD countries economies grew by 16% and conventional fuel consumption decreased by 6%, leading to emissions reductions of 6.4%.

The ten-year growth rates for the OECD countries (red curve) and the world (blue curve) in **Figure 2** visualize annual developments based on a normalization of the 2004 values to 100. Weak and strong decoupling, as defined above, are displayed by the angle of the curves. A positive but decreasing gradient indicates weak decoupling, while negative angles between 0 and -90° indicate strong decoupling, i.e., positive growth combined with less conventional energy use. Furthermore, the dotted curves indicate the emissions to GDP nexus.

Figure 2 – Development of conventional energy consumption and related CO_2 emissions worldwide and in OECD countries from 2004 to 2014



Source: BP Statistical Review of World Energy (2015); World Bank (2015)

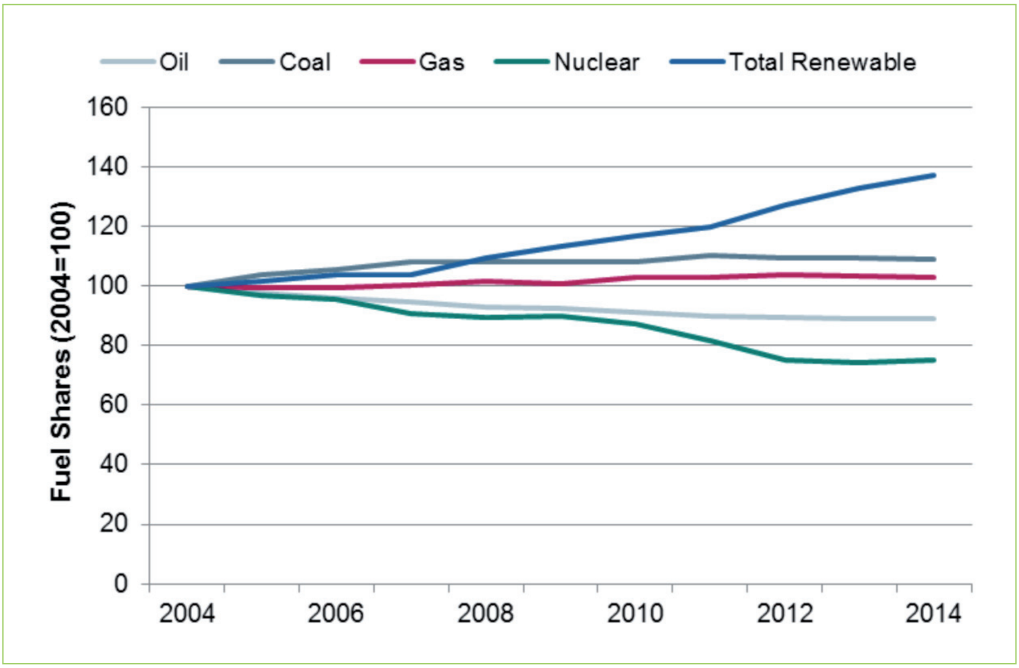
We find that on the global scale conventional energy consumption and GDP weakly decoupled after the financial crisis, since the red curve shows signs of leveling off (with the exception of 2012-2013). There is little evidence for a changing relation between fossil energy consumption and growth. However, before drawing policy conclusions, this has to be assessed taking into account a variety of important parameters – including fuel prices and annual climatic conditions.

Prior to the 2009 financial crisis, the gradient had been almost constant, indicating no decoupling for the period between 2004 and 2008. Regarding energy related CO_2 emissions, the global picture follows the conventional fuel consumption curve closely, as indicated by the dotted red curve. However, the increasing gap indicates the use of more emission-intensive energy sources or less efficient conversion technology.

Global trends clearly differ from those in the developed world as indicated by the red and blue curves in **Figure 2**. Although OECD countries accounted for 42% of fuel consumption and 46% of world GDP in 2014, the global growth rate appears to be dominated by developments in China and India, who lead global developments due to their ever-increasing share in both energy consumption and worldwide GDP.

The main drivers of fossil fuel consumption and its potential decoupling from economic growth are structural change, conversion efficiency, efficiency on the demand side and the substitution of less emission-intensive energy for fossil fuels. Out of those four factors, the last one is the focus of this study, since renewable energy economics are particularly promising due to a significant technological learning curve, at least in the case of wind power and solar energy. We therefore highlight the renewable energy option, its position in the overall primary energy provision and the technology over the period between 2004 and 2014 **(see Figure 3)**.

Figure 3 – Share of different energy carriers in total worldwide energy consumption between 2004 and 2014

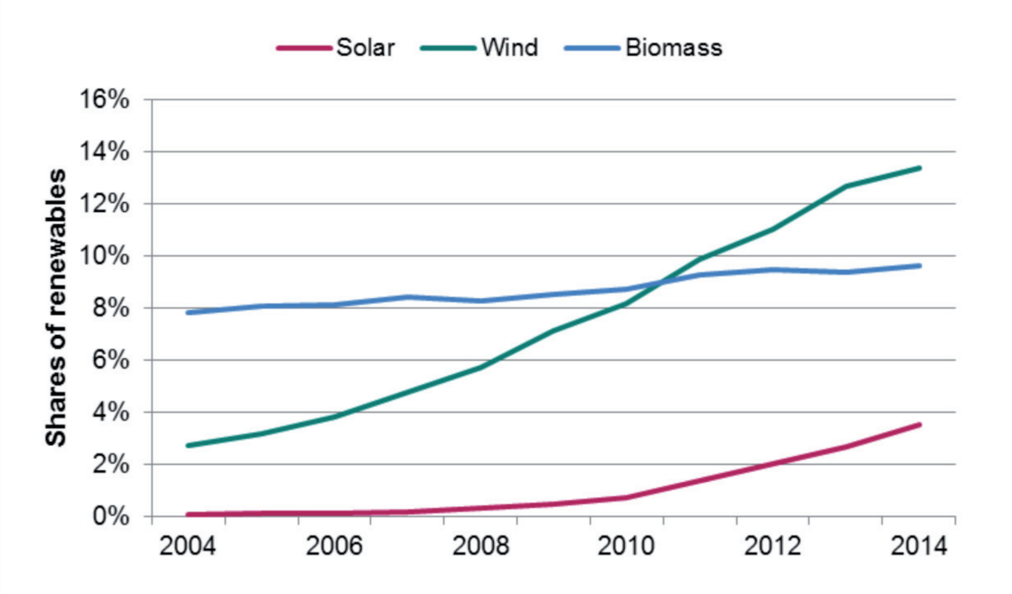


Source: BP Statistical Review of World Energy (2015)

Renewable energy reached a share of 9.3% of the world aggregate of primary energy consumption in 2014. This corresponds to a 37% increase compared to 2004. Over the same period, coal consumption saw the highest growth in absolute terms, increasing its share of primary energy consumption by 8.8%. Furthermore, gas consumption increased its share by 2.8%, corresponding to a total increase of gas usage by 26%. However, since the 2009 financial crisis, the growth of gas and coal utilization has been leveling off. By contrast, renewable energies continue to grow, with a particular spike after 2011 **(Figure 3)**. On the other hand, the global role of nuclear power and oil consumption is declining. Between 2004 and 2012 nuclear energy declined by 8%, resulting in a 25% drop of its share of the global energy mix. Finally, the share of oil in the global energy mix dropped by 11% – and that despite a 9% growth in total oil consumption.

