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LETTER

Turning the corner on US power sector CO_2 emissions—a 1990–2015 state level analysis

Kristina Mohlin[1,4,6], **Alex Bi**[1,4], **Susanne Brooks**[1,4], **Jonathan Camuzeaux**[1,4] **and Thomas Stoerk**[2,3,5]

1 Environmental Defense Fund, New York, NY, United States of America
2 Directorate General for Climate Action, European Commission, Brussels, Belgium
3 Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, United Kingdom
4 The author's contribution to this research represents their personal opinions only, and not necessarily those of Environmental Defense Fund.
5 Stoerk's contribution to this research represents his personal opinions only, and not necessarily those of the European Commission.
6 Author to whom any correspondence should be addressed.

E-mail: kmohlin@edf.org

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Abstract

Total CO_2 emissions from the United States power sector increased over the period 1990–2005, but peaked soon after, and by 2015 they had declined by 20% compared to 2005. This study analyzes the supply-side drivers of the increasing trend up until 2005 as well as the factors across US states that enabled significant reductions in the following decade. Using index decomposition analysis, we show that the two main factors driving the CO_2 decrease were natural gas substituting for coal and petroleum, and large increases in renewable energy generation (primarily wind)—which were responsible for 60% and 30% of the decline respectively since 2005. Both effects were concentrated in states where low natural gas prices or a combination of federal tax credits, state energy policies, decreasing costs of renewables, and advantageous wind conditions drove significant reductions of CO_2 emissions—resulting in the overall national emissions decline.

Introduction

The United States is the second largest CO_2 emitter globally and its power sector was the single largest source of its emissions from 1990 to 2015, responsible for more than 30% of total US CO_2 emissions (EPA—United States Environmental Protection Agency 2018). CO_2 emissions from the US power sector increased over the period 1990–2005. But soon after, emissions peaked and decreased such that by 2015, they had declined by 20% compared to 2005 levels[7]—two thirds of the way to the Clean Power Plan's goal of reducing emissions by 32% by 2030.[8]

A clearer understanding of the factors that turned the corner on US power sector emissions is valuable for informing climate and energy policy, both in the US and internationally. In this paper, we analyze the supply-side drivers of the increasing trend up until 2005 as well as the factors that enabled the drastic reduction in the decade following using index decomposition analysis (IDA), an established method for analyzing the drivers of CO_2 emissions and energy use (see e.g. Ang 2015, Ang and Su 2016, Goh and Ang 2018, Mohlin *et al* 2018). We quantify the contribution from five underlying supply-side drivers: changes in renewable and nuclear energy generation (further decomposed into nuclear, hydro, wind, utility scale solar, geothermal, wood and waste), natural gas substitution for coal and petroleum, changes in power plant conversion efficiency, intra-fossil fuel substitution (e.g. between different types of coal), and changes in total electricity generation—for all 50 states.

Our analysis contributes to the literature that examines the impact of the recent increases in electricity generation from renewables and natural gas on US power sector CO_2 emissions (for renewables see

[7] Note that since our CO_2 emissions data are based on state-level fuel use and emissions factors from the US Environmental Protection Agency (EPA) as further described in the data section, there are instances throughout the paper where our CO_2 emission numbers slightly differ from the national level CO_2 emissions reported by the Energy Information Agency (EIA).

[8] This analysis does not extend beyond 2015 because data on state-level CO_2 emissions and its different fuel sources is not yet available for more recent years. However, it is worth noting that preliminary data suggests that national level power sector emissions have continued to decrease since 2015 (with the exception of 2018) indicating a further decrease by 6%-points in US power sector emissions compared to 2005 (EIA—US Energy Information Administration 2019).

