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Neither euphoria nor despair: Understanding the fall and rise of global energy-related CO_2 emissions

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After stagnation or modest decline in the previous three years, global energy-related CO_2 emissions grew again in 2017 and 2018. Several factors drove this hiatus in global emissions growth. The global economy was weak in the period 2014-16, and then recovered in 2017-18, particularly in manufacturing but also consumer spending, thus driving higher energy demand, while the rate of improvement in global energy intensity slowed. In the face of increased energy demand, the continued but modest expansion of low- and zero-carbon energy supply was revealed as fundamentally inadequate. Increased fossil fuel supply filled the gap.

This Study examines the drivers of both the previous decline in global energy-related CO_2 emissions, and their subsequent growth in recent years (in the EU, US, India and China), and argues that this trend was in neither case a good indicator of climate policy effort or effectiveness. Global emissions are merely the outcome of the complex relationships between economic activity and energy demand, energy demand and energy supply, and energy supply and energy-related emissions. Climate policy must influence these relationships.

KEY MESSAGES

Short-term fluctuations in global emissions do not necessarily signal that a fundamental transition is underway. Looking in-depth at the underlying economic and energy system drivers of emissions can reveal more durable emissions trends. There is an urgent need for a systematic, annual analysis of the pace and direction of the global energy transition, which goes beyond headline emissions to analyse the underlying drivers across technology, investment, innovation, the economy, and global markets.

The global energy transition is: (1) slow: even in sectors where a transition is occurring, such as electricity generation, this transition is occurring too slowly compared to what needs to be done to limit warming to less than 2°C; (2) superficial: much of the observed emissions mitigation is being driven by measures that will only serve to reduce emissions in the short term (such as coal to gas switching), and not the fundamental and profound transition required for a zero-carbon global energy system by 2050; (3) scattered: changes are so far largely limited to electricity generation; major sectors such as transport and industry are not as yet undergoing any discernible transition away from fossil fuels.

Absent stronger policy, the global energy transition will remain inadequate to meet the 2 degrees objective, despite the spectacular increase in the competitiveness of certain low-carbon technologies. Without policy, rapid bifurcations in the pathway of the global energy system are unlikely, given the system's size, complexity and path dependency. Enhanced climate action commitments (NDCs) in 2020 need to be not just more stringent, but also smarter and in line with long-term decarbonisation strategies. They need to kickstart decarbonisation of end-use sectors, reboot energy efficiency policies, and open up new options, by devoting resources to research and deployment.

STUDY

N°04
September
2019

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EXECUTIVE SUMMARY

Global energy-related CO_2 emissions increased in 2017 and 2018, after a period of stabilisation or modest decline in the preceding three years. This drew much commentary regarding the causes of this return to emissions growth, and its implications for judgements on the strength and effectiveness of climate policies. This paper examines the drivers of both the previous decline in global energy-related CO_2 emissions, and their subsequent growth in recent years. It comes up with the following three messages.

Short-term fluctuations in emissions are not a good indicator of climate policy strength nor effectiveness

The study shows that much of the decline of global energy-related CO_2 emissions in the period 2014-16 must be attributed to adverse or sluggish economic conditions, particularly in the Chinese industrial sector but also more broadly at the global level. There is substantial evidence that the rate of Chinese economic growth was lower than officially reported in the period 2014-16, and this biased upwards estimates of the rate of global energy intensity improvement. We estimate that in these years the rate of global energy intensity improvement may have been inflated by as much as a 30%, if we accept the hypothesis that Chinese GDP growth was not as fast as reported.

Thus, global energy demand growth was low in the period 2013-16, driven by *apparently* rapid improvements in the energy intensity of global economic activity. In turn, the growth of low-carbon energy was substantial relative to more sluggish energy demand growth. Global economic conditions improved in 2017 and 2018, driving a return to more rapid energy consumption growth. In the face of this energy demand growth, the underlying inadequacy in the rate of expansion of zero-carbon energy was revealed.

Moreover, the study shows that much of the emissions abatement achieved in the period 2013-18 was due to improvements in the carbon-intensity of the fossil fuel mix. For example, in the electricity sector we estimate that a reduction in the carbon intensity of the fossil-based generation mix in the four geographies studied provided 753 $MtCO_2$ of emissions abatement, substantially more than the emissions abatement provided by the increase in the share of zero-carbon generation in total generation (590 Mt of CO_2 emissions abatement). Cleaner fossil-based electricity is welcome in the short term, but it cannot be the basis for the complete decarbonisation of electricity production, as required by scenarios to limit warming to less than 2°C.

Thus, short-term fluctuations in global emissions can be misleading: they do not necessarily signal that a fundamental transition away from fossil fuels is underway. Looking in-depth at the underlying economic and energy system drivers of emissions can reveal more durable emissions trends. There is an urgent need for a systematic, annual analysis of the pace and direction of the global energy transition, which goes beyond headline emissions to analyse the underlying drivers across technology, the economy and global markets. The transparency regime and Global Stocktake under the Paris Agreement can provide one aspect of this assessment. But these tools are too dependent on data given by countries, and probably lacking in the political willingness and technical capacity to analyse the underlying drivers of emissions trends.

The Paris Agreement transparency regime thus needs to be supplemented by more frequent, in-depth analysis by either other international organisations or academia and civil society. Otherwise, we risk gravely misleading ourselves by reading too much into annual fluctuations of emissions. Global emissions are merely the outcome of the complex relationships between economic activity and energy demand, energy demand and energy supply, and energy supply and energy-related emissions. Climate policy must influence these relationships, and hence efforts at climate policy transparency must go deeper to analyse them, and not focus on the superficial level of emissions.

The global energy transition is as yet barely emerging

A detailed examination of these underlying economic and energy system drivers of emissions reveals unambiguously: the global energy transition is as yet barely emerging. It can be characterised as 'slow, superficial and scattered':

— *Slow*: Even in sectors where a transition is occurring, such as electricity generation, this transition is occurring too slowly compared to what needs to be done to limit warming to less than 2°C
— *Superficial*: much of the observed emissions mitigation is being driven by measures that will only serve to reduce emissions in the short term (such as coal to gas switching), and not the fundamental and profound transition required for a zero-carbon global energy system by 2050.
— *Scattered*: changes are so far largely limited to electricity generation; major sectors such as transport and industry are not as yet undergoing any discernible transition away from fossil fuels.

Firstly, energy efficiency policies are too weak to drive the necessary 3% annual improvement in global energy intensity. In 2014-16 the global rate of energy intensity improvement was about 2.3%, if official GDP statistics are assumed for China. Using alternative GDP estimates for China the global rate of energy intensity would have been about 0.4 percentage points lower. Thus, it seems that the 2017 and 2018 rate of energy intensity improvement of 1.4% per year is a better reflection of the actual, underlying rate of global energy intensity improvement, which has averaged only about 1.6% per year since 1980. The acceleration in energy intensity improvement in 2015 and 2016 was thus a statistical aberration, not a trend. More rapid energy demand growth compounds the challenge of satisfying energy demand with zero-carbon supply.

Secondly, the decarbonisation of energy supply is occurring too slowly. Granted, the decarbonisation of electricity supply on a per unit basis is occurring in all major geographies studied. But it is occurring too slowly to keep pace with electricity demand growth in emerging countries, and thus electricity sector total emissions continue to rise. Renewables are increasing their share in power generation in all major geographies, but from a low level and too slowly.

Thirdly, the decarbonisation of energy consumption in end-use sectors—buildings, transport and industry—has barely been initiated. These sectors are showing, in all geographies studied, rates of energy consumption decarbonisation at around -1% per year or less. This is no faster than the background rate of energy consumption decarbonisation over the last forty years, which has ranged from -0.12% per year in transport to -1.16% per year in the buildings sector, globally. Thus, the observed rates of energy consumption decarbonisation are firmly in line with historical experience, and do not yet show evidence of the required acceleration.

Looking back is looking forward

This study is based solely on historical data, albeit quite up-to-date. To what extent therefore can concerns about future trajectories be justified solely on historical analysis? A good example of this question would be the decarbonisation of transport, where historical analysis shows essentially no progress, while future projections now hold out the prospect of rapid global penetrations of electric vehicles. However, the global energy system is huge, characterised by vast stocks of often long-lived assets. Changing the global energy system, therefore, will be constrained by the rate of turnover of these assets. Of course, policy can, and arguably should, accelerate this turnover to a degree, but this may come at the cost of asset stranding or asset impairment. Thus, rapid bifurcations in the pathway of the global energy system, absent much more robust policy, are unlikely, given the system's size, complexity and path dependency. Certainly, a study of the drivers of the global energy transition could incorporate more forward-looking indicators, such as physical asset lock-in, stranding or accelerated retirement; investments and project pipelines; and indicators of research, innovation and technology learning. But this point does not by any means invalidate the main conclusions of this study, namely that the global energy transition is currently too slow, superficial and scattered to limit warming to less than 2°C, let alone 1.5°C. Much more needs to be done.

1. INTRODUCTION

Between 2013 and 2016, global energy-related CO_2 emissions were essentially constant or slightly declining. This was greeted with a lot of enthusiasm, as a sign that global efforts to control climate change were bearing fruit.[1] Then, in 2017 and 2018 energy-related CO_2 emissions rose sharply, reaching an all-time record high of 32.8 billion tons (Gt). In turn, this was greeted with despair as a sign that climate policies were failing.

But are these vacillations between 'euphoria and despair' justified? We suggest that both interpretations were incorrect. We argue in this paper that the decline and then rise of global emissions was in neither case a good indicator of climate policy effort or effectiveness. The fall then rise of emissions did not signal a fundamental shift in the relationship between global economic activity and energy consumption, nor global energy supply and CO_2 emissions. Rather, those relationships remain largely as they have for decades; and where they are changing, they are changing only slowly. In simple terms: the global energy transition is barely emerging.

This raises the question: what has caused the stagnation and then rebound of global emissions? What is actually happening on the energy transition? These are the questions we aim to address in this paper.

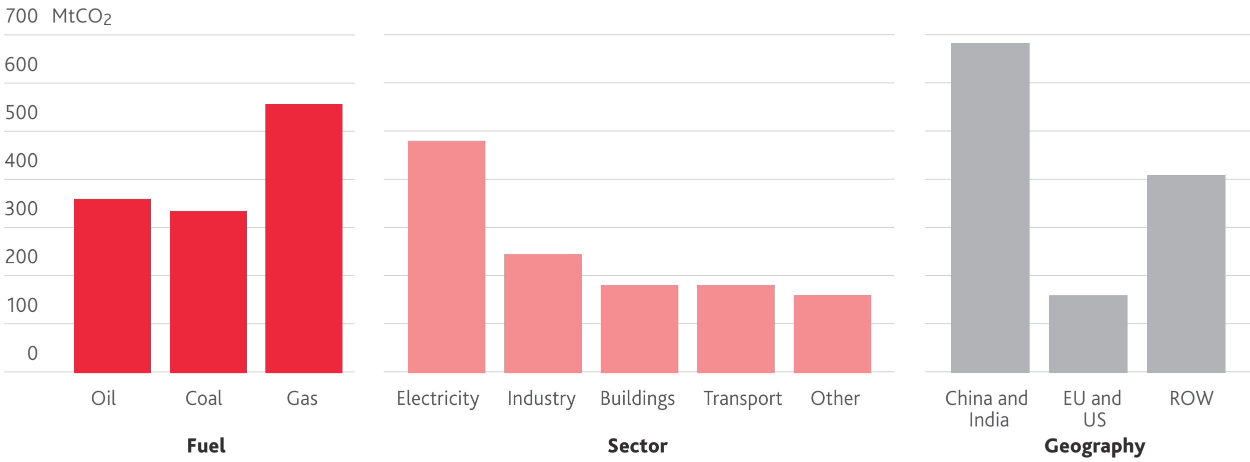
Figure 1 shows the incremental energy-related CO_2 emissions from 2016 to 2018, in million tons (Mt) of additional emissions from the 2016 level. It attributes these incremental emissions in three different ways: by fuel, by sector, and by geography. **Fundamentally, Figure 1 shows that rising emissions is not just a problem of one fuel, one sector or one geography.**

- *Fuel*: natural gas was the largest source of emissions growth (44% of the observed emissions growth), followed by oil (29%). Coal, traditionally the largest driver of global emissions increases, was third (27%).
- *Sector*: electricity production was the largest contributor to incremental emissions in the period 2016 to 2018 with a share of 20%, followed by the consumption sectors industry, buildings, and transport with relatively similar contributions (20%, 14%, and 14% respectively). Other sectors, including agriculture, non-electricity energy transformations, and non-energy uses also contributed significantly (13%).
- *Geography*: the two large emerging countries, China and India, contributed the largest share of incremental emissions (54%). But the largest developed and high-emitting economies, the United States (US) and the European Union (EU), still contributed 13% to the growth of emissions. The rest of the world contributed 33%.