Over the last decade, the dominant renewable energy technology was hydro power, contributing 50% to the increase in renewable energy generation. However, its share in the renewable energy mix has decreased continuously – from 90% in 2004 to 73% in 2014 – due to the rapid development of solar and wind energy. **Figure 4** shows how the share of the most important renewables has developed.

Figure 4 – The most dynamic renewable energy technologies worldwide



Source: BP Statistical Review of World Energy (2015)

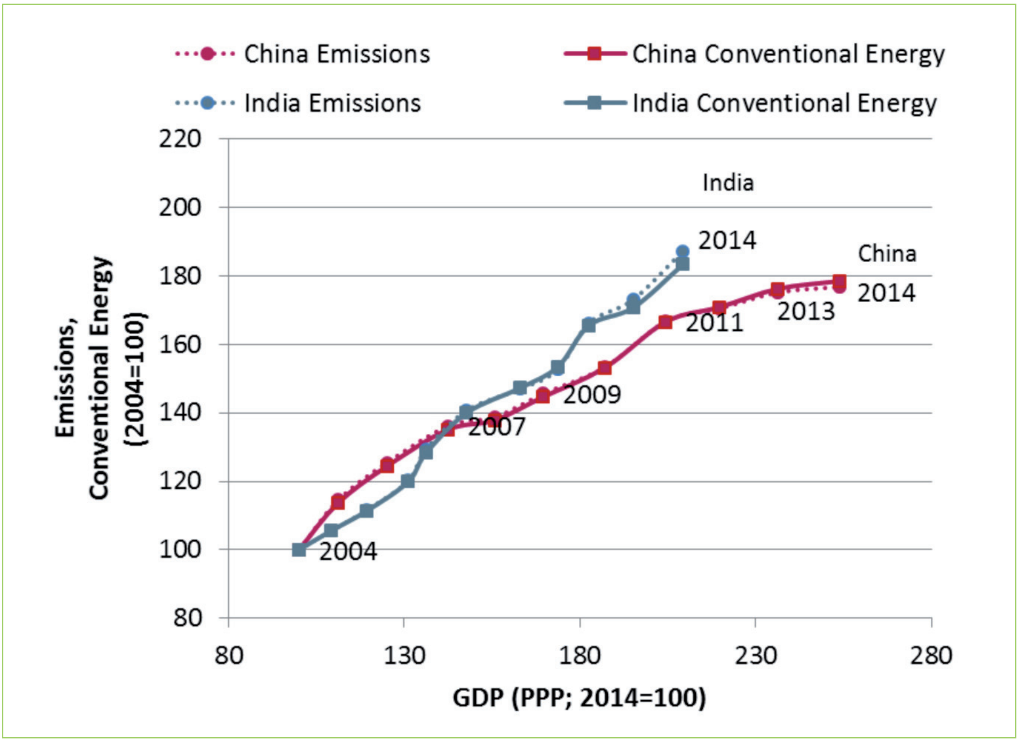
Wind energy grew from a 3% share in 2004 to over 13% in 2014, and solar energy accounted for almost 4% of all renewables in 2014, while, in 2004, it had been virtually non-existent. Due to the differences between countries and their aggregates it is essential to investigate OECD countries as well as emerging economies and work out their respective contributions.

2.3 China

China is of central importance for the global development of energy consumption and emissions. Chinese energy consumption and the related development of emissions over the last twenty-five years have been determined, to a large part, by phases of sectoral restructuring developed in the five-year plans. Between 1990 and 2005, China saw a strong increase in emissions due to rapid industrialization with double digit annual growth in the heavy industries. During this phase of development, the emission intensity of GDP grew, since emission-intensive production changed faster than other sectors (UN 2014a). The 11th five-year plan for the period 2005 to 2010 introduced targets for energy intensity related to economic performance (GDP) and sulfur dioxide targets, whereas the 12th five-year plan for the period 2010 to 2015 aims also to reduce CO_2 emission in relation to GDP, as well as reduce NO_x emissions (Juan and Zuho 2011). Moreover, for 2015, China has adopted a target of an 11.4% share of non-fossil energy regarding total energy consumption. All of this has strongly influenced the development of energy generation and emissions (UN 2014a).

In 2004, China accounted for 9% of world GDP and 13% of world energy consumption. Since, these figures have changed considerably, and in 2014, China accounted for 16% of global GDP and 23% of global primary energy consumption. By comparison, over the same period, India increased its share in worldwide GDP from 4% to 6% and its share in energy consumption from 3% to 5%. Today, China and India account for over a quarter of the world's conventional energy consumption, and the development of these two countries shapes to a large part the worldwide growth of energy consumption and GDP. In China, GDP has grown by 154%, while conventional energy consumption increased by 88%;

Figure 5 – Development of conventional energy consumption and related CO_2 emission in China and India from 2004 to 2014



Source: BP Statistical Review of World Energy (2015)

the respective figures for India are 109% and 85%. In both countries energy consumption as well as emissions grew at a lower rate than GDP, and we can thus detect weak decoupling over the last decade compared to the values for 2004.

For China, we also observe a slight decrease in energy intensity, indicated by the bottoming out of the curve in **Figure 5**.

Over the last two years, China has been heading towards strong decoupling, as suggested by roughly constant emissions and continued strong growth **(see the dotted red curve in Figure 5)**. The latest data shows that the modest increase of energy consumption (2014: +3%) is fed mainly by less emission-intensive fuels. Renewable energy and natural gas grew by 27% and 22% respectively and facilitated a zero growth of coal. This assessment is supported by a recent report on Chinese coal consumption based on import and stockpile calculations. It was conducted by Greenpeace and looks at 2014 and the first months in 2015.[3] However, whether this trend of growth accompanied by emission stagnation will survive the current economic cooling in China remains to be seen.