e.g.; Cullen, 2013, Kaffine *et al* 2013, Callaway *et al* 2015, Novan 2015, Millstein *et al* 2017; and for natural gas; Lu *et al* 2012, Knittel 2015, Kotchen and Mansur 2016, Holladay and LaRiviere 2017, Linn and Muehlenbachs 2018; for both factors EIA—US Energy Information Administration 2018a, Fell and Kaffine 2018 for the period 2008–2013; and for a descriptive analysis of CO_2 intensity trends, Schivley *et al* 2018). Most of these studies, however, are limited in scope: they either provide estimates of the marginal emissions impact or the CO_2 reduction impact during a limited time period, without yielding an overview and quantification of the relative contributions for the range of factors behind recent US CO_2 reductions. Our study adds to this literature by providing a comprehensive assessment of the relative contributions from different electricity resources to power sector CO_2 emissions across all US states over a 25 year period.

We find that the two main drivers for the CO_2 decrease of 480 million tonnes (Mt) from 2005 to 2015 were increased electricity generation from natural gas (primarily substituting for coal) and intermittent renewables (primarily wind), contributing 60% and 30% of the decline respectively. The remaining 10% of CO_2 reductions were driven by changes in nuclear power generation, improvements in power plant efficiency, and shifts in electricity generation to relatively lower emissions-intensive states. The contributions from natural gas substitution were primarily concentrated in states such as Alabama, Florida, Georgia, and Pennsylvania, which have historically relied heavily on coal-fired electricity generation but where gas-fired electricity generation became competitive following the so-called shale gas boom and related drop in US natural gas prices. The contribution from renewables primarily resulted from increased wind energy generation in states such as Iowa, Illinois, Kansas, Oklahoma, and, in particular, Texas. In these states, a combination of federal renewable energy tax credits, decreasing costs of renewables, state energy policies such as renewable portfolio standards (RPSs), and advantageous wind conditions drove reductions. Together, along with federal air quality regulations, these market and policy factors increased the share of renewables and natural gas in the US electricity mix, while reducing the share of coal and thereby significantly drove down the nation's CO_2 emissions. In addition, although this research focuses on supply side drivers, it is worth noting that power sector CO_2 emissions would likely have been substantially higher in the absence of energy efficiency improvements on the demand side that also happened over this period.

Method and data

The method used is IDA which is an established method for analyzing the drivers of CO_2 emissions and energy use (see e.g. Ang and Zhang 2000, Ang 2004, Xu and Ang 2013, Ang 2015, Ang and Su 2016). IDA attributes contributions to changes in CO_2 emissions by decomposing the change in emissions, into a sum of changes in each of a number of driver variables. The method is based on defining an identity where the variable of interest equals the product of all the driver variables. Specifically, we use the additive logarithmic mean divisia index method recommended by Ang (2004) and described in detail in Ang (2005), with the renewable and nuclear energy contributions calculated with the two-step procedure suggested by Goh and Ang (2018). The drivers considered are:

- Changes in total net electricity generation.
- Changes in the share of non-fossil fuel generation in net electricity generation (i.e. renewable and nuclear energy—further decomposed into their respective subcategories).
- Changes in the relative shares of natural gas, coal and petroleum in total fossil fuel net generation (i.e. fossil fuel switching).
- Changes in the average heat rate for natural gas, coal and petroleum based electricity generation, respectively, (i.e. changes in average efficiency of the thermal power plant fleet).
- Changes in the emission intensity per unit of primary energy for natural gas, coal and petroleum, respectively.

These drivers thus focuses on important indicators of the composition of state-level electricity supply that are significant determinants of CO_2 emissions and do not explicitly consider demand-side factors.[9] The decomposition is made for each state individually year-to-year meaning that changes in state-level power sector CO_2 emissions is attributed to changes from the previous year in the driver variables for the state itself, and thus abstracts away from inter-state dependencies in CO_2 emissions through the electricity markets.