In the sections that follow, we analyse what has driven the increase in energy-related CO_2 emissions since 2016. To do so, we also need to examine what had driven their stagnation or decline in the years 2014-16. First, we look at energy demand, then at electricity production, and finally at the decarbonisation of end-use sectors, namely industry, buildings and transport. In this regard, we follow the three pillars of the energy transition: improving energy efficiency; decarbonising energy supply, in particular electricity; and decarbonising end-use sectors through the transition to zero-carbon fuels (Bataille *et al.*, 2016). In terms of geographical focus, this study focuses on the two largest developed country jurisdictions, the EU and US, and the two largest emerging countries, India and China.

1 See e.g. https://www.iea.org/newsroom/news/2017/march/iea-finds-co2-emissions-flat-for-third-straight-year-even-as-global-economy-grew.html

FIGURE 1. Fuel, sector and geography of global emissions growth, 2016-18



Notes: Electricity includes heat production. Other includes agriculture and non-electricity transformations and non-energy uses. EU = European Union with 28 members. US = United States. ROW = Rest of the World.

Source: Authors based on data from (Enerdata, 2019)

2 ENERGY DEMAND AND THE ECONOMY

Energy demand reduction and improved energy efficiency are crucial pillars of the energy transition. Minimising energy demand through efficiency measures reduces the amount of zero-carbon energy that needs to be supplied in order to decarbonize the energy system. In turn, this reduces the cost and enhances the feasibility of the energy transition. Most energy scenarios leading to a decarbonised energy system demonstrate very rapid rates of improvement in global energy intensity, at around 3% per year, leading to absolute declines in energy demand in developed economies and slower energy demand growth in developing and emerging countries. At the global level, scenarios consistent with limiting warming to less than 2°C typically demonstrate reductions in global energy demand of in the order of at least one third, relative to a baseline scenario (Clarke *et al.*, 2014). In this section, therefore, we analyse energy demand in our four regions of study over the period 2013-18.

2.1. Methodology

In this section we analyse the annual rate of final energy demand growth in two periods, namely 2013-16 and 2016-18. Final energy consumption refers to the energy consumption of the end-consumer, after any transformation processes required to transform energy into the desired form. For example, consider the following chain:

- Primary energy: this refers to the energy content of a given energy source at its first point of entry in the energy system, for example the energy content of a ton of coal.
- Energy transformation: this refers to the transformation of one energy source into another, for example the combustion of the aforementioned ton of coal in a coal-fired power plant to produce electricity. This transformation is often associated with considerable losses (60-70% in the case of coal-fired power).
- Final energy consumption: this refers to the final consumption of the energy source in question, for example the consumption by an industrial consumer of the electricity generated in the aforementioned transformation process.

Final energy consumption is thus the closest approximation of the actual energy demand of the economy, and provides the closest picture of how energy demand is actually evolving.

In the analysis of the following sections, we present data for six different indicators. In each case, the indicators presented represent the annual rate of change in the given period, i.e. 2013-16 and 2016-18. The indicators presented are as follows:

- *Total_FEC*: this represents total final energy consumption (FEC) of all fuels in all sectors.
- Coal_Final: this represents the total final consumption of coal in all end-use sectors. It thus excludes coal consumed in transformation sectors such as electricity (we deal with electricity generation in the following chapter). Final coal consumption largely refers to coal consumed in industry to generate high-grade process heat, although in some countries coal will also be used in the buildings sector for heating.
- Electricity_Final: this represents the total final consumption of electricity in all end-use sectors.
- Gas_Final: this refers to total final consumption of natural gas in all end-use sectors. As with coal above, energy transformation sectors are excluded. Final consumption of natural gas is more diversified than in the case of coal, and occurs in the buildings sector for heating and cooking, in industry, and to a lesser extent in the transportation sector.

- Oil_Final: this refers to total final consumption of all oil products in all end-use sectors, excluding energy transformation sectors. Final oil consumption typically occurs in the transport sector, and to a lesser extent in the buildings and industry sectors.
- Energy_Intensity: this represents the ratio of total final energy consumption over GDP, measured at constant purchasing power parities. This represents a broad measure of the improvement in the energy efficiency of the economy.

2.2. China and India

2.2.1. Results

China and India are two major emerging countries with still large unmet energy needs. Their energy demand can be expected to increase as their economies grow and the welfare of their citizens improves. However, in aggressive mitigation scenarios consistent with limiting warming to less than 2°C, the energy intensity of their economic growth needs to fall dramatically, by around 75% by 2050. This equates to an annual improvement of above 3% (Bataille *et al.*, 2016b). **Figure 2** shows the annual rate of energy demand increase in China and India, across two periods, namely 2013-16 and 2016-18.

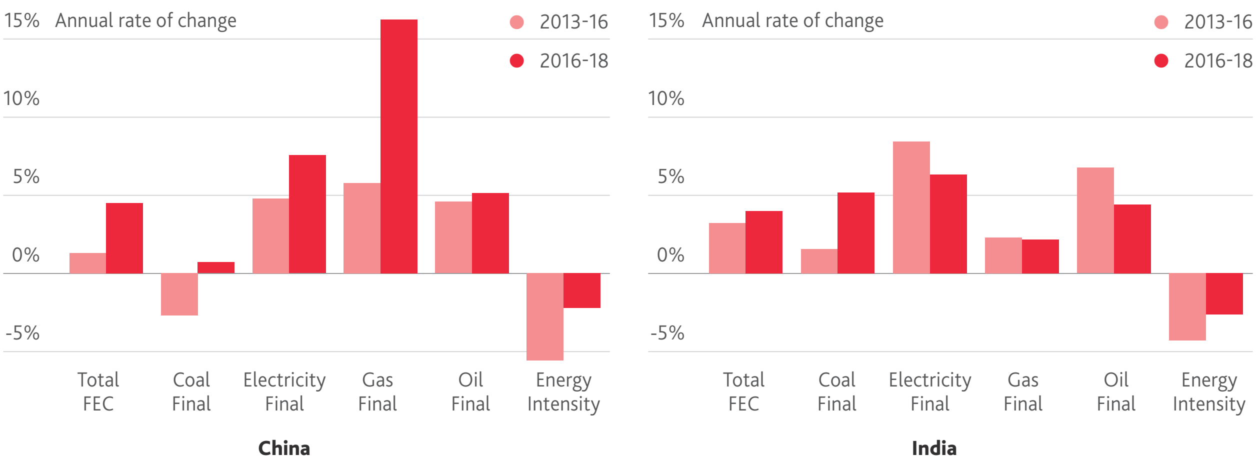
China's total final energy consumption displays a contrasting pattern in the two periods, with much slower growth in the period 2013-16 (1.3% per year) and significantly faster growth in the period 2016-18 (4.5% per year). In the case of final coal consumption, demand growth was even negative in the period 2013-16 before returning to positive growth in the period 2016-18. Given that the industry sector accounts for 81% of final coal consumption in China, the explanation for this trend must lie with phenomena occurring in the industry sector. Oil demand growth was relatively stable across the two periods. On the other hand, both electricity and natural gas demand growth accelerated significantly in the period 2016-18, compared to the previous period. In absolute terms, energy demand growth from oil and gas was significantly larger than from coal in the period 2016-18. Gas and oil added 93 million tons of oil equivalent (Mtoe) of incremental energy demand between 2016 and 2018, compared to only 12 Mtoe from final coal consumption. The improvement in the final energy intensity of the economy was much faster in the period 2013-16 at 5.6% yoy, compared to 2.2% in the period 2016-18.

The picture that thus emerges for China is one of more muted energy demand growth in the period 2016-18, led in particular by an absolute decline in final coal demand. This was followed by an acceleration of demand growth across all fuels, but particularly electricity and natural gas in the second period. We investigate the causes of this pattern in the following section.

India

India displays some interesting similarities but also contrasts in comparison with China. India's total final energy consumption growth was slightly faster in the period 2016-18, compared to 2013-16. Similar to China, India saw a similar pattern of subdued final coal consumption in the period 2013-16, followed by a recovery in the period 2016-18. As with China, final coal consumption in India is dominated by the industry sector (90%). Thus, the pattern of muted final coal demand growth in the period 2013-16, followed by an acceleration in the period 2016-18 must be accounted for by trends in the industry sector. In contrast to China, however, the growth rate of electricity and oil demand was higher in the first period, compared to the second. This being said, the growth rate of electricity and oil demand was still substantial in the period 2016-18, at 6.3% and 4.3% per year, similar to the growth rates seen in China for these fuels. India's final coal demand is significant enough that the rebound in its growth rate in the period 2016-18 was sufficient to raise the growth rate of total final energy consumption

FIGURE 2. Annual rate of final energy demand growth and energy intensity improvement, China and India, 2013-16 and 2016-18



Source: authors, based on data from (Enerdata, 2019).

in this period above the rate of the previous period. As with China, India saw a slowing of the rate of final energy intensity improvement, from 4.3% per year in 2013-16 to 2.2% per year in 2016-18.

2.2.2. Interpretation

In this section, we study the drivers of the trends observed above. To do so, we show the sectoral contributions to the growth of total final energy consumption and consumption of different fuels.

India

Table 1 shows the growth of final energy consumption by sector and fuel for India for the period 2016-18. Growth was relatively evenly spread between the sectors, with industry accounting for the largest share of growth (38%). Within industry, coal accounted for the largest share of incremental energy demand growth. What was happening in India's industry sector in this period? The growth rate of the Index of Core Industries was relatively constant across the two periods analysed in this paper, although it did accelerate somewhat in the latter period (from 3.5 to 3.9%). However, the recovery in the growth rate of steel and cement was much more marked, increasing by 0.6 and 6.7 percentage points for steel and cement respectively from 2013-16 to 2016-18 (DPII, 2019). Hence, we can ascribe the turnaround in final coal consumption seen in Figure 2 to a cyclical recovery in these coal-intensive sectors. Figure 2 also showed that the growth rates of other fuels, namely natural gas, electricity and oil, slowed in the second period analysed. In the case of oil, the rising global oil price and the depreciation of the rupee provide an adequate explanation. In the case of electricity, consumption continued to grow albeit at a slower rate in the second period, compared to the first. Private final consumption expenditure appears to have accelerated a bit in the period 2016-18, so slowing private consumption expenditure does not seem to provide an explanation for this slowdown in electricity consumption growth.

Thus, the overall picture that emerges is one of continued growth in buildings and transport energy consumption, led by oil in transport and electricity in buildings. This is consistent with India's circumstances as a still poor developing country with large unmet energy needs. The jump in the growth rate of industry energy consumption appears driven by a cyclical recovery in large, coal-intensive sectors like steel and cement.

Table 2 displays the same indicators for the case of China. It can be seen that the industry sector accounted for some 42% of total incremental final energy consumption, with all fuels contributing to this growth. The largest contributions, however, were from electricity and then natural gas. The buildings sector accounted for 32%, in the form of gas and electricity. As a middle-income country China's building sector energy consumption is expected to increase, particularly of electricity. In addition, gas is the preferred fuel for replacing coal in residential heating, although the risks of lock-in into gas intensive infrastructure are high. Likewise, in a middle-income country we would expect transport energy consumption to rise, as indeed it did. Electricity and natural gas satisfied a fairly large share of this transport sector increase, testament to China's efforts to reduce the reliance on oil in the transport sector.