China's energy usage and emissions were predominantly shaped by coal (as shown in Figure 6). Over the course of the last decade, Chinese coal consumption grew by 74%. Nevertheless, the overall share of coal actually decreased, as total energy consumption rose by 88%. While coal usage in China grew by 71% between 2004 and 2012,

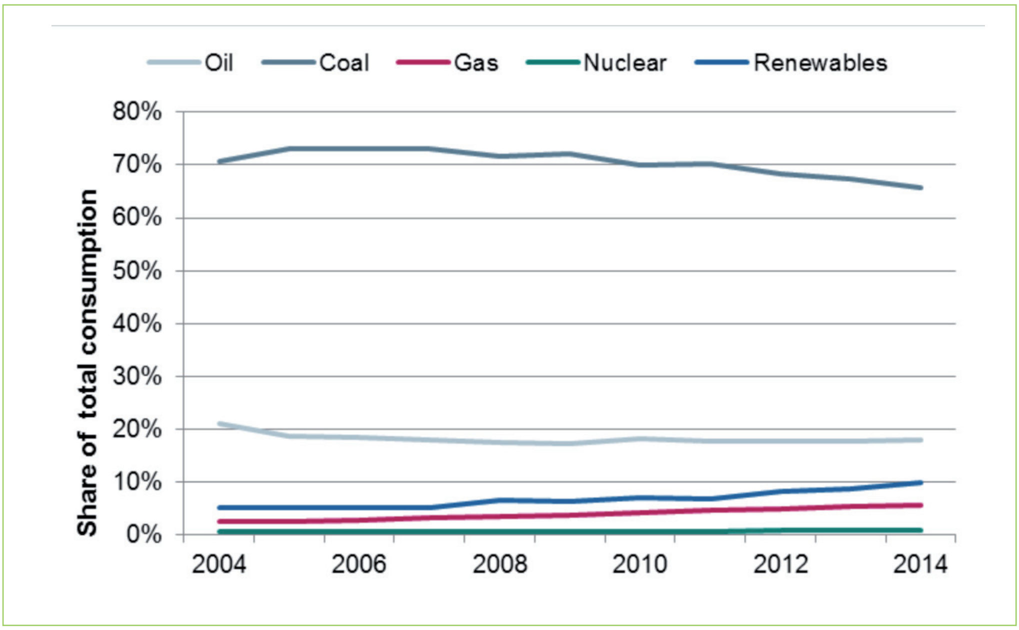
3 Greenpeace Energydesk China: http://energydesk.greenpeace.org/2015/05/14/china-coal-consumption-drops-further-carbon-emissions-set-to-fall-by-equivalent-of-uk-total-in-one-year/

it has since slowed down considerably, hardly increasing in 2013 and stagnating in 2014.

Correspondingly, the share of coal in China's energy mix decreased between 2004 and 2014 – and particularly after the financial crisis of 2008/2009 **(compare Figure 6)**. In 2006, coal's share of primary energy consumption was 73%; by 2014 this had decreased to about 66%. For this, main drivers are environmental regulations introduced in recent five-year plans, as well as restrictions imposed by extraction and import capacity limits. Since 2012, natural gas consumption has increased by 22% and renewable energy has gained 27%. The main source of renewable energy in China is hydro power with a current share of 82% and an increase of 22% over the last two years. By contrast, in 2004 hydro power had a 99% share of China's renewable energy. The new renewable energy sources PV and wind show the largest growth rates and contribute an increasing share, while the use of biomass has not increased in recent years.

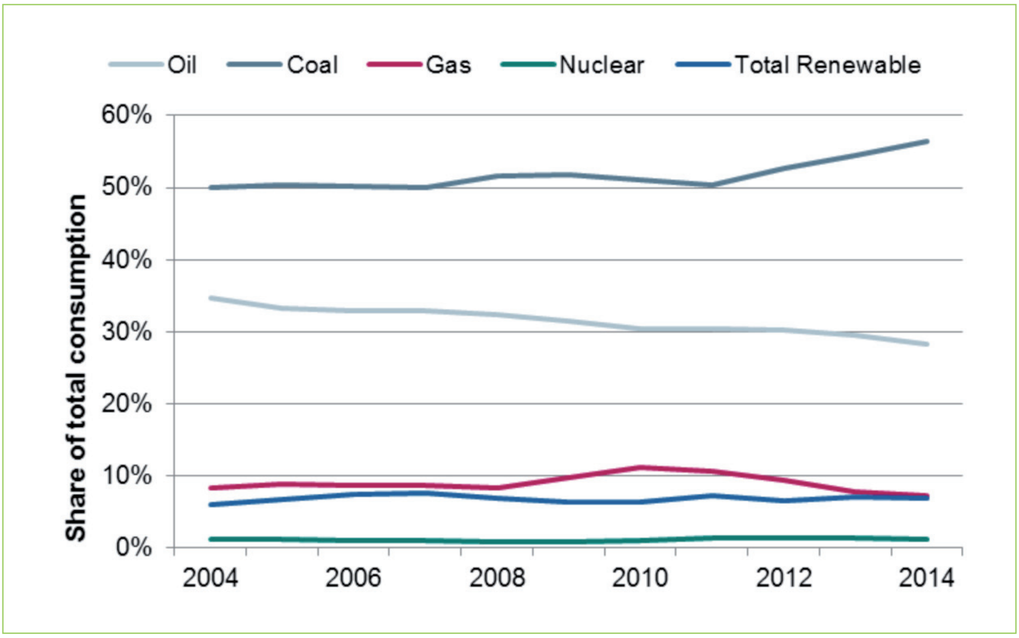
By contrast, India has seen an accelerated increase of coal consumption, more than doubling since 2004, and with a share of 56% in 2014 **(see Figure 7)**. Moreover, the strong rise of coal consumption since 2011 explains, to a great part, the increase in India's emission intensity as compared to China.