Decomposition analysis is a descriptive method (see further discussion in Löfgren, Muller 2010) which does not involve any statistical estimation of relevant parameters or a representation of the underlying market structure. Its advantage is that it gives a transparent assessment of key drivers underlying past emission trends, even in cases where there are too few data points for statistical analysis. However, due to the descriptive character of the method, no statistical and causal inference is possible. To further inform policy, it is best complemented with statistical analysis that

[9] The exclusion of energy efficiency is partially due to the lack of a reliable index of aggregate electricity service demand—rather than electricity consumption—which would be required to quantify the impact of energy efficiency using this methodology.

allows for inference, in particular regarding the emission impacts of specific policies.

The full decomposition results for each state for the time period 2005 to 2015 aggregated across years is presented in tables 1 and 2.

Data

State-level CO_2 emissions data was calculated by multiplying energy use data with EPA's carbon coefficients and compared for consistency with EPA's directly-reported emissions data from State CO_2 Emissions Data from Fossil Fuel Combustion and the State Inventory and Projection Tool (EPA—United States Environmental Protection Agency 2017a). (Such directly-reported state level CO_2 emissions data were not yet available for 2015 at the time.) Data for carbon coefficients by fuel type, state, and sector for those calculations were taken from the CO_2 FCC Module of the US Environmental Protection Agency's (EPA) State Inventory and Projection Tool (EPA—United States Environmental Protection Agency 2017b). Energy use data by fuel type, state, and sector were taken from the US Energy Information Administration's (EIA) State Energy Data System (SEDS) for 1990–2015 for consumption estimates in Btu (EIA—US Energy Information Administration 2017a). Electricity generation data was taken from the US EIA's Net Generation by State by Type of Producer by Energy Source table (EIA-906, EIA-920, and EIA-923) (EIA—US Energy Information Administration 2017b).

Results

We present our results by first describing the US power sector's overall CO_2 emissions trend between 1990 and 2015 and the main drivers behind the decreasing trend between 2005 and 2015 at the national level. We then go on to describe the distribution of power sector CO_2 emissions across the US states and which states saw the most significant decreases from 2005 to 2015. Next, we describe the contribution of natural gas to power sector decarbonization at the state level, and then go on to describe the contributions from renewable and nuclear energy. Lastly, we look at California and Texas, which provide two interesting case studies for how power sector CO_2 emissions and their drivers have played out differently since 2005.

US power sector emission trends 1990–2015

Figure 1 documents the overall trajectory of CO_2 emissions in the US power sector from 1990 to 2015. The time period includes two important policy-relevant baseline years used in international negotiations on climate policy: 2005 used e.g. by the US, Canada and China as the reference year, and 1990 used by the European Union.

Despite a near doubling of real GDP between 1990 and 2015 (US Bureau of Economic Analysis 2018), and a 35% increase in net electricity generation, CO_2 emissions in 2015 were roughly the same level as they were in 1990 (1860 Mt CO_2 in 2015 compared to 1810 Mt CO_2 in 1990). However, this masks two distinct trends of rising emissions in the early years and falling dramatically thereafter as illustrated in figures 2 and 3. These figures present our decomposition results on the drivers of year-to-year differences in CO_2 emissions across all the US states over this period.

For the first part of our study period, from 1990 to 2005, CO_2 emissions increased approximately linearly to reach 2340 Mt in 2005, an overall growth of 30% relative to the 1990 baseline. The main driver was increased electricity generation (as shown by the positive grey bars in figure 2) which grew by 35% from 1990. The growth of CO_2 emissions was less than that of electricity generation because the decarbonizing effects of natural gas substituting for coal and petroleum (negative black bars) together with improved average heat rates for the fossil fuel plant fleet (negative beige bars) were sufficient to offset increased CO_2 emissions from limited availability of hydropower due to dry years (positive blue bars) and the retirement of nuclear capacity (positive orange bars).