TABLE 1. Final energy consumption growth by fuel and sector, India, 2016-18

	Coal	Oil	Gas	Electricity	Total (Mtoe)	Total (%)
Total Growth in FEC, 2016-18 (Mtoe)	11.88	16.34	1.39	12.45	47.59	100%
Of Which, Industry	10.65	0.84	1.41	4.73	18.31	38%
Of Which, Buildings	0.76	2.85	0.06	5.49	13.92	29%
Of Which, Transport	0	11.23	0.07	-0.04	11.33	24%
Other, Including Non-Energy Uses	0.47	1.42	-0.15	2.27	4.03	8%

Source: authors, based on data from (Enerdata, 2019)

TABLE 2. Final energy consumption growth by fuel and sector, China, 2016-18

	Coal	Oil	Gas	Electricity	Total (Mtoe)	Total %
Total Growth in FEC, 2016-18 (Mtoe)	11.5	52.14	40.83	69.72	191.47	100%
Of Which, Industry	9.32	8.06	15.82	37.18	79.75	42%
Of Which, Buildings	0.96	6.28	15.39	30.88	60.32	32%
Of Which, Transport	0	20.92	5.98	1.53	28.65	15%
Other, Including Non-Energy Uses	1.22	16.88	3.64	0.13	22.75	12%

Source: authors, based on data from (Enerdata, 2019)

However, we are presented with a paradox in the case of the recovery of Chinese industrial energy consumption. Across the period 2013-18, the growth rate of industrial value added declined smoothly from 8% in 2013 to 5.8% in 2018 (World Bank, 2019). Thus, while the growth rate of industrial energy demand recovered from the first period to the second, the growth rate of industrial value added followed the opposite trend. Put simply, energy indicators for industrial energy demand and monetary indicators for industrial value added are telling us two different stories about the Chinese economy.

It is worth noting that there is a large amount of uncertainty regarding Chinese GDP statistics, particularly for the manufacturing sector. For example, Chen *et al.* (2019) find that Chinese GDP growth was likely to be overstated by as much as 2 percentage points in recent years due to inflation of the statistics for industrial value added and investment. Kerola's reconstruction of the Chinese GDP series and comparison with other survey-based indicators suggests that the "rate of real GDP growth declined in 2015-16, then picked up in 2017, only to decelerate again in 2018. Furthermore, the constructed growth rates seem to be below the recent official figures" (Kerola, 2018).

This is consistent with the picture seen in energy statistics of sluggish demand growth in the period 2013-16 followed by a recovery in the period 2016-18.

We can investigate this further by examining the historical relationships between industrial value added, industrial energy demand, and physical output of industrial goods. **Figure 3**, left panel shows the elasticity of industrial final energy consumption to industrial value added. Elasticity is a measure of the proportional change in one variable in response to another. In this instance, it shows how much industrial energy demand changes in response to a change in industrial value added. An elasticity of 1 implies that one extra unit of industrial value-added entails one extra unit of industrial energy demand. An elasticity less than one implies that one extra unit of industrial value-added entails proportionally less than one extra unit of industrial energy consumption. Across the period 2007-2011, the elasticity of industrial energy demand to industrial value added was fairly stable and less than one (around 0.6). This implies that industrial value added grew faster than industrial energy consumption, equating to rapid improvements in industrial energy intensity. However, we see a complete trend break after 2012, with the elasticity falling rapidly, and even becoming negative in 2014-16. This implies that an additional unit of industrial value-added entailed a reduction of industrial energy consumption, equating to extremely rapid improvements in industrial energy intensity. After 2016, the relationship between industrial value-added and industrial final energy demand recovered back to its historical level.

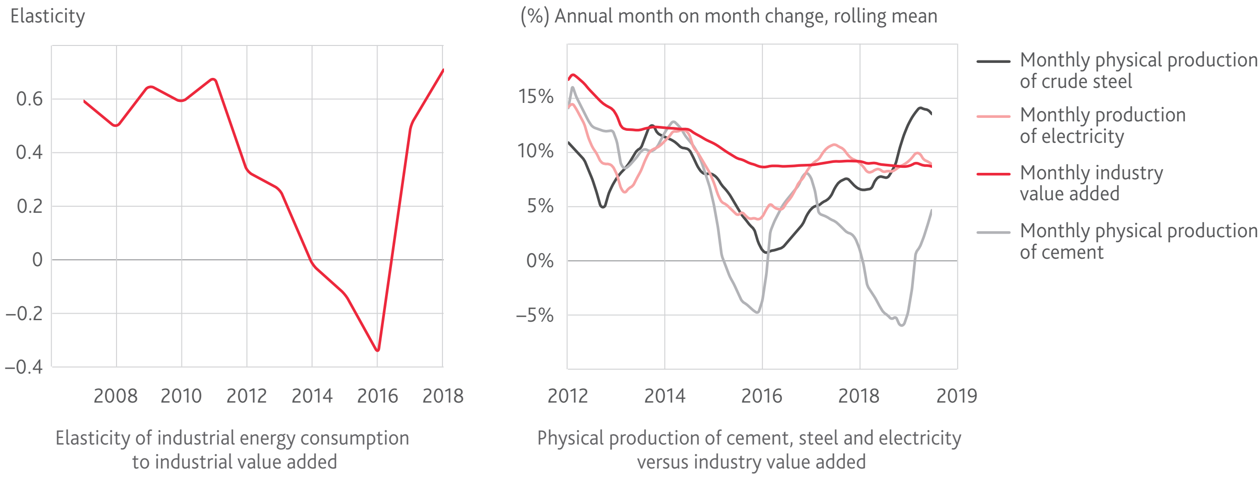
Figure 3, right panel shows the monthly annualised growth rates of the physical production of key heavy industry commodities, namely cement and crude steel, as well as electricity. It also shows the growth rate of industrial value added. Why should we expect these four indicators to be related?

— The industry sector is responsible for 62% of Chinese electricity consumption
— The basic metals and non-metallic minerals sectors account for 9% of total industrial value added and 14.6% of industrial intermediate consumption (i.e. inputs into other industrial production processes) (Timmer *et al.*, 2015). Within these sectors, iron and steel and cement would be the largest subsectors respectively.

Figure 3, right panel shows a large decoupling of all three physical indicators, namely cement, steel and electricity production, from industrial value-added in the period from mid-2014 to 2017. Indeed, production of both cement and steel was both negative, cement sharply so, for extended periods. Subsequent to this, the relationship between physical output and monetary output was re-established in the case of electricity and steel, although it continued to diverge in the case of cement. One can debate the reasons for this divergence between cement and steel. It may be due to the fact that much of the stimulus measures in 2017-18 have targeted real-estate construction, not infrastructure. For example, the 2019 IMF Article IV consultation report on the Chinese economy notes that the growth rate of infrastructure investment has become negative in 2018, while that of real-estate reached about 10% per year in the second half of 2017 and all of 2018 (IMF, 2019, p. 42). Real-estate is more steel intensive, and less cement intensive, and hence this may account for the divergent trajectories in the production of cement and steel.

This section has gathered three strands of evidence: one from academic reconstructions of Chinese GDP, one from comparisons of industrial monetary and energy data, and one from comparisons of industrial physical and monetary output. All of these strands of evidence are consistent with a theory of industrial slowdown in the period 2013-16, which was not reflected in monetary statistics.

FIGURE 3. **Industrial final energy consumption *versus* industrial value added (left panel), physical industrial production *versus* industrial value added (right panel)**



Source: authors, based on data from (Enerdata, 2019; National Bureau of Statistics China, 2019a; World Bank, 2019).

There remain two alternative hypotheses to refute, however. The first is that a change in the structure of industrial production could have occurred in the period of 2013-16, and then reversed in the period 2016-18. In simplistic terms, the value added of energy intensive industries could have declined, while that of high value added, low energy intensity industries could have risen. Theoretically, this could explain the pattern of stable aggregate industrial value added and declining industrial energy consumption. Even considered *a priori*, however, this hypothesis is fragile. China's industry sector is a 6.6 trillion USD behemoth. It is simply implausible that its structure of production could change within the space of a few years so significantly as to induce the decline in the elasticity of industrial energy demand to value added seen in **Figure 3**. It is even more implausible that this shift in the structure of production should reverse itself within the span of 2016-18, so as to induce the recovery in the energy demand to value added elasticity seen in **Figure 3**. Thus, even *a priori* this competing hypothesis can probably be rejected.

But we can also refute this empirically. In 2012, the share of energy intensive sectors in the sales value of industry was 25%. By 2016, it had fallen only 1 percentage point, to 24%. Meanwhile the share of knowledge intensive sectors grew from 17% to 20%. Within privately owned industry, the share of energy intensive sectors fell only 1 percentage point, while that of knowledge intensive sectors rose only 3 percentage points.[2] Thus we see a slow change in the structure of production consistent with China's climb up the industrial value chain. But the shift is surely too small and too slow to explain the trends shown in **Figure 3**.

The final hypothesis to reject is that China's energy intensity trajectory could have been influenced by global energy prices. This is also easy to do. Global energy prices and energy intensity are generally inversely related. High global energy prices induce faster declines in energy intensity, and vice versa. Global oil prices collapsed from above 100 USD/bbl in 2012 to 40 USD in 2016. This was exactly the time that China's energy intensity improvement was reported to be fastest. Likewise, global oil prices recovered in 2018 to 70 USD, exactly the period that China's energy intensity improvement was slowing down. In simple terms: this is exactly the opposite of the relationship we would expect to see. The trends in China's energy intensity therefore cannot be explained by global energy prices.

The weight of evidence is thus fairly incontrovertible: Chinese industrial value-added data appear overstated in the period 2013-2016. While industrial energy demand fell, industrial value added was reported to be growing rapidly. Given that industrial energy intensity is the ratio of the two, a falling numerator (industrial energy consumption) and a rapidly rising denominator (industrial value added) translated into extremely rapid declines in industrial energy intensity, reaching a peak of almost 6% per year in 2016. This in turn contributed to the rapid declines in total final energy intensity of the entire economy in the period 2013-16. But the evidence gathered here suggests that this rapid decline in energy intensity was actually due to the inflated industrial value added in the numerator. **China's rapid improvement in energy intensity in this period thus appears to be an artefact of inflated GDP data, and does not reflect the actual rate of improvement.**

2.2.3. How significant is China's rate of energy intensity improvement for the global level?

The above discussion is of more than academic interest. If the inflation of China's energy intensity improvement in the period 2013-16 is significant at the global level, it could seriously bias our understanding of how fast the global rate of energy intensity improvement was in this period. In this section we investigate this issue by building official and adjusted series for the rate of global and Chinese final energy intensity improvement in the period 2010 to 2018. To do so, we use two different GDP series as the denominator in the indicator of the final energy intensity of GDP. The first comes from GDP growth rates in the World Bank World Development Indicators, based on official sources (World Bank, 2019). The second comes from the adjusted Chinese GDP growth rate developed by the consultancy The Conference Board (The Conference Board, 2019a). The rationale and methodology for the adjusted series are described in The Conference Board (2015). Consistent with the discussion developed in section 2.2.2, the adjusted Chinese GDP growth rate diverges markedly from the official rate particularly in the period 2014-2017, when the average delta between the two series was about 2.7 percentage points (compare the findings of Chen *et al.* (2019) quoted above).