Figure 6 – Primary energy consumption shares by fuel in China from 2004 to 2014



Source: BP Statistical Review of World Energy (2015)

Figure 7 – Primary energy consumption shares by fuel in India from 2004 to 2014



Source: BP Statistical Review of World Energy (2015)

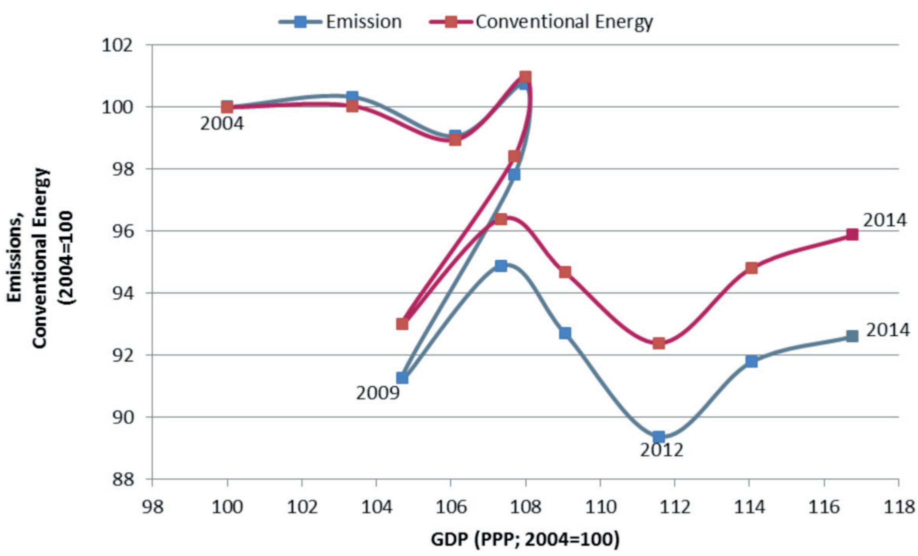
2.4 The United States of America

Emissions of CO_2 from industrial combustion accounted for 78% of all GHG emissions in 2012, and they increased almost continuously between 1990 and 2005. In particular, energy emissions rose due to the increasing use of coal in the power sector. However, greater energy efficiency led to a decrease of emissions relative to economic output. After 2005, the picture began to change due to new power-generating technology and a slack growth dynamic (UN 2014b).

Despite a 17%-growth of GDP between 2004 and 2014, US energy consumption has been stagnating during this period (-2%), and conventional energy use declined by 4%. Moreover, emissions related to conventional fuel combustion dropped significantly faster (-7.4 %) than fossil fuel consumption. Both figures indicate a strong decoupling – and that despite very low prices for natural gas, something that came about through the shale gas boom and enduring energy export restrictions in favor of domestic consumption.

Figure 8 shows the development of energy consumption, carbon dioxide emissions and GDP over the last ten years on a year-to-year basis. Before the onset of the financial crisis emissions and conventional energy consumption developed almost at the same pace, accompanied by a steady increase of GDP. However, in 2008, with the financial crisis, both curves started to diverge. Between 2008 and 2012, emissions became strongly decoupled from economic growth. Over the last two years, however, the pronounced growth in energy consumption could not be compensated by higher efficiency or renewable energy, resulting in an upswing of emissions.

Figure 8 – Development of conventional energy consumption and related CO_2 emissions in the US

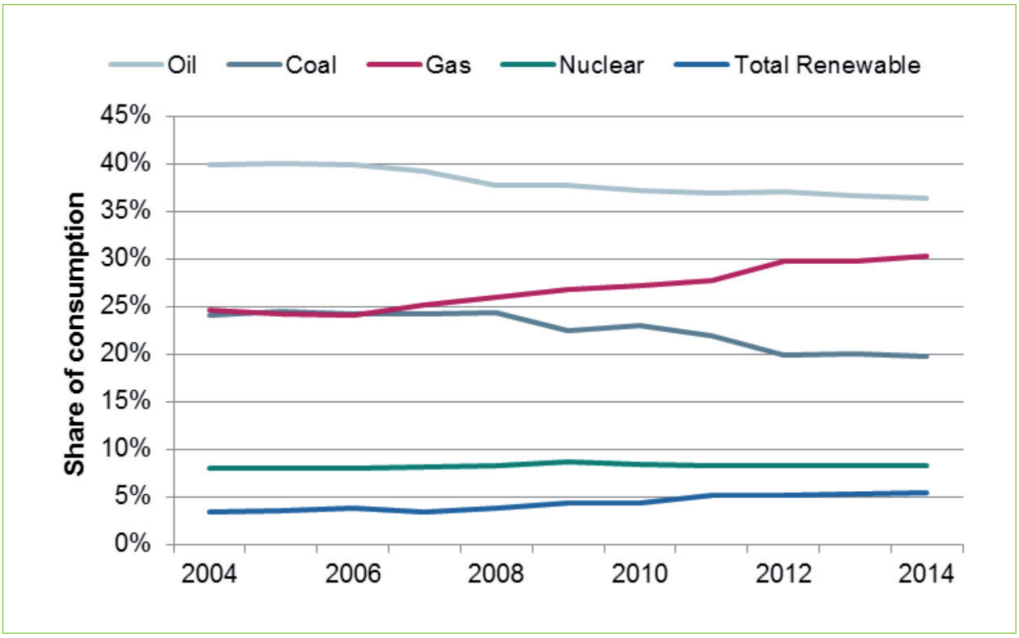


Source: BP Statistical Review of World Energy (2015); World Bank (2015)

In 2009, the abrupt decrease in both energy consumption and GDP was followed by a decoupling of energy and emissions due to a pronounced decrease of oil and coal consumption, as shown in **Figure 9**. The central driver of this development is the substitution of coal by gas in the power-generation sector, which increases the conversion efficiency and reduces the primary energy demand for electricity production.

Primary consumption of gas increased by 20%, while the corresponding coal consumption decreased by the same amount measured in tons of oil equivalents. In addition, total renewables increased by 53% to a 5.4% share in the total primary energy mix in 2014. Since the financial crisis the development has been dominated by a continuous increase of the exploitation of shale gas resources in the US. Thus, the decoupling of GDP and emissions, as suggested by **Figure 8**, seems not to be due to a robust decoupling of overall energy consumption and GDP. Since the financial crisis, primary energy consumption in the US has increased by 4%.

Figure 9 – Share of primary energy consumption by fuel type in the US from 2004 to 2014



Source: BP Statistical Review of World Energy (2015)