In the second part of our sample period, CO_2 emissions turned a corner, decreasing by 20% from their 2005 levels in 2015. This is despite the fact that total net electricity generation stayed roughly the same in 2015 as it was in 2005 (3920 TWh versus 3900 TWh). In other words, the US power sector experienced a rapid decarbonization of substantial magnitude during this period, while still producing the same amount of electricity. The main drivers were, as shown in figure 3, natural gas substituting for coal and petroleum (negative black bars) and increasing renewable electricity generation—primarily wind (negative green bars). Natural gas was responsible on net for 280 Mt or 12%-points and intermittent renewables for 150 Mt or 6%-points of the 20% decline in US power sector emissions between 2005 and 2015.

The distribution of power sector CO_2 emissions across states

In 2005, Texas was with respect to power sector CO_2 emissions the highest emitting state in the country at 10% (229 Mt), followed by Ohio, Florida, Pennsylvania, Indiana, Illinois, Kentucky, West Virginia, Georgia, Alabama and Missouri. Together with Texas, these ten states were responsible for more than 50% of US power sector emissions due to their historically heavy reliance on coal-fired electricity generation (see figure 4 which ranks the states according to their power sector CO_2 emissions). Figure 4 also shows the distribution of power sector emissions across the states in 2015, where we can see that states such as Georgia, Indiana, Maryland, Massachusetts, Nevada, New York, Ohio, Pennsylvania and Tennessee significantly

Table 1. State-level decomposition results of changes in CO_2 emissions between 2005 and 2015 by factor.

					Contribution of each factor to change in CO_2 emissions (Mt CO_2)					
State	Total emissions in 2005 (Mt CO_2)	Total emissions in 2015 (Mt CO_2)	Total electricity generation in 2005 (TWh)	Total electricity generation in 2015 (TWh)	Change in total electricity generation	Change in CO_2 intensity (intra-fuel substitution)	Cross fossil fuel substitution	Change in average heat rate	Substitution renewables + nuclear	Total change in CO_2 emissions, 2005–2015 (Mt CO_2)
US Total	2340.1	1863.4	3902.2	3919.3	−24.4	2.4	−278.6	−12.3	−163.8	−476.7
Alabama	79.5	60.9	133.3	148.3	8.2	0.0	−22.4	−0.6	−3.8	−18.5
Alaska	3.2	2.9	6.1	6.0	0.0	0.0	0.3	−0.4	−0.2	−0.3
Arizona	50.3	49.2	101.0	113.0	5.9	0.0	−2.2	0.5	−5.3	−1.1
Arkansas	25.1	26.8	45.8	53.8	4.3	0.0	−3.6	−0.8	1.9	1.8
California	41.9	44.2	181.5	179.3	−0.7	0.8	−4.1	−4.0	10.4	2.3
Colorado	40.1	36.1	49.5	52.3	2.3	0.0	−0.5	0.1	−5.9	−4.0
Connecticut	9.8	7.4	33.3	36.6	0.6	0.0	−3.0	0.2	−0.1	−2.4
Delaware	6.3	3.2	7.2	6.6	−0.9	0.0	−2.2	0.1	−0.1	−3.1
District of Columbia	0.2	0.0	0.2	0.0	−0.3	0.0	0.0	0.0	0.0	−0.2
Florida	124.3	106.5	214.8	232.0	8.3	1.0	−28.8	−0.1	1.7	−17.8
Georgia	83.1	54.8	131.5	123.7	−5.1	0.0	−22.6	2.0	−2.7	−28.4
Hawaii	7.8	6.4	11.0	9.3	−1.2	0.0	0.0	0.4	−0.7	−1.5
Idaho	0.6	1.5	10.2	15.1	0.2	0.0	0.0	0.0	0.6	0.9
Illinois	91.3	74.9	190.6	190.8	0.4	0.0	−2.4	−0.4	−14.1	−16.5
Indiana	118.8	85.1	126.7	100.5	−23.3	0.1	−7.4	2.3	−5.4	−33.7
Iowa	35.2	28.1	42.7	54.3	9.1	0.0	0.1	−2.1	−14.2	−7.1
Kansas	36.4	25.9	45.9	45.5	−0.1	0.0	−0.2	0.5	−10.7	−10.4
Kentucky	90.0	74.8	97.3	83.0	−13.4	−0.1	−2.3	1.5	−0.9	−15.1
Louisiana	42.6	39.1	70.5	76.9	3.3	0.4	−5.4	−3.0	1.3	−3.5
Maine	3.8	1.6	13.9	9.3	−1.0	0.0	−0.1	0.1	−1.2	−2.2
Maryland	31.6	16.4	52.0	35.6	−9.1	0.0	−1.3	1.6	−6.3	−15.2
Massachusetts	24.1	11.2	46.6	31.4	−6.4	0.0	−5.5	0.7	−1.7	−12.8
Michigan	74.3	61.4	119.3	110.7	−5.8	0.1	−4.1	0.6	−3.7	−12.9
Minnesota	35.2	26.7	51.1	55.3	2.4	−0.1	−2.7	−1.9	−6.1	−8.4
Mississippi	24.5	24.5	43.3	62.8	8.9	0.0	−8.9	−1.6	1.5	−0.1
Missouri	76.8	64.7	90.5	83.4	−5.6	0.0	−0.7	−0.9	−4.9	−12.1
Montana	19.1	17.4	27.9	29.3	1.1	0.0	−0.2	−0.3	−2.2	−1.6
Nebraska	21.1	23.2	31.4	39.5	5.3	0.0	0.2	−0.7	−2.8	2.1
Nevada	26.1	14.4	40.2	38.6	−1.8	0.0	−7.6	0.0	−2.3	−11.7