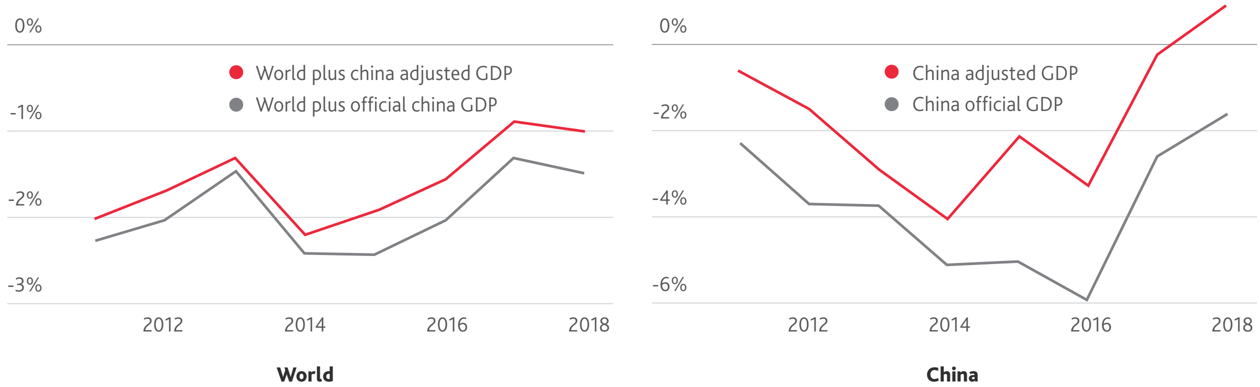
Figure 4 displaysdisplays the results of this analysis. The analysis suggests that with an adjusted world GDP series based on adjusted Chinese GDP growth rates, the global rate of energy intensity improvement would have been about 0.5 percentage points lower during the years 2014-16.

Across the period 2010-18 the average rate of energy intensity improvement in the adjusted GDP series is 1.6% per year, which is almost the same as the global long-term average for the period 1990-2010 (also 1.6% per year). By contrast, the average rate of energy intensity improvement in the official GDP series was 1.9% per year. During the years of stagnant global emissions, the global rate of energy intensity improvement was about 2.4% per year in the official GDP series, compared to about 1.9% in the adjusted GDP series.

The right panel of **Figure 4** shows China's rate of energy intensity improvement using the official and adjusted GDP series. In the years 2014-16, the adjusted GDP series yields a rate of energy intensity improvement that is almost 2.2 percentage points lower than the official GDP series. The adjusted series also suggests that the current rate of energy intensity improvement is even lower than in 2010-11, when China undertook a

2 Based on data from (National Bureau of Statistics China, 2019b). Energy intensive sectors are: pulp and paper, chemicals, non-metallic minerals, ferrous metals, and non-ferrous metals. Knowledge intensive sectors are: special purpose machinery, automobiles, transport equipment, electrical machinery, computers and other electronic equipment.

FIGURE 4. World and China final energy intensity improvement, official and adjusted China GDP



Source: authors, based on data from (Enerdata, 2019; The Conference Board, 2019b; World Bank, 2019).

tremendously resource and energy intensive stimulus program following the global financial crisis. The energy intensity data suggests that something similar occurred in 2018, albeit with still lower returns in terms of incremental GDP output. Indeed, the China adjusted GDP series suggests that energy intensity actually increased in 2018.

In summary: the hypothesised inflation in Chinese GDP was significant enough to substantially inflate the global rate of energy intensity improvement, because China is such a large part of the global economy. The real underlying rate was probably close to the long-term average of about 1.6% per year. This is half of the roughly 3% per year improvement required in global energy scenarios that limit warming to less than 2°C. The inflation in the global rate of energy intensity improvement thus biased our understanding on the progress being made in decoupling global energy consumption from global economic activity. However, it should be highlighted that the pattern of accelerating global energy intensity improvements in the period 2014-16 followed by a slowdown thereafter is present even after adjusting for Chinese GDP (see the series World Plus China Adjusted GDP in). This pattern must therefore be explained by factors outside of China. We thus turn to the major developed economies, the EU and the US.

2.3. The EU and the US

2.3.1. Results

As would be expected for developed, high energy consumption economies, rates of energy demand growth in the EU and US are significantly lower than in the emerging economies of China and India. However, the EU and the US still make up 27% of world total final energy consumption, compared to 29% for China and India. Thus, small changes in the growth rates of their energy demand have an appreciable impact on world energy demand growth. Moreover, most energy scenarios consistent with a less than 2°C warming would see absolute energy demand declining in developed economies such as the EU and US, as improved energy efficiency allows essentially saturated demand for energy services to be satisfied with a declining energy input. For example, in the Deep Decarbonization Pathways Project, absolute changes in final energy demand by 2050 ranged +4% for Canada to -30 to -50% for Japan and the EU countries studied, relative to the 2010 level (Bataille *et al.*, 2016a). Thus, even slow rates of energy demand growth from developed economies are a cause of concern, if we consider pathways consistent with limiting warming to less than 2°C.

Figure 5 displays the results for the EU and US. It shows the same indicators as Figure 2 for China and India.

The EU

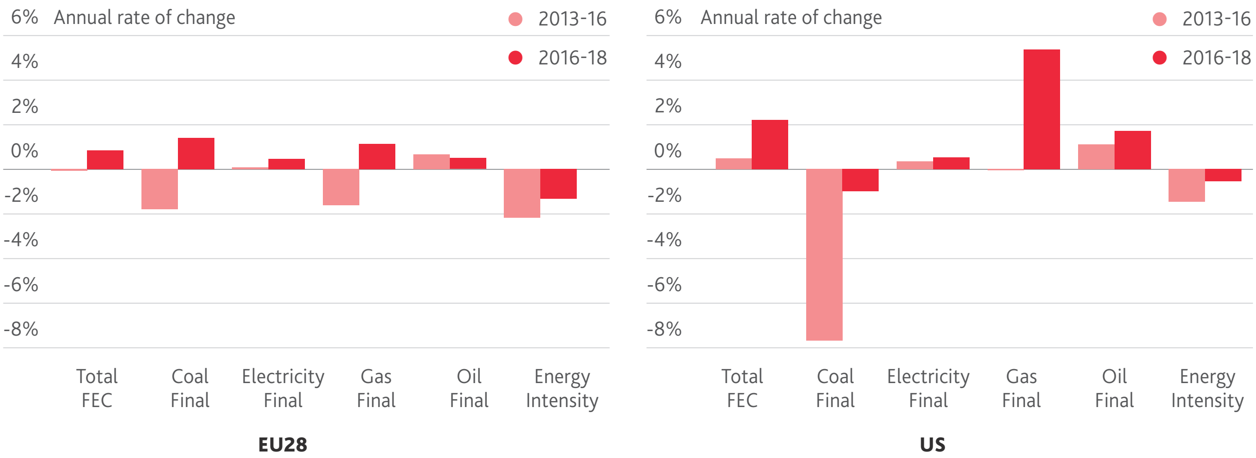
In the period 2013-16, the growth rate of total final energy consumption in the EU was negative, albeit very marginally so (at -0.09% per year). In the subsequent period 2016-18, this shifted to a positive but small growth rate (0.85% per year). Final coal consumption fell by -1.8% per year in the first period, but rebounded to grow at 1.4% per year in the second period. Electricity demand growth was positive but very small in both periods. Natural gas demand growth showed a similar pattern to coal rebounding from -1.6% per year growth in 2013-16, to 1.1% per year in 2016-18. Oil demand growth was positive but small in both periods, and unlike other fuels oil demand growth decelerated in the latter period compared to the former. Final energy intensity improvement was significantly faster in the first period, at 2.2% per year slowing to 1.3% per year in the second period.

Thus, although the growth rates are much lower, the EU also displayed a similar pattern to China and India, with muted demand growth in the first period and an acceleration of demand growth in the second period.

The US

In the US, total final energy consumption grew in both periods, although much more slowly in the first period (0.5% per year) compared to the second (2.2% per year). Final coal consumption collapsed in the first period, falling by -7.7% per

FIGURE 5. Annual rate of final energy demand growth and energy intensity improvement, EU and US, 2013-16 and 2016-18



Source: authors, based on data from (Enerdata, 2019).

year. In the second period, final coal consumption continued to decline, albeit more slowly. Electricity demand growth was positive but low in both periods. Natural gas displayed an exaggerated version of the trend observed more generally, shifting from a very small positive growth rate in the first period to grow at 5.1% per year in the second period. Oil demand growth was positive in both periods, and generally faster than in the case of other fuels (1.1% per year and 1.7% per year in the two periods respectively). The rate of improvement in US final energy intensity slowed from 1.5% per year in the first period to 0.5% per year in the second.

In summary, the picture seen in both the EU and US is one of an acceleration in energy demand growth and a decline of the rate of energy intensity improvement over the two periods studied.

2.3.2. Interpretation

In this section, we study the causes behind the trends observed in the section above. Let us start by analysing the sectoral contributions to final energy demand growth by fuel in the EU and US in the period 2016-18.

The EU

Table 3 displays final energy consumption growth by fuel and sector in the EU from 2016-18. Transport was responsible for about 48% of the total final energy consumption growth in this period. The period 2016-18 was one of economic recovery for the EU, after an extended period of recession and slow growth following the financial crisis. The rate of GDP per capita growth doubled in the period 2016-18, compared to 2013-16, from 1.1% per year to 2.2%. Household final consumption expenditure accelerated from 1.2% per year from to 2.0% per year in the two periods (World Bank, 2019). Meanwhile, although global oil prices rose somewhat, they remained well below the peaks of 110 USD/bbl seen in 2011 and 2012. Thus, we can see the recovery in EU transport energy demand as being driven by the improved economy combined with a still benign global fuel price environment.

Table 3 also shows that the industry sector was responsible for 33% of the growth of final energy consumption, which was split roughly two thirds natural gas and one third electricity. The growth rate of industrial value of industrial value added in the EU accelerated only marginally across the two periods (Eurostat, 2019), so the growth of industrial final energy consumption was thus driven by the continued recovery of the EU industry sector after 2013.

TABLE 3. Final energy consumption growth by fuel and sector, EU, 2016-18

	Coal	Oil	Gas	Electricity	Total (Mtoe)	Total (%)
Total Growth in FEC, 2016-18 (Mtoe)	1.52	4.66	5.65	2.2	19.68	100%
Of Which, Industry	1.04	-0.71	2.89	1.63	6.42	33%
Of Which, Buildings	0.29	-1.56	2.33	0.4	3.03	15%
Of Which, Transport	0	7.06	0.01	0.09	9.53	48%
Other, Including Non-Energy Uses	0.19	-0.13	0.42	0.08	0.7	4%

Source: authors, based on data from (Enerdata, 2019)

The US

Table 4 shows the sectoral contribution to final energy consumption growth in the US in the period 2016-18. Both transport and the industry sector contributed a similar amount to the observed growth. The cause of this increase in the transport sector is similar to the EU: recovery of income growth, benign global fuel prices, and in the case of the US far lower energy taxes and fuel efficiency standards. In the case of industry, there was a marked acceleration in the growth rate of industrial value added, from 1.1% per year in the period 2013-16 to 2.7% per year in the period 2016-18 (BEA, 2019). This drove the growth in industrial energy demand, which was satisfied by a combination of gas and to a much lesser extent oil. With the advent of cheap shale gas in the United States, there is evidence of a trend towards an increasing lock-in towards natural gas as the preferred fuel. Natural gas has increased its share in industrial final energy consumption from 40% in 2010 to 47% in 2018 (Enerdata, 2019). This is concerning given the need ultimately for full decarbonisation of the energy and industrial system by 2050 if warming is to be limited to less than 2°C. Oil and gas consumption in the Other, Including Non-Energy Uses Sector also contributed significantly to the rise in US final energy consumption.

However, the lion's share of consumption increase was driven by the buildings sector, most of which came in the form of natural gas but also a significant contribution from electricity. Although not visible in **Table 4**, most of the increase in both gas and electricity consumption in the buildings sector occurred in 2018. Some commentators have attributed the increase in natural gas to the extreme weather conditions seen in the United States in 2018 (IEA, 2019).

However, weather-related factors do not seem to be an adequate explanation for the increase in natural gas consumption in the residential and services sector, where natural gas would primarily be consumed for heating. The US Energy Information Agency (EIA) calculates population-weighted heating-degree-days in an annual series dating back to 1949. Heating-degree-days is a weather-related index that proxies heating demand. The higher the index value, the higher the heating demand. This series has seen a long-term declining trend, consistent with global warming.[3] 2018 was also below the long-term mean (by 10%).[4] But 2017 was the second lowest recorded value in the series and 2016 the third (20% and 19% below the long-term mean). Thus, the increase in natural gas consumption in the residential and services sector in 2018 relative to 2017 was driven by the base effect of the low level of 2017 and 2016 consumption. In fact, we see a modestly declining long-term trend of natural gas consumption in the residential sector, *a priori* consistent with the decreasing heating needs seen in the declining trend of heating degree days.