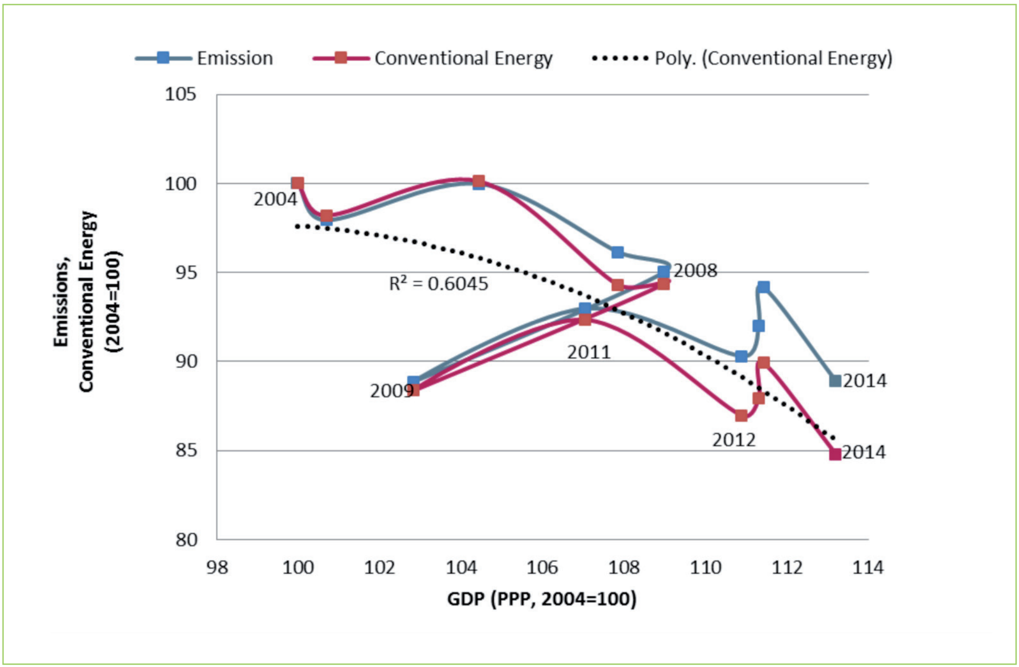
2.5 Germany

Between 1990 to 2005, energy usage and emissions in Germany have been driven by two factors: the economic transformation of East Germany since 1990 and the transition away from fossil fuel combustion towards renewable energies. Furthermore, Germany has realized significant energy efficiency improvements, particularly in the industry and buildings sectors, which has led to a decrease in energy intensity (UN 2015c). Since the beginning of the 21st century, renewable energy rollout has been particularly fast.

In addition to the financial crisis, Germany's decision to phase-out nuclear energy and shut down several reactors after the 2011 Fukushima disaster has changed the relationship between energy consumption and emissions – at least in the short-term. However, the increased usage of renewable energies and the advent of PV-generated electricity on an industrial scale has compensated for the reduction of nuclear power.

Although GDP grew by 13%, Germany's emissions have decreased by 11% since 2004, and conventional energy usage, including nuclear power, by 15%. Thus, despite strong decoupling of both energy and emissions from GDP, the emission intensity of the conventional energy sector has increased. This development is indicated by the growing gap between emissions and conventional energy consumption in **Figure 10**.

Figure 10 – Development of conventional energy consumption and related CO_2 emissions in Germany

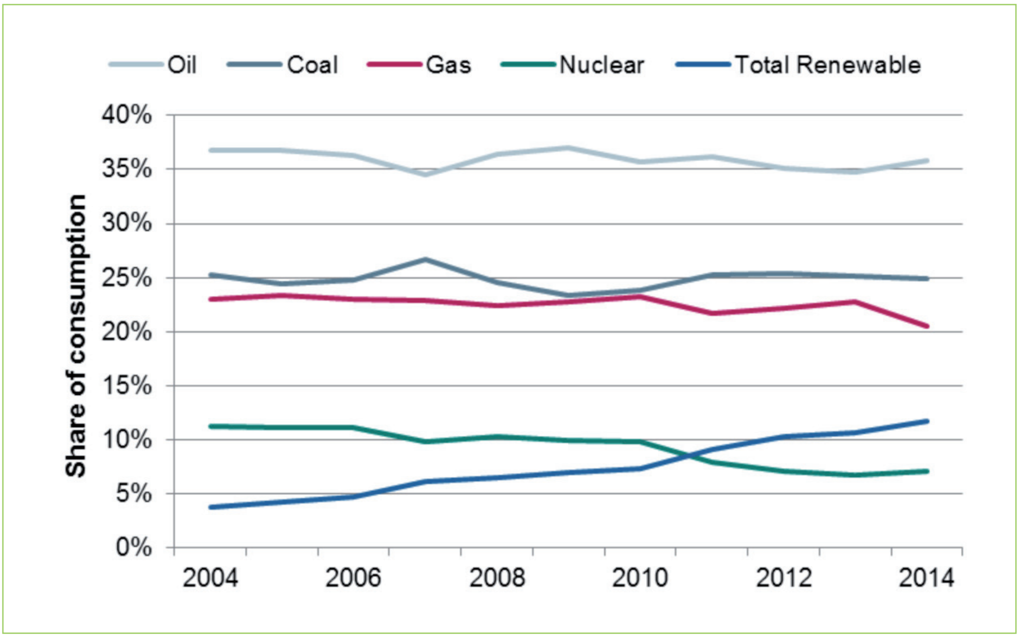


Source: BP Statistical Review of World Energy (2015); World Bank (2015)

In the wake of the 2008 financial crisis, Germany's conventional energy consumption as well as emissions have decreased substantially. This is mainly due to a pronounced drop in energy consumption and emissions after 2013, which more than compensated for the increase in both emissions and energy consumption immediately after the crisis in 2010 and 2011. The dotted curve in **Figure 10** shows the trend in conventional energy consumption. The shape of the gradient suggests not only a strong decoupling but also an acceleration of strong decoupling from conventional energy.

However, Germany's total energy consumption declined by only 8% over the last ten years. Nuclear power generation decreased by 42%, while gas, oil and coal consumption dropped by 17%, 10% and 9% respectively. These cutbacks where accompanied by a 185% increase in the use of renewable energy. By 2014, renewables provided a 12% share of total primary energy consumption as indicated by **Figure 11**. Today, wind and biomass power each contribute 4% to Germany's primary energy mix, followed by solar power at around 3% – all of which more than compensates for the reduction in nuclear energy generation.

Figure 11 – Share of primary energy consumption by fuel type in Germany from 2004 to 2014



Source: BP Statistical Review of World Energy (2015)

2.6 Findings from the statistical facts

Given the variety of country-specific factors such as natural conditions and policies, national developments show a mixed picture when comparing the four countries, China, India, the US and Germany. While in India there is no sign of decoupling whatsoever, China has decoupled both conventional energy and emissions from growth, if only slightly. The US and Germany, on the other hand, are examples for strong decoupling that took place over the last decade and resulted in substantial growth, while decreasing conventional energy consumption and emissions. However, this is not true for all the years studied.

A common feature of the four countries in question is a rise in the share of renewable energy generation resources, indicating their increasing importance. Importantly, developing and emerging countries like China and India will shape the future course of global development. This is underlined by the fact that energy consumption and related CO_2 emissions in the OECD countries have been strongly affected by the 2008 financial crisis, while in China and India the respective areas saw hardly any change. The fact that global development was only moderately influenced by OECD variations shows how important developing countries have become. The financial crisis seems to have coincided with an accelerated roll-out of renewable energies.