Table 1. (Continued.)

State	Total emissions in 2005 (Mt CO_2)	Total emissions in 2015 (Mt CO_2)	Total electricity generation in 2005 (TWh)	Total electricity generation in 2015 (TWh)	Contribution of each factor to change in CO_2 emissions (Mt CO_2)					Total change in CO_2 emissions, 2005–2015 (Mt CO_2)
					Change in total electricity generation	Change in CO_2 intensity (intra-fuel substitution)	Cross fossil fuel substitution	Change in average heat rate	Substitution renewables + nuclear	
New Hampshire	7.7	3.5	24.1	19.9	−1.2	0.0	−1.6	0.3	−1.7	−4.2
New Jersey	19.1	17.8	59.4	73.2	3.6	0.0	−6.9	−0.3	2.4	−1.2
New Mexico	31.8	24.4	34.8	32.6	−1.5	0.0	−3.3	−0.7	−1.9	−7.4
New York	54.7	29.1	144.7	136.5	−2.8	0.1	−13.6	−2.4	−7.0	−25.6
North Carolina	72.9	50.9	126.6	126.2	−1.3	0.0	−16.3	−0.7	−3.7	−22.0
North Dakota	32.8	31.0	31.7	37.0	4.8	0.0	−0.4	0.5	−6.8	−1.9
Ohio	129.3	80.8	155.9	120.9	−27.1	0.1	−16.2	2.3	−7.5	−48.4
Oklahoma	48.9	39.3	67.4	75.2	5.2	0.0	−5.1	−0.6	−9.1	−9.6
Oregon	8.0	8.5	47.8	57.1	1.3	0.0	−0.8	−0.1	−0.1	0.4
Pennsylvania	121.0	86.0	214.5	211.4	−0.5	0.0	−28.3	1.1	−7.3	−35.0
Rhode Island	2.4	2.8	6.0	6.9	0.3	0.0	0.0	0.1	−0.1	0.4
South Carolina	38.9	28.7	100.4	94.8	−2.0	0.0	−6.7	1.0	−2.5	−10.2
South Dakota	3.2	1.9	6.5	9.6	1.5	0.0	−0.4	−0.1	−2.4	−1.4
Tennessee	53.3	32.7	94.0	72.9	−11.4	0.0	−4.7	1.9	−6.5	−20.6
Texas	228.8	213.6	356.9	407.1	29.7	−0.1	−16.6	−4.3	−23.8	−15.2
Utah	34.8	32.0	37.4	40.9	3.2	0.0	−3.1	−2.2	−0.8	−2.8
Vermont	0.0	0.0	5.7	2.0	0.0	0.0	0.0	0.0	0.0	0.0
Virginia	40.9	31.4	76.0	81.5	0.9	0.0	−10.6	0.1	0.1	−9.5
Washington	13.9	10.8	101.0	107.7	0.6	0.0	−2.5	0.4	−1.7	−3.2
West Virginia	83.8	65.0	92.3	71.2	−19.4	0.0	−0.4	2.6	−1.5	−18.8
Wisconsin	48.1	41.1	59.2	64.5	3.3	0.0	−3.5	−5.3	−1.5	−7.0
Wyoming	42.9	42.8	44.7	47.5	2.5	0.0	0.0	0.4	−2.8	0.0