Regarding the growth of electricity consumption, a number of commentators have ascribed this to the exceptionally hot summer that occurred in 2018 (BP, 2019). Here again we can refer to the indices constructed by US EIA, this time for cooling-degree-days. 2018 has the highest number of cooling degree days ever, 36% above the long-term mean. However, it is worth noting that the second highest value on this index was 2016, 34% above the long-term mean. Yet 2016 saw muted growth of residential electricity demand. Air conditioner sales were also not exceptionally higher in 2018 than in previous years. Thus, the relationship between temperature and electricity demand requires further investigation. Certainly 2018 was quite exceptional in recent years and growth was overwhelmingly concentrated in the residential sector where short-term cyclicality should be more muted than in the industry sector. The EIA's US-wide cooling degree day index is based on a weighting of population according to location, and thus should reflect overall weather conditions as experienced by the US population as a whole. Investigating the relationship between temperature and electricity consumption would require more granular state-level analysis of electricity demand and cooling degree days than we can provide here.

TABLE 4. Final energy consumption growth by fuel and sector, US, 2016-18

	Coal	Oil	Gas	Electricity	Total (Mtoe)	Total (%)
Total Growth in FEC, 2016-18 (Mtoe)	-0.42	25.92	35.36	3.44	66.93	100%
Of Which, Industry	-0.33	1.89	9.93	-1.75	10.76	16%
Of Which, Buildings	-0.08	1.93	23.68	5.14	32.91	49%
Of Which, Transport	0	11.56	0.15	0.03	11.09	17%
Other, Including Non-Energy Uses	-0.01	10.54	1.6	0.02	12.17	18%

Source: authors, based on data from (Enerdata, 2019)

2.4. Conclusion

This chapter has examined energy demand in the China, India, the EU and US. Improved energy efficiency and reduced energy demand is a crucial pillar of energy sector decarbonisation, because it reduces the total amount of zero-carbon energy that needs to be supplied and hence lowers the costs and raises the feasibility of transition. From the analysis in this section, a number of key conclusions can be drawn:

— *We do not see any strong evidence of a decoupling of global economic activity and energy consumption*. In the cyclical global economic upswing that lasted from roughly 2017 to the last quarter of 2018, energy consumption followed. Energy intensity improvements slowed in all the countries studied, as manufacturing grew more strongly and consumers spent additional disposable income on energy services. Even in high energy consumption, developed economies like the EU and US, the we do not yet see a sustained and substantial absolute decoupling of economic activity from energy demand, leading to absolute declines in energy demand.

— *There is strong evidence that China's economy grew more slowly than officially reported in the period 2013-16 and this*

3 Given that the EIA's index is population weighted, some of this decline may also be due to the geographical shift of the US population towards the Southern 'Sunshine States'.

4 We take the long-term mean to be the mean of the entire series.

biased upwards the rate of global energy intensity improvement. The real underlying rate of energy intensity improvement was most likely much closer to the long-term trend of about 1.6% per year, about half of that required in scenarios consistent with limiting warming to less than 2°C.

— *The growth of natural gas in both China and the US risks locking in gas intensive infrastructure.* For different reasons, gas is becoming a preferred fuel in the US and Chinese industry and buildings sectors. While the substitution of coal for gas may make sense from a local air pollution perspective in China, it also risks locking in gas intensive infrastructure.

— *The growth rate of electricity demand in emerging countries poses a challenge to the decarbonisation of electricity supply.* In both China and India, electricity demand grew at or above 5% per year in both periods studied. This rapid rate of growth creates a challenge for the rate at which zero-carbon electricity supply must be expanded, if electricity sector emissions are to be controlled.

3 DECARBONISING ELECTRICITY PRODUCTION

The previous section studied energy demand. In this section, we turn to the decarbonisation of energy supply. The decarbonisation of energy supply essentially involves the transition to zero-carbon electricity, as well as the production of zero-carbon liquid and gaseous fuels, for example biofuels, hydrogen, ammonia or synthetic hydrocarbons. Energy transition scenarios show, however, that the decarbonisation of electricity supply is the most significant, cost effective, and feasible measure in the short-term. In a decarbonised energy system, zero-carbon electricity is the fuel of choice. Hence, the rapid decarbonisation of electricity is a crucial measure in itself to reduce emissions, but also to enable the reduction of emissions in other sectors, through the switch away from fossil fuels to zero-carbon electricity (for example, away from internal combustion engine vehicles to battery electric vehicles in transport). For this reason, in this section we focus on electricity.

3.1. Methodology

In this section we examine the decarbonisation of electricity production in the period 2013-2018. The methodology uses decomposition analysis to break down the observed annual change in emissions from the electricity sector into its constituent drivers, and ascribes to each of these drivers an absolute value in $MtCO_2$ (Ang, 2005). This value represents that driver's contribution to the observed change in electricity sector emissions, *in the absence of any other factor*. However, *the sum of all the contributions* from all drivers in the decomposition analysis equates to the actually observed changes in emissions from the electricity sector. For example, imagine a simple model in which the observed changes in electricity sector emissions was decomposed into only two drivers: economic growth and the emissions intensity of economic activity. Suppose that the total change in emissions between one year and the next was +70 $MtCO_2$, and according to the decomposition the contribution from economic growth was +100 Mt and the decline in the emissions intensity of economic activity contributed -30 $MtCO_2$. Here, the net contribution would be 100 – 30 = 70 $MtCO_2$ of emissions increase.

The terms of the decomposition are as follows:

— *Economic growth*: this measures the annual change in constant price GDP at purchasing power parity (USD2015 PPP).

— *Electricity intensity of GDP*: this measures the annual change in the ratio between total electricity generation and GDP (kWh/1000 USD2015 PPP)

— *Growth of the share of zero-carbon electricity*: this measures the annual change in the share of new renewables (wind, solar, biomass, and tidal) and other zero-carbon sources (nuclear and hydro) in total power generation (%). Although the terms of the equation do not allow us to distinguish between new renewables and other zero-carbon sources, we discuss their relative contributions in the text. Obviously, this indicator is inversely related to CO_2 emissions from the electricity sector, and an increase in the share of zero-carbon electricity generation in total generation appears as a negative contribution to emissions growth in the analysis below.

— *CO_2 intensity of fossil electricity supply*: this measures the annual change in the ratio between total emissions from the electricity sector and total fossil fuel-based electricity generation (gCO_2/kWh)

The graphs of this section are divided into two panels. The left-hand panels show the annual change in CO_2 emissions from the power sector attributed to each of the drivers described in the bullet points above. Positive values imply that the driver in question would have contributed to growth of emissions, *all other things being equal*, and vice versa for a negative value. The red line labelled 'Net Change' represents the sum of the contributions of each individual driver and equates to the observed annual change in total emissions from the electricity sector. The graphs present data for the years 2014-2018, with each timestamp representing the change on the previous year. The right panel of **Figure 6** represents the cumulative changes for each driver across the whole period 2013-18.

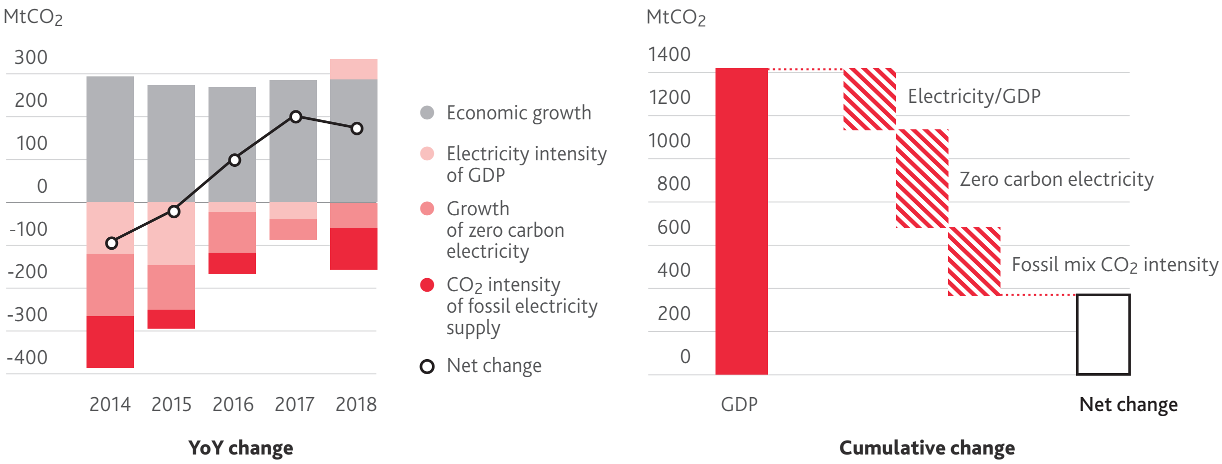
3.2. China and India

3.2.1. Results

China

Figure 6, left panel shows the results of the annual analysis for China. In each year, economic growth provided a large upwards impetus to electricity sector emissions. Improved electricity intensity of GDP helped to mitigate a portion of this, particularly in the early years of the analysis (2014, 2015). However, the mitigating contribution of improved electricity

FIGURE 6. China, change in electricity sector emissions by driver, 2013-18



Source: authors, based on data from (Enerdata, 2019)

intensity of GDP waned in the later years, and even turned to an upward contribution to emissions growth in 2018 (i.e. the electricity intensity of GDP increased in this year). This pattern is consistent with the analysis developed in section 2.2.2, of an unreported industrial slowdown in the period 2014-16, followed by an energy-intensive, stimulus-driven industrial recovery thereafter.

On the supply side, the growth of the share of zero-carbon sources in electricity production provided substantial mitigation of electricity sector emissions in every year, although the size of this mitigation faded in later years. This is because in the later period electricity demand growth was faster. Because of the faster demand growth, a roughly constant annual growth in zero-carbon electricity generation had a diminishing impact on raising the share of zero-carbon electricity in total generation.

In the early part of the period, a larger contribution to growing the share of zero-carbon electricity came from hydro and nuclear. However, the share of nuclear and hydro in electricity generation peaked in 2016 and declined marginally thereafter. Thus, the growth in the share of zero-carbon electricity generation after 2016 was due solely to the accelerating growth of the share new renewables, which nonetheless remained quite small in 2018 at 9.0% of generation, up from 3.8% in 2013. In most years, improvements in the carbon intensity of the fossil fuel generation mix made quite substantial contributions to mitigating emissions. This was due to a combination of the dispatch of more efficient coal-fired plants, the addition of new, efficient coal-fired plants, and the retirement of inefficient plants.

The net effect of these drivers resulted in falling emissions in the years 2014 and 2015, but rising emissions in all subsequent years.

Figure 6, right panel shows the cumulative contribution of these drivers. The largest mitigation of electricity sector emissions came from the growth in the share of zero-carbon electricity, followed by the improvement in the CO_2 intensity of the fossil fuel mix, and finally by the improvement in the electricity intensity of GDP. Overall, China saw a growth in electricity sector emissions of 368 Mt CO_2 across the period.