Regarding the decoupling hypothesis, the comparison of OECD countries, exemplified by the US and Germany, with China and India shows the importance of respective income levels. However, a clear distinction as formulated in hypothesis 3 regarding decoupling in developed countries is contradicted by the facts. The status of a country as developed or developing does not determine its success in decoupling. Conversely, a high level of development is not sufficient to achieve continuous decoupling – be it strong or weak. Whereas both the US and Germany have shown strong decoupling of emissions from growth only after the financial crisis, weak decoupling appears to have occurred in China over the whole past ten years. India, on the other hand, has not shown any signs of decoupling.

3. Regression Analysis

The previous chapter provided a description of the empirical development of energy consumption and emissions over time. The facts found contradicted the development hypothesis 3, that is, that developed countries show a strong decoupling from conventional energy consumption, while developing countries show a weak decoupling. Hypothesis 1 (renewable energy expansion decreases the conventional energy intensity) and hypothesis 2 (effective energy efficiency policy decreases the energy intensity) will be further investigated.

Of special concern is the impact of renewable energy and energy saving projects on economic growth. It is often argued that the introduction of new technologies on the energy supply side, in form of renewables and energy efficiency measures, hinders economic growth, and that relevant policies may seriously compromise future economic development. Other observers, however, stress that such policies create great opportunities.

A growing literature therefore uses methods to determine the causal relationship between important energy and economic variables. The chapter Literature review lists and discusses publications about current scientific research in this area.

However, existing research is only based on data up to 2010. There are several reasons for a more up-to-date investigation: First, the financial crisis coincided with significant changes in the empirical picture. Second, the advent of shale gas may be a game changer, at least in the US. Thirdly, substantial reduction in cost has made renewables competitive in many parts of the world and has lead to an accelerated rollout, particularly since 2010. In the chapter Approach, we therefore introduce a methodology to analyze current data.

3.1 Literature review

There seems to be a wide consensus among scientists that energy consumption and economic growth have been closely linked in the past. In addition, some authors claim that economic growth follows an inverted U-shape, when compared to energy intensity (i.e. energy consumption divided by economic activity, usually GDP) over time (Goldenberg and Reddy (1990): Energy for the developing world, *Scientific American*). Other authors question this claim, and point out that some traditional energy consumption is missing from the data (Gales et al. 2007). Furthermore, when energy consumption is compared with income data, various studies find that the energy intensity increases, decreases or exhibits an inverted U-shape with growing income, as summarized in Csereklyei et al. (2014).

The question of a possible causal relationship between different energy carriers and national GDP has lead to heated debate in a growing body of literature. The following hypotheses have been put forward (see Payne 2009; Tugcu 2012):

- growth hypothesis, suggesting a positive uni-directional causality between energy consumption to economic growth;

- conservation hypothesis, claiming a uni-directional causality between economic growth to energy consumption;

- feedback hypothesis, arguing for a bi-directional causality between economic growth and energy consumption;

- neutrality hypothesis, proposing that there is no causal relationship between economic growth and energy consumption.

The literature can be divided further by the energy aggregates used for the respective analyses; growth is compared to varying aggregates of energy, from total energy – including traditional forms of energy (Gales et al. 2007; Kander and Stern 2014) – to renewable energy consumption only. We refer to the meta-analysis by Bruns et al. (2014) that treats the connection between energy use and economic output in more general terms. The literature is inconclusive on whether there is any causality (Bruns et al. 2014), a result confirmed by the literature overview provided in Belke et al. (2011). However, one notable finding is that there is a causality between GDP and energy usage – if energy prices are controlled for. This supports the conservation hypothesis.

If one distinguishes between different energy carriers the results remain ambiguous. Our literature review does not offer any clear conclusions on whether there is a causal relationship between the output of renewable energy and production **(see Table 1)**. This conclusion is also supported by the meta-study carried out by Sebri and Salha (2014).

The econometric estimations depend on the applied estimation technique (referred to as methodology in **Table 1**), the country or country group under investigation, the time period and the actual model specification. Sadorsky (2009 a,b) uses oil prices and emissions as control variables. He finds evidence for the conservation hypothesis for both the G7 countries and a set of 18 emerging countries. Apergis and Payne (2010a) apply a model with capital, labor and renewable electricity as controls and find evidence favoring the feedback relation for 17 Eurasian countries. Using the same framework, they arrive at this result for 20 OECD countries (Apergis and Payne 2010b). In a similar model including non-renewable energy consumption, the authors find more evidence for the feedback hypothesis in a sample of 80 countries (Apergis and Payne 2012). However, for a study on the US, Payne (2011) further disaggregates renewable energy consumption and finds a causal relationship between biomass consumption and GDP growth, which is interpreted as support for the growth hypothesis. More recently, Inglesi-Lotz (2015) incorporated R&D expenditures into a framework closely related to the paper by Apergis and Payne (2012), and found a significant contribution of renewable energy consumption to economic growth. These findings are in contrast to Menegaki (2011), who uses a random effects framework with renewable energy consumption, final energy consumption, greenhouse gas emissions and employment. Menegaki finds evidence for the neutrality hypothesis for 27 countries of the European Union, recommends, however, to take this empirical evidence only as a basis for future analysis.

Tugcu and colleagues exemplify the variety of potential outcomes in energy consumption-growth research in a single paper: Using a classical production function in their auto-regressive distributed lag model, they generate evidence for the feedback hypothesis for all seven OECD countries under consideration (Tugcu et al. 2012). By contrast, evidence for conflicting hypotheses for different country groups are found when the estimated production function is augmented by human capital and R&D indices.

From the perspective of climate policy, the implications of each of the four hypotheses differ substantially. For instance, the growth hypothesis would imply that energy conservation is harmful for economic development, challenging its contribution to a sustainable climate policy. By contrast, evidence supporting the growth hypothesis underlines the potential of renewables to stimulate growth, as this would support economic growth while reducing carbon emissions at the same time.

Evidence for the growth hypothesis, that is, a nexus between renewable energy and GDP, supports growth policies based on renewables. Evidence for the conservation hypothesis would indicate that substitutability between conventional and renewable energy is necessary for a decoupling of growth from fossil fuels, otherwise, a policy of energy conservation would be indicated. If the neutrality hypothesis is correct, policies favoring energy conservation and renewable energies both present viable options, provided there is substitutability. If renewables do not replace conventional energies, neutrality would also emphasize a conservation policy.

In summary, the more up to date the research, the more support there is for the growth hypothesis, be it in relation with total, or conventional and renewable energy. Given the new dynamics of renewable energy, shale gas and energy savings that have come to the fore since the financial crisis, a more robust conclusion for the possible growth to energy nexus may be drawn based on more recent data. Moreover, there is no research known to the author that analyses the impact of energy efficiency policy. This study tries to fill these gaps.