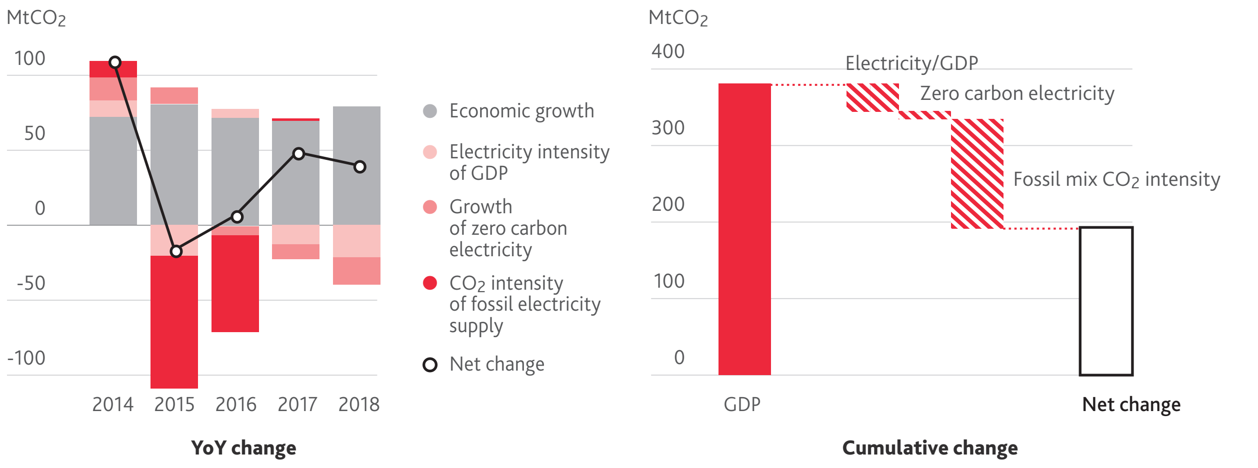
India

Figure 7 shows the results of the analysis for India. As with China, in each year economic growth provided a large upward contribution to emissions growth from the electricity sector. In comparison with China, however, improved electricity efficiency of GDP made a much smaller mitigating contribution to emissions growth from the power sector. Indeed, in 2014 and 2016 the electricity intensity of GDP increased, while it fell in the other years.

On the supply side, the growth in the share of zero-carbon sources in electricity generation contributed to mitigating electricity sector emissions in 2016, 2017, and 2018 (i.e. in these years the share of zero-carbon electricity in total generation increased). However, in 2014 and 2015 this driver provided an upward contribution to electricity sector emissions (i.e. the share of zero-carbon sources in total generation fell in these years). Why was this?

In 2014 and 2015, the share of zero-carbon sources declined due to the decline in the share of hydro and nuclear and sluggish growth in the share of new renewables. Nuclear and hydro declined solely due to declines in the output of hydro, with 2014 and 2015 being drought years. However, the long-term trend is for a declining share of power generation from hydro and nuclear, as capacity addition from these sources has not been sufficient to keep pace with electricity demand growth. In their place, coal-fired electricity increased its share in electricity generation, driving up CO_2 emissions. From 2016 onwards, however, new renewables increased their share in total generation. In the same period, the decline in the share of nuclear and hydro slowed, but did not halt. The net effect of this accelerating growth in the share of new renewables and slower decline in the share of nuclear and hydro was a marginal growth in the total share of zero-carbon sources from 2016 onwards.

FIGURE 7. India, change in electricity sector emissions by driver, 2013-18



Source: authors, based on data from (Enerdata, 2019).

Thus, this driver mitigated emissions growth in the years 2016, 2017 and 2018. By 2018, the share of new renewables in India was 9.3%, quite similar to that of China, and up from 5.1% in 2013.

As in China, substantial reductions in the CO_2 intensity of the fossil mix contributed to decreasing emissions growth in 2015 and 2016. The improvement in the CO_2 intensity of fossil electricity supply was due to overcapacity in the electricity sector, which allowed more efficient coal plants to be dispatched on a priority basis, as well as the substantial addition of new, more CO_2-efficient coal plants that occurred throughout the period 2010-15.

Figure 7, right panel shows the cumulative impact of these drivers across the period 2013-18. As can be seen, the improvement in the electricity intensity of GDP provided only limited mitigation of electricity sector emissions across the period. A country of India's very low level of development might expect electricity demand to grow as fast, or indeed faster than GDP, and thus for the electricity intensity of GDP to provide only a marginal mitigation of electricity sector emissions growth. On the supply side, the lion's share of emissions mitigation was provided by the improving CO_2 intensity of the fossil fuel mix. By comparison, the growth in the zero-carbon share of electricity provided only a small contribution to the mitigation of electricity sector emissions. The cumulative net effect of these drivers was emissions growth of 194 $MtCO_2$ across the period studied.

3.2.2. Interpretation

In both China and India, CO_2 emissions from the electricity sector grew in the period studied. Improvements in the electricity intensity of GDP were too small to fully counteract the growth of GDP, and thus electricity demand grew. In fast-growing, emerging countries like China and India, one would expect relatively rapid economic growth to drive up electricity demand. Electricity is also a preferred fuel of households and industries as incomes rise and the sophistication of economic production processes increases, and hence its share in the energy consumption mix tends to increase as countries develop. Thus, electricity demand can grow faster or only marginally slower than GDP in developing and emerging countries. In the case of China, however, we must explain why the improvement of the electricity intensity of GDP slowed across the period studied, and even reversed in 2018. As discussed in section 2.2.2, the hypothesis of a slowdown in electricity intensive industry in the period 2013-16 and then a recovery in electricity intensive industry can explain this trend.

On the supply side, the decarbonisation of electricity generation was too small to meet all incremental demand, leading to an increase in fossil fuel electricity generation and hence an increase in emissions. In both countries, the reduction in the carbon intensity of fossil-fuel generation provided a large negative contribution to emissions in cumulative terms across the period. This is because both countries have a huge fossil fuel mixes dominated by coal, and thus small improvements in their carbon intensity can have very substantial impacts on emissions. In the short-term, this can help to constrain emissions growth, but cannot be the foundation of long-term complete power sector decarbonisation , as required by scenarios consistent with 2°C.

In China, the growth of zero-carbon electricity generation provided substantial emissions abatement, although it slowed in the later part of the period studied. In India, growth in the share of zero-carbon electricity provided only a small emissions abatement, as the growth of these sources of supply was too slow to maintain or significantly increase their share in electricity generation, due notably to the declining share of nuclear and hydro. In both countries, the growth of new renewables made a consistent and substantial negative contribution to emissions growth, but far too small to hold down emissions.

The overall picture that emerges is one of rapid electricity demand growth driven by fast GDP growth and slow

improvements in the electricity intensity of GDP, and the inability of zero-carbon sources of generation to grow fast enough to keep pace with demand. This is despite both countries having ambitious renewables capacity addition programmes.

3.3. The EU and the US

3.3.1. Results

The EU

Figure 8 shows the results for the EU. In all years, GDP growth was relatively moderate, and provided an upwards contribution to electricity sector emissions growth. In all years, improvements in the electricity intensity of GDP were substantial, the contributed to mitigating CO_2 emissions from the electricity sector.

Only the supply side, the share of zero-carbon sources in total electricity generation actually fell marginally in 2015, 2016, and 2017. This drove emissions higher. This decline in the share of zero-carbon sources in total electricity generation was due to a combination of bad years for hydro generation and the decline of nuclear capacity, which fell by 1.6 GW in 2015 (largely due to a decline of 1.3 GW in Germany) and by 1 GW in 2017. In these years, the growth of the share of new renewables was insufficient to compensate for the decline in the share of nuclear and hydro. In 2014 and 2018, however, zero-carbon sources substantially increased their share in generation. This provided substantial power sector CO_2 emissions abatement. Across the period of analysis, new renewables have shown a consistent increase in the share of power generation from 16% in 2013 to 22% in 2018.

Additionally, substantial negative contributions to emissions were made from the decline in the carbon intensity of the fossil fuel mix in 2015, 2016, and 2017. Little to no fossil-fuel based net-capacity addition has occurred in these years, and hence this contribution was most likely due to increased dispatch of gas over coal and to the dispatch of more efficient coal plants. This fuel switching was due to the favourable equation of gas, coal and higher carbon prices in the Emissions Trading Scheme (ETS).

The net effect of these drivers was that electricity sector emissions fell in every year, except 2017 when a marginal increase occurred. Figure 8, right panel shows the cumulative effect of all drivers across the period 2013-18. GDP growth and improved electricity intensity of GDP effectively cancelled each other out. The growth of the share of zero-carbon generation provided substantial cumulative emissions abatement, followed by the improvement in the CO_2 intensity of the fossil fuel mix. The cumulative net effect of these drivers was that EU CO_2 emissions from the power sector fell by 202 Mt across the period studied.

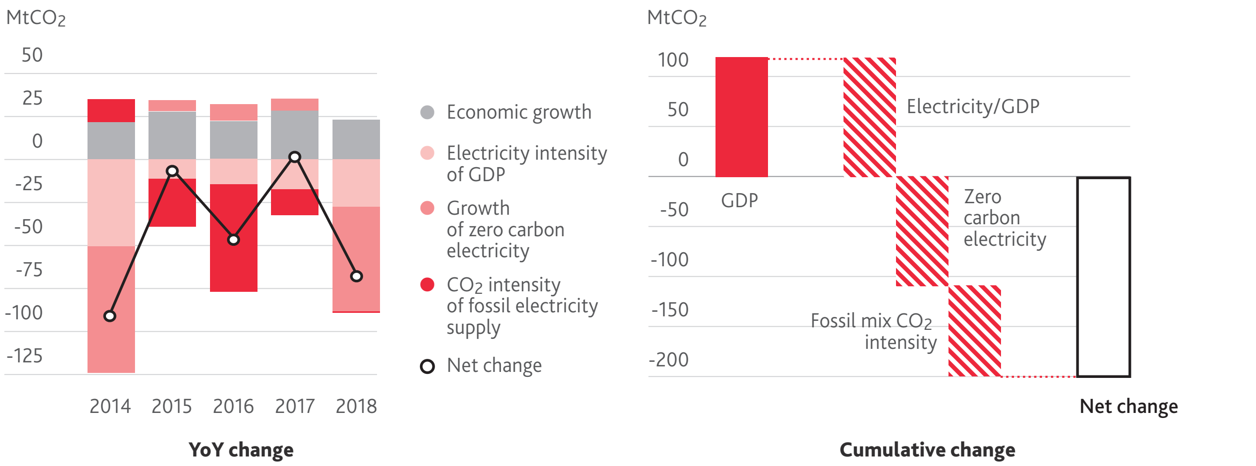
The US

Figure 9 shows the results for the United States.

As with the EU, US GDP growth was relatively moderate and provided small upward contributions to electricity sector emissions in all years. In 2015 and 2017, the improvement in the electricity intensity of GDP was larger than growth of GDP, implying falling electricity consumption in these years. In 2014 and 2016, GDP grew faster than the improvement in electricity intensity of GDP; while in 2018, the electricity intensity of GDP actually increased, driving substantial growth in electricity demand.

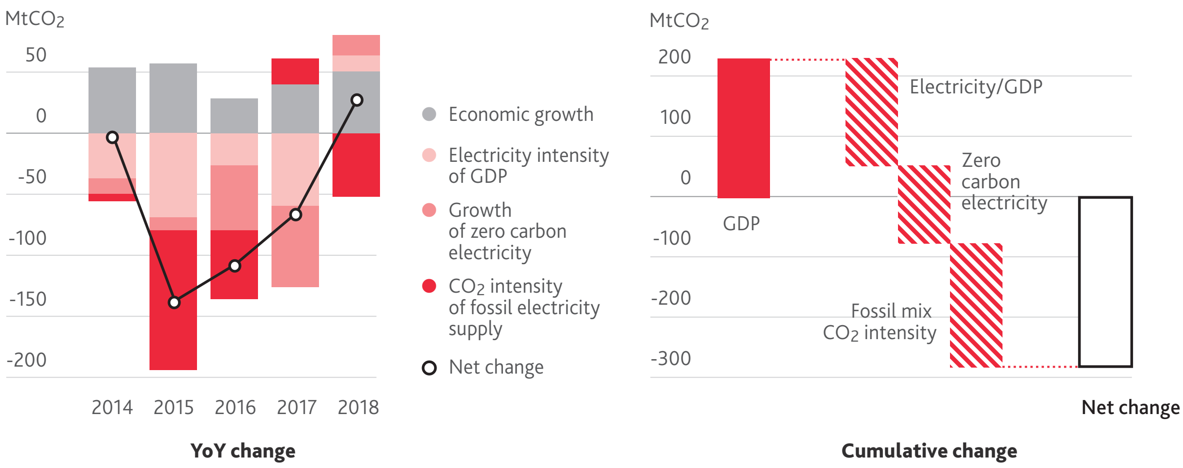
On the supply side, the share of zero-carbon sources grew in all years except 2018, providing a negative contribution to emissions growth. This growth in the share of zero-carbon electricity has been driven solely by the growth of the share of new renewables, with the share of nuclear and hydro being essentially steady. By 2018, new renewables comprised 10.6% of the electricity mix, up from 6.6% in 2013. Large contributions to emissions mitigation came from the declining carbon intensity of the fossil generation mix in 2015, 2016, and 2018, which was due to the transition from coal to natural gas as a result of the cheap availability of shale gas.

FIGURE 8. EU, change in electricity sector emissions by driver, 2013-18



Source: authors, based on data from (Enerdata, 2019).

FIGURE 9. US, change in electricity sector emissions by driver, 2013-18



Source: authors, based on data from (Enerdata, 2019).

Figure 9, right panel shows the cumulative contribution of each driver across the period. The largest contribution to the mitigation of electricity sector emissions came from the improving carbon intensity of the fossil fuel mix, driven by fuel switching from coal to natural gas. This was followed by quite substantial improvements in the electricity intensity of GDP. Finally, the increase in the share of zero-carbon sources in total generation provided the smallest contribution to electricity sector emissions mitigation. The net cumulative effect of these drivers was that electricity sector CO_2 emissions fell by 282 Mt in the period studied.

3.3.2. Interpretation

In both the EU and US, electricity demand growth was either generally negative or positive but small, except for 2018 in the case of the US when electricity demand grew strongly. In both economies, the hydro and nuclear sectors are quite mature, and do not generally see significant capacity addition. In both the US and the EU, the change in the share of zero-carbon electricity generation made mostly negative contributions to emissions growth. In some years, however, this driver made an upward contributions to electricity sector emissions, i.e. the share of zero-carbon sources in total generation fell in these years, due to poor hydro conditions or the decommissioning of nuclear in the case of the EU. Declines in the carbon intensity of the fossil mix made quite substantial negative contributions to emissions growth in both the EU and the US, as the economics of natural gas versus coal improved, due in part to carbon pricing in the EU.

3.4. The drivers of electricity demand growth

One of the important messages emerging from the analysis above is the challenge, in the context of rapidly rising electricity demand, of growing zero-carbon electricity sources fast enough to increase their share in electricity generation substantially. This is particularly the case in developing countries and emerging countries like China and India, although the example of the US in 2018 is also relevant. In this section we investigate the sources of electricity demand growth in China, India, the US and EU.

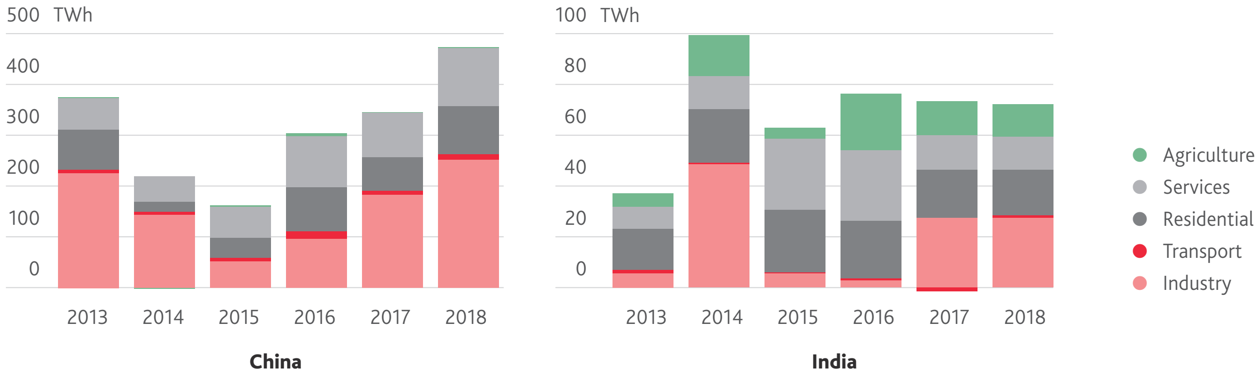
3.4.1. China and India

Figure 10 shows the sectoral contribution to electricity demand growth in the period 2013-18 in China and India in absolute terms in terawatt hour (TWh). The sharp decline in the quantum of incremental industrial electricity demand in the middle years of the period is quite visible for both countries. This was followed by a pick-up in subsequent years. In both China and India annual growth from the buildings sector (i.e. residential and services) was substantial, indicating the large pent up demand from these sectors. In India, agriculture is also a large sector for electricity demand for the pumping of groundwater.

3.4.2. The EU and the US

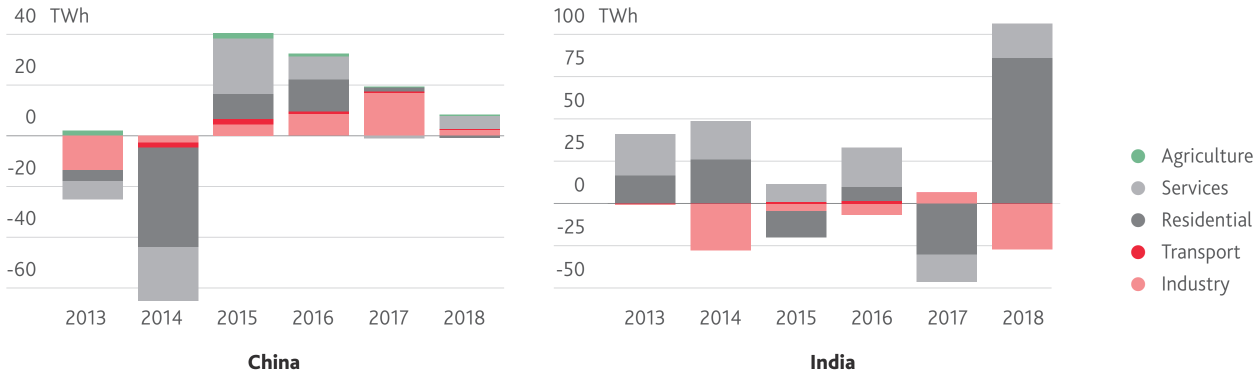
Figure 11 shows the sectoral contribution to electricity demand growth in the EU and the US across the period 2013-18. As can be expected for developed, high energy consumption economies, the level of demand growth was far lower than in the case of China and India, and in some years was negative. The exceptional level of electricity demand growth in the US residential sector in 2018 can clearly be seen. This was discussed in section 2.3.2. We noted that 2018 was exceptionally hot measured in terms of cooling-degree-days, and thus the demand for electricity for residential cooling may have been very high. However, we noted that 2018 was only marginally hotter than 2016 measured in cooling-degree-days, but 2016 did not see anything near the level of electricity demand growth. The links between weather and electricity demand need further study,

FIGURE 10. Sectoral contribution to electricity demand growth, China and India, 2013-18



Source: authors, based on data from (Enerdata, 2019).

FIGURE 11. Sectoral contribution to electricity demand growth, EU and US, 2013-18



Source: authors, based on data from (Enerdata, 2019).

probably at the subnational level which is beyond the scope of this study.

3.5. Conclusion

This section has examined the decarbonisation of electricity supply, a major component of the energy transition towards zero emissions energy systems. Several key conclusions emerge:

- *Fast electricity demand growth makes growing the share of zero-carbon sources extremely difficult*. In 2017 and 2018 electricity demand growth was much more significant in China than in the preceding years. Zero-carbon sources were unable to increase their supply fast enough to substantially grow their share and reduce power sector emissions. Similar situations occurred in India and in the US in 2018. Thus, while electricity is expected to be the key fuel in a zero-carbon energy system, every effort must be made to ensure maximum electricity efficiency. Because per capita consumption is so much lower in developing and emerging countries, there is huge pent up demand, particularly in the residential and services sectors. Appliance and building envelop efficiency policies are crucial to slow the rate of electricity demand growth and bring it within the feasible range for the growth of supply of zero-carbon sources.
- *The growth of renewables has made a consistent contribution to mitigating power sector emissions, but its scale is still small*. With the exception of China, in all other countries the growth of the share of zero-carbon electricity generation came largely from modern renewables (wind and solar). The share of nuclear and hydro was either stable (US), or falling slightly (EU and India). But the growth of renewables in the share of generation was still slow and small scale, in the order of a few percentage points in all countries studied. Despite the revolution in the costs of renewables and strong policies to push their growth, their aggregate impact is still small relative to the massive scale of electricity systems in these economies. Much faster growth would be required to substantially reduce electricity system emissions, and this must be facilitated by reductions in demand growth.
- *In all geographies studied, cleaner fossil fuel power made substantial contributions to emissions mitigation.* In the US and India, cleaner fossil fuel power made a larger contribution to

mitigating electricity sector emissions than did the growth of zero-carbon electricity supply. In this US this came from coal to gas fuel switching, while in India it came from preferential dispatch of cleaner coal plants and the large addition of new, more efficient coal plants. However, even in China and the EU cleaner fossil fuel made a substantial contribution to emissions mitigation. We estimate that reduction in the carbon intensity of the fossil-based generation mix in the four geographies studied provided 753 $MtCO_2$ of emissions abatement, substantially more than the emissions abatement provided by the increase in the share of zero-carbon generation in total generation (590 Mt of CO_2 emissions abatement). This is certainly welcome in the short-term, but it cannot be the basis of a strategy to reach essentially zero emissions from the electricity sector before 2050, as required by scenarios to limit warming to less than 2°C.

4 DECARBONISING END-USE SECTORS

4.1. Methodology

The energy transition consistent with limiting warming to below 2°C requires not just improvements in energy efficiency and the decarbonisation of electricity supply, but also the decarbonisation of final energy consumption. This needs to occur through the transition to zero-carbon fuels such as electricity, for example away from petroleum products to electricity in transport. In addition to electricity, other decarbonised fuels include: zero-carbon hydrogen, i.e. produced through electrolysis based on zero-carbon electricity; sustainably produced biofuels; and other zero-carbon synthetic fuels (synfuels).

Public discourse and policy debates tend to focus on electricity sector decarbonisation. This is partly because decarbonisation is the most technically feasible and cheapest in the electricity sector in the short-term. Decarbonised electricity is also a crucial enabler of decarbonisation in end-use sectors, both as a fuel (for example, in electrified transport) but also as an input into synthetic fuel generation (for example, 'green' hydrogen based on electrolysis with renewable energy). But decarbonisation of end-use sectors is also a crucial pillar of the energy transition, and needs to be focused on in analysis, policy debate, and public discourse.

For this reason, we provide a focus here on progress in decarbonising end-use sectors, and compare it with the progress achieved in decarbonising electricity supply. Figure 12 presents two different indicators:

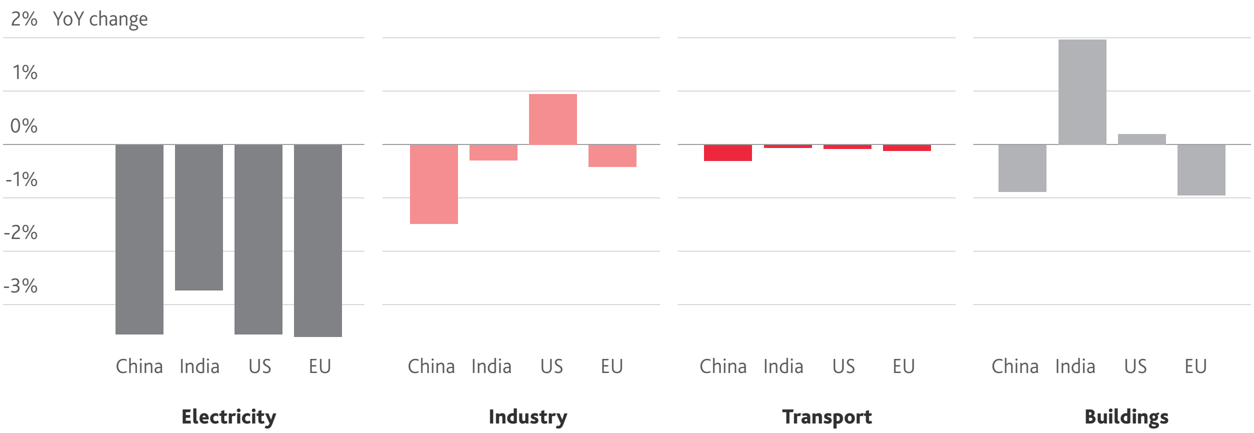
— *Decarbonisation rate of electricity supply*: this is the change in the annual ratio of emissions from electricity production divided by total electricity production. This actually represents the rate of decarbonisation of one crucial sector in energy supply, and was analysed in Section 3. We include it here in the chapter on decarbonisation of energy consumption in order to be able to compare the rate of decarbonisation of electricity production with the rate of decarbonisation of energy consumption in end-use sectors.