Table 1 – Literature on the renewable energy growth nexus

<table>
<tr><th rowspan="2">Study</th><th rowspan="2">Methodology</th><th rowspan="2">Period</th><th rowspan="2">Country</th><th colspan="2">Confirmed hypothesis</th></tr>
<tr><th>Growth</th><th>Energy</th></tr>
<tr><td>Chien and Hu (2007)</td><td>Data envelopment analysis</td><td>2001-2002</td><td>45 economies</td><td colspan="2">←</td></tr>
<tr><td>Chien and Hu (2008)</td><td>Structural Equation Modeling</td><td>2003</td><td>116 economies</td><td colspan="2">←</td></tr>
<tr><td>Sadorsky (2009a)</td><td>Panel cointegration and Panel Causality Tests</td><td>1994-2003</td><td>G7 countries</td><td colspan="2">→</td></tr>
<tr><td>Sadorsky (2009b)</td><td>Panel cointegration and Panel Causality Tests</td><td>1994-2003</td><td>18 emerging countries</td><td colspan="2">→</td></tr>
<tr><td>Pao and Fu (2013)</td><td>Panel cointegration and Panel Causality Tests</td><td>1980-2009</td><td>Brazil</td><td colspan="2">↔</td></tr>
<tr><td>Apergis and Payne (2010a)</td><td>Panel cointegration and Panel Causality Tests</td><td>1992-2007</td><td>13 countries within Eurasia</td><td colspan="2">↔</td></tr>
<tr><td>Apergis and Payne (2010b)</td><td>Panel cointegration and Panel Causality Tests</td><td>1985-2005</td><td>20 OECD countries</td><td colspan="2">↔</td></tr>
<tr><td>Payne (2011)</td><td>Toda-Yamamoto procedure</td><td>1949-2007</td><td>US</td><td colspan="2">←</td></tr>
<tr><td>Apergis and Payne (2012)</td><td>Panel cointegration and Panel Causality Tests</td><td>1990-2007</td><td>80 countries</td><td colspan="2">↔</td></tr>
<tr><td>Menegaki (2011)</td><td>Random effect model, Panel Causality Tests</td><td>1997-2007</td><td>27 European countries</td><td colspan="2">0</td></tr>
<tr><td>Fang (2011)</td><td>OLS</td><td>1978-2008</td><td>China</td><td colspan="2">←</td></tr>
<tr><td>Tiwari (2011)</td><td>Structural VAR</td><td>1960-2009</td><td>India</td><td colspan="2">←</td></tr>
<tr><td rowspan="3">Tugcu et al. (2012)</td><td rowspan="3">Autoregressive Distributed Lag (ARDL); augmented production function</td><td rowspan="3">1980-2009</td><td>France, Italy, Canada, USA</td><td colspan="2">0</td></tr>
<tr><td>England, Japan</td><td colspan="2">↔</td></tr>
<tr><td>Germany</td><td colspan="2">→</td></tr>
<tr><td>Sebri and Salha (2014)</td><td>Autogressive Distributed Lag (ARDL); VECM</td><td>1971-2010</td><td>BRICS</td><td colspan="2">↔</td></tr>
<tr><td>Inglesi-Lotz (2015)</td><td>Panel cointegration</td><td>1990-2010</td><td>34 OECD countries</td><td colspan="2">←</td></tr>
</table>

Source: DIW Econ

3.2 Approach

For the investigation of hypothesis 1, which states that renewable energy is a substitute for conventional energy *and* has a positive effect on economic growth, we assess both energy carriers and economic output. Hypothesis 2, which postulates a reduction of energy intensity through greater energy efficiency, requires an assessment of the evidence in a restricted set of countries with ambitious energy efficiency policies.

Following the recent literature (Sadorsky 2009a, 2009b; Apergis and Payne 2012) this study uses panel co-integration techniques to infer causal relationship between GDP and primary energy consumption divided into renewable and a non-renewable energy consumption. The box "Methodology" summarizes the empirical procedure. Regarding **hypothesis 1**, we find that co-integration of the full panel data is acceptable[4] and causality therefore assessable. To generate results regarding **hypothesis 2**, we turn to restricted data sets and their co-integration properties.

We selected a group of countries on the basis of the IEA energy efficiency policy database[5] and an assessment of the American Council for an Energy Efficient Economy.[6] The countries with the most ambitious energy efficiency policies are Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Japan, Portugal, Sweden and the United Kingdom. We find that for this country group co-integration cannot be rejected.[7]

In addition, we tried to address the influence of the financial crisis. Therefore, we tested co-integration properties of the full panel over different periods. Co-integration was not found in the period after the crisis.[8] However, co-integration cannot be rejected for the time between 1990 and 2008, which is therefore used as our pre-crisis panel. Changes in the results for the whole period compared to the pre-crisis subsample may highlight possible changes induced by the financial crisis.

Methodology

To infer properties of causal relationships between energy and economic activity most recent literature (Sadorsky 2009a; Apergis and Payne 2012) apply techniques developed by Engel and Granger (1987), and Pedroni (2001). We closely follow this literature but adopt a homogeneous production structure across countries, as in Belke et al. (2011).

After the data is transformed into stationary variables by the use of first differences, the procedure is based on three steps:

1 Test for co-integration;
2 Estimating the co-integrating relationship;
3 Estimating the error correction model.

The first step applies the tests for co-integration developed by Pedroni. Since co-integration is a prerequisite for the inference of causal relations, data sets for which co-integration cannot be rejected are needed. We find three panels with this property.

4 See Table 2 in the appendix that provides the results of the panel co-integration tests.
5 See IEA's website: http://www.iea.org/policiesandmeasures/energyefficiency/
6 International Energy Efficiency Scorecard 2014.
7 See Table 2b of the Appendix.
8 This is probably owing to the limitation to a maximum of five years following the crisis, i.e., 2009 to 2014. Given the necessary lag of at least one year to detect short run relations, the core observations shrink to three years.

In the second step we postulate a long-run linear relationship between the natural logarithms of renewable energy consumption *(RE)*, GDP *(Y)* and conventional energy consumption *(CE)* for the countries i over periods t:

$$Y_{i,t} = \beta_{0,i} + \beta_1 CE_{i,t} + \beta_2 RE_{i,t} + u_{i,t} \tag{1}$$

with *u* denoting the residuals that indicate deviations from the long-run relationship.
The coefficients *ß1* and *ß2* are estimated with the dynamic OLS (DOLS) suggested by Pedroni and are interpreted as the long-run elasticities between GDP and the respective energy carriers *CE* and *RE*. Furthermore, the residuals provide the error terms used in step three.