— *Decarbonisation rate of energy consumption in end-use sectors (Industry, Transport, Buildings)*: this represents the change in the annual ratio of emissions from direct fuel combustion in end-use sectors over total final energy consumption in the end-use sectors. This represents the rate at which the final energy consumption mix of each sector is transitioning away from CO_2 intensive fossil fuels towards zero-carbon energy sources, such as decarbonised electricity, biofuels, or synfuels.

4.2. Results

The decarbonisation of end-use sectors is illustrated in Figure 12.

FIGURE 12. Decarbonisation rate of energy supply (electricity) versus decarbonisation rate of final energy consumption, 2013-18



Source: Authors based on data from (Enerdata, 2019).

The first thing to note is the much faster rate of decarbonisation in electricity production (≈3.5% per year) compared to the rate of decarbonisation of energy consumption in the end-use sectors (generally <1% per year). This is not necessarily a cause of concern, as it is known from energy scenario analysis that energy supply, and in particular electricity generation, has cheaper and more significant mitigation options in the short-term. Thus, most mid-century energy transition scenarios see earlier decarbonisation of electricity supply, with the decarbonisation of end-use sectors catching up as mitigation options become available and cheaper through innovation and learning. However, the rate and direction of transition in end-use sectors may nonetheless be a cause for concern if it implies that decarbonisation options for these sectors are not being adequately prepared for future mass deployment.

We move now to a brief discussion of each individual sector.

Industry

In the case of industry, we see a generalised slow rate of change, with the maximum rate of change being a decarbonisation rate of about 1.5% per year in China. This decarbonisation rate is probably due to structural transition within the industrial sector of China, rather than the fuel substitution within the energy consumption mix of China's industrial sector. If the above-discussed hypothesis is correct, and China indeed went through an industrial slowdown in the period 2014-16, this would have disproportionately hit heavy, coal-dependent sectors such as iron and steel and cement (recall **Figure 3**). The ensuing reduction of the share of such carbon-intensive sectors in the industrial energy consumption mix would reduce the overall carbon intensity of industrial energy consumption. This is not necessarily a bad thing, as a crucial part of China's low-carbon pathway is controlling the excessive growth of heavy industry.

But it should not be taken as a sign that fundamental technological substitutions are being implemented. We can see the continued lock-in into high carbon modes of industrial production in the case of the EU and India, where the carbon intensity of industrial energy consumption has been essentially flat, showing only negligible decline. More concerning, the carbon intensity of industrial energy consumption in the US is increasing, i.e. the energy consumption mix of the US industrial sector is *carbonising* not *decarbonising*. Here we can likely see again a recurring theme of this paper, namely the increasing specialisation and lock-in of the United States into energy intensive and gas intensive sectors, on the back of cheap shale gas. Unlike the electricity generation sector, the results of this structural change towards gas intensive industrial sectors has been too significant to be compensated for by the substitution of coal with natural gas within the fuel consumption matrix, leading to the increasing direct carbon intensity of the US industrial sector. Since 2010, the share of zero direct emissions fuels in the US industry final energy consumption mix has declined by two percentage points, while that of natural gas has grown by 7 percentage points and that of coal and oil has fallen 3 percentage points (Enerdata, 2019). The net effect of this was the increase in the direct carbon intensity of the industry sector fuel consumption.

Transport

In the transport sector, rates of change have been absolutely negligible, well below 1% per year. The transport sector is almost completely dominated by oil, and modal shift or fuel substitution has been negligible. At least in the case of light-duty transport, technical substitutions are emerging, with the increasing competitiveness of electric vehicles. But as can be clearly seen from **Figure 9**, the progress to-date in rolling out electric vehicles has been far too small to make any dent in the carbon intensity of fuel consumption in the transport sector. To put this in perspective, Norway, the world leader in electric vehicles, has been able to decarbonize energy consumption in transport at a rate of about -1.7% per year in the period 2013-18, due to a combination of bio-fuel and electric vehicle deployment. Other major regions are clearly far away from such rates of transport sector decarbonisation.

Buildings

In the buildings sector (i.e. services and residential), we see a diversity of outcomes, with India and the US increasing the carbon intensity of their buildings sector energy consumption, while the EU and China decreased the carbon intensity of their buildings energy consumption. The situations of the US and India differ. A large share of India's residential energy consumption still comes from traditional biomass, which is combusted for cooking in tremendously inefficient stoves and with all sorts of negative socio-economic consequences. India's carbon intensity of energy consumption in the buildings sector is rising because of an ongoing transition away from traditional biomass and towards modern fuels like liquid petroleum gas and kerosene (not such a modern fuel, but better than traditional biomass). In the US on the other hand, natural gas has gained 2 percentage points in the share of the buildings final energy consumption since 2010, at the expense of oil, biomass and coal. The net effect has been the small increase in the carbon intensity of buildings energy consumption in the US. The increase in the share of gas in buildings final energy consumption in the US after 2010 is another example of the apparent lock-in into gas intensive infrastructure in the US on the back of cheap shale gas.

In the EU, oil, gas, coal, and district heat have lost share in the final energy consumption mix of the buildings sector. On the other hand, electricity and biomass have gained share since 2010 (1.95 percentage point, and 1.52 percentage point respectively). In China, there has been a quite substantial change in the final energy consumption mix of the buildings sector. Biomass has lost 17.4 percentage points, due to the decline in the use of traditional biomass in the household sector. Oil, gas and electricity have gained shares (1.94 percentage point, 4.11 percentage points, and 11.44 percentage points respectively). Meanwhile the share of coal has fallen 4.64 percentage points, while the share of district heat has risen 4.51 percentage points. The net effect of this is the decline in the carbon intensity of buildings energy consumption see in **Figure 12**.

While the substitution out of coal is a positive development, increased lock-in to fossil fuel fired district heat and natural gas infrastructure may be a concern in the context of longer-term decarbonisation strategies (Jun *et al.*, 2010).

Our analysis finds only a slow decarbonisation in the end-use sectors; and in the case of the United States, a trend towards increasing carbon intensity in several sectors. While slower decarbonisation in these sectors is to be expected relative to the easier-to-decarbonize electricity sector, the current rates of change in end-use sectors may raise a number of concerns.

5 CONCLUSION AND DISCUSSION

This paper analysed the drivers of energy related CO_2 emissions across energy demand, electricity supply, and end-use energy consumption. The motivation was to understand what has driven the increase in global emissions in the years 2017 and 2018, relative to the stagnation or decline of 2014-16. The answer is not simple, but can be thought of in three parts.

- Firstly, the slow rate of energy demand growth in the preceding period of 2013-16 was driven by adverse economic conditions, from sluggish GDP growth, industrial value-added growth and higher global energy prices (up to the middle of 2014). Slow energy demand growth was not matched by correspondingly slow growth of monetary statistics (i.e. GDP). The most likely explanation is that the GDP and industrial growth was overstated in China. At the global level, China is so large that this made a measurable impact on global rates of energy intensity improvement, effectively inflating them by 0.5 percentage points. In the cyclical global upswing of 2017-18, accompanied by large energy intensive stimulus in China, the relationship between global economic activity and energy consumption returned to a more normal level compared to long-run trend. The rapid improvements in global energy intensity of 2014-16 were thus not driven by fundamental progress in the decoupling of global economic activity from energy demand.
- Secondly, slower energy demand growth 'flattered' the growth in the share of the zero-carbon energy sources. Slower energy demand growth allowed zero-carbon sources to increase their share in total energy demand faster than would have been the case had energy demand grown faster. Once energy demand growth resumed in 2017 and 2018, the fundamental inadequacy of the rate of the global expansion of zero-carbon energy was revealed.
- Thirdly, while mitigating climate change requires an *energy system* transition to zero emissions, what have seen so far is essentially an *electricity system* transition (and too slow to boot). That is to say: end-use sectors have not yet started to decarbonize their energy consumption by shifting to electricity, biomass or synthetic fuels. While the prospects of end-use decarbonisation have improved in some sectors, for example with the emerging competitiveness of electric vehicles, in others such as heavy industry there is little to no progress in prospect.

What then are the prospects for the coming years? Firstly, it appears likely that the global economy will slow down in coming years and that China will resume its inevitable transition to a less industry-dependent economy. This should help to constrain the rate of Chinese energy demand growth, and bring it within reach of the rate of zero-carbon energy supply growth. It could thus be hoped that China's emissions may generally plateau in the coming year few years. If the US and the EU continue their slow rate of decoupling of GDP and energy demand, and decarbonisation of electricity, their emissions should continue to decline, potentially counteracting emissions growth from emerging economies. It therefore appears possible that global emissions may experience a period of 'spikey plateau', i.e. small increases and declines around a broadly stable level. Time will tell.

But this is really beside the point. Firstly, this paper argues that we should not pay so much attention to the level of global emissions as an indicator of the energy transition, as we should to the underlying drivers thereof. Secondly, what is required is a rapid *decrease* in global emissions, not a *plateau*. To achieve this decrease, policy is essential. If the recent increase in global emissions tells us anything it is that the prospects of an 'autonomous' energy transition driven by the spectacular increase in the economic competitiveness of zero-carbon technologies is a mirage. An 'autonomous transition' would look much more like an emissions peak, plateau, and slow decline than the abrupt decline required to meet the 2°C goal.

In the face of these sobering trends, a rethink of global policy is required. Firstly, a global transparency regime under the UNFCCC and the broader institutional network must focus not on trends in emissions, but on the underlying drivers. The global stocktakes foreseen under the Paris Agreement, as well as non-governmental contributions from international organisations and think tanks, must provide a clear and targeted understanding of the actual state of progress on decarbonising the drivers of emissions growth. This includes understanding both energy systems but also the macroeconomy. Secondly, it is absolutely critical that countries climate action commitments (NDCs) under the Paris Agreement are strengthened in 2020. But more important than the fact is how they are strengthened. Enhanced NDCs in 2020 need to be not just more stringent, but also smarter and in line with long-term decarbonisation strategies. They need to kickstart decarbonisation of end-use sectors, reboot energy efficiency policies, and open up new options, by devoting resources to research and deployment.

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Neither euphoria nor despair: Understanding the fall and rise of global energy-related CO_2 emissions

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The Institute for Sustainable Development and International Relations (IDDRI) is an independent think tank that facilitates the transition towards sustainable development. It was founded in 2001. To achieve this, IDDRI identifies the conditions and proposes the tools for integrating sustainable development into policies. It takes action at different levels, from international cooperation to that of national and sub-national governments and private companies, with each level informing the other. As a research institute and a dialogue platform, IDDRI creates the conditions for a shared analysis and expertise between stakeholders. It connects them in a transparent, collaborative manner, based on leading interdisciplinary research. IDDRI then makes its analyses and proposals available to all. Four issues are central to the institute's activities: climate, biodiversity and ecosystems, oceans, and sustainable development governance.
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Citation: Spencer, T., Robiou du Pont, Y., Colombier, M. (2019). Neither euphoria nor despair: Understanding the fall and rise of global energy-related CO2 emissions. IDDRI, *Study* N°04/19.

ISSN: 2258-7535

This article has received financial support from The French government in the framework of the programme "Investissements d'avenir", managed by ANR (the French National Research Agency) under the reference ANR-10-LABX-01.

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