Finally, step three estimates the error correction model, given the previously derived error terms. The estimated coefficients of the error correction terms derived from this model reflect short-run adjustments to the long-term equilibrium described in equation (1). They provide information on short-run elasticities between all variables, i.e., income, conventional energy and renewable energy.

3.3 Results[9]

This procedure has lead to mixed findings. One central result was that we found further evidence supporting the growth hypothesis and the substitutability of conventional sources by renewables – as described in the literature, e.g., in Apergis and Payne (2012). However, we had largely similar results for all three panels.

The coefficients found for the DOLS model provide long-run elasticities of GDP with respect to conventional and renewable energy.[10] Our results suggest that a one-percent increase of global renewable energy goes along with an about 0.1% increase of GDP. Regarding conventional energy, a one-percent increase results, in the long run, in a 0.8% increase of GDP.

In order to interpret the differences in these elasticity values it is furthermore necessary to compare the levels of both variables. In the full panel, the ratio of conventional and renewable energy has been 90% by 2014. In other words, a percentage increase of renewables in 2014 equals a 0.11 increase of conventional energy. Factoring in this ratio to the estimated elasticities yields a slightly higher renewable energy increase with income growth compared to conventional energy.

We confirm that conventional and renewable energy consumption growth is related to an increase in GDP in the long-run.

A unit of additional renewable energy has a 1.2 times larger effect on GDP when compared to a unit of conventional energy.

These values do not change substantially in the case of restricted panels.

The error correction models reveals the following about short-run elasticities and causality directions:[11]

First, both renewable energy and conventional energy have positive effects on growth and vice versa, that is, we find support for the feedback hypothesis. Second, we find negative elasticities of conventional energy with regard to renewable energy and vice versa, which suggests substitutability of both forms of energy. Combined, these findings support hypothesis 1, which states that renewables

9 The appendix provides the numerical results in regard to all three panels.
10 See table 3a) of the appendix.
11 Table 4 in the appendix summarizes short-run elasticities in the error correction model.

decrease the conventional energy intensity. This result is clearly in favor of a growth policy based on renewable energies, however this requires further confirmation – for the following reasons:

Methods to infer causal relationships in the short term often use several decades of data panels if only annual values are available. With the rapidly changing cost of alternative energy, the growth stimulus may increase over time. Therefore, a new type of energy model may take specific account of the fast-growing electricity sector where data of higher frequency is available that could account for the rapidly changing cost. Studies of the electricity sector are, however, confined to this type of energy, while energy efficiency and storage opens up new possibilities in the heating and transport sectors. Comprehensive energy models that treat electricity separately may thus lead to new results.

Energy investments require time and significant financial means to reshape the energy capital stock of an industrialized country. Typically the capital cycle of a large conventional power plant is between 30 and 50 years. Rapidly emerging countries with dynamic investments like China and India have the opportunity to reshape their energy capital stock in shorter periods. Reshaping the energy sector with renewables requires a particularly high investment per annually delivered energy. The most successful energy sources, solar and wind power, as well as mature hydro power have negligible variable costs of about 1 to 2 percent of unit costs. Therefore, positive effects last for a long time (at least 20 years) and can probably only be fully assessed over long periods of time.

4. Conclusion

We observe a global trend of weak decoupling of conventional energy from growth (measured as reduced conventional energy intensity) over the last five years. A global strong decoupling from energy-related emissions seems viable.

Strong decoupling over the last decade with a reduction of total energy consumption and emissions despite economic growth is observed for the OECD countries.

Since 2004, solar and wind are the fastest growing energy sources worldwide, and they saw substantially accelerated growth over the last four years.

Germany, thanks to a substantial hike in energy efficiency over the last decade, exemplifies strong decoupling of energy and emissions. The rollout of renewables has more than compensated for the nuclear-phase out and the slight rise in coal usage after the financial crisis.

In the US, absolute energy consumption has been growing lately, and shale gas usage and renewable energy may suffice only for a weak decoupling of emissions from growth. On a ten-year basis, total energy slightly decreased despite only moderate energy savings.

China is on a weak decoupling course with decreasing energy requirements and emissions per additional GDP. Strong decoupling seems possible in the near future.

In India, renewable energies are challenged by investment in conventional emission-intensive types of energy generation.

China and India are particularly important for worldwide trends due to their high growth rates.

An empirical causality analysis of panel data including the years 1990 to 2014 reveals bi-directional impacts between renewables, conventional energy and GDP, indicating a feed-back relationship. Substitutability of conventional energy by renewable energy together with growth effects of renewables gives support for a viable decoupling policy.

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6. Appendix

Table 2 – Panel cointegration tests

2a) Full panel

Test Stats.	Panel	Group
v	11.13	-
rho	0.334	2.06
t	-3.918	-3.607
adf	-3.955	-3.731

2b) Front runner panel

Test Stats.	Panel	Group
v	7.57	.
rho	-0.433	0.675
t	-3.199	-3.039
adf	-3.375	-2.269

2c) Pre-crisis panel

Test Stats.	Panel	Group
v	5.93	.
rho	3.023	4.508
t	-1.327	-1.648
adf	4.963	2.574

Source: DIW Econ

Table 3 – Results for the long run elasticities

3a) Full panel

	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]
ln RE	0.0995132	0.021948	4.53	0.000	0.0564959
ln CE	0.8077371	0.0634394	12.73	0.000	0.6833982

3b) Front runner panel

.	Coef.	Std. Err.	z	P>|z|	[95% Conf. Interval]
ln RE	0.1099645	0.0332956	3.3	0.001	0.044706
ln CE	0.8491724	0.1297724	6.54	0.000	0.594823

3c) Pre-crisis panel

Test Stats.	Coef.	Std. Err.	z	P>|z |	[95% Conf. Interval]
In RE	0.0860277	0.030739	2.8	0.005	0.02578
In CE	0.819231	0.0755598	10.84	0.000	0.671137

Source: DIW Econ

Table 4 – Results for short run elasticities (two lags and two leads)

		Independent variable		
	Dependent variable	△Y	△CE	△RE
Full Panel	△Y	–	0.229 (0.000)	0.016 (0.060)
	△CE	0.829 (0.000)	–	-0.056 (0.001)
	△RE	0.968 (0.013)	-0.919 (0.001)	–
Front runner	△Y	–	0.250 (0.000)	0.029 (0.000)
	△CE	0.965 (0.000)	–	-0.114 (0.000)
	△RE	1.545 (0.011)	-1.558 (0.007)	–
Pre-crisis	△Y	–	0.185 (0.008)	0.016 (0.090)
	△CE	0.718 (0.000)	–	-0.059 (0.005)
	△RE	1.105 (0.045)	-1.038 (0.004)	

Source: DIW Econ