Table 2. State-level decomposition results of changes in CO_2 emissions between 2005 and 2015: the renewable and nuclear effect disaggregated by resource type.

	Change in emissions from substitution renewables + nuclear						
State	Nuclear	Wind	Solar	Geothermal	Wood and waste	Hydro	Total
US Total	−17.9	−135.7	−12.8	−0.9	−8.3	11.8	−163.8
Alabama	−5.1	0.0	0.0	0.0	0.0	1.3	−3.8
Alaska	0.0	−0.1	0.0	0.0	0.0	−0.1	−0.2
Arizona	−2.8	−0.3	−2.5	0.0	−0.1	0.4	−5.3
Arkansas	1.9	0.0	0.0	0.0	0.0	0.0	1.9
California	8.2	−3.8	−6.2	0.5	−0.3	12.0	10.4
Colorado	0.0	−5.7	−0.2	0.0	0.0	0.0	−5.9
Connecticut	−0.3	0.0	0.0	0.0	0.1	0.1	−0.1
Delaware	0.0	0.0	0.0	0.0	−0.1	0.0	−0.1
District of Columbia	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Florida	1.8	0.0	−0.1	0.0	0.0	0.0	1.7
Georgia	−3.5	0.0	−0.1	0.0	−0.5	1.4	−2.7
Hawaii	0.0	−0.5	0.0	0.0	−0.1	0.0	−0.7
Idaho	0.0	−0.8	0.0	0.0	0.0	1.5	0.6
Illinois	−3.8	−10.3	0.0	0.0	0.1	0.0	−14.1
Indiana	0.0	−4.8	−0.2	0.0	−0.4	0.0	−5.4
Iowa	0.5	−14.9	0.0	0.0	0.0	0.2	−14.2
Kansas	0.1	−10.7	0.0	0.0	−0.1	0.0	−10.7
Kentucky	0.0	0.0	0.0	0.0	−0.1	−0.9	−0.9
Louisiana	1.3	0.0	0.0	0.0	0.0	−0.1	1.3
Maine	0.0	−0.6	0.0	0.0	−0.2	−0.4	−1.2
Maryland	−4.9	−0.4	−0.1	0.0	−0.3	−0.6	−6.3
Massachusetts	−0.9	−0.1	−0.2	0.0	−0.4	0.0	−1.7
Michigan	0.9	−4.0	0.0	0.0	−0.1	−0.6	−3.7
Minnesota	1.6	−7.0	0.0	0.0	−0.6	0.0	−6.1
Mississippi	1.5	0.0	0.0	0.0	0.0	0.0	1.5
Missouri	−3.0	−1.1	0.0	0.0	−0.1	−0.7	−4.9
Montana	0.0	−2.0	0.0	0.0	−0.3	0.0	−2.2
Nebraska	0.6	−2.7	0.0	0.0	0.0	−0.6	−2.8
Nevada	0.0	−0.1	−0.8	−1.0	0.0	−0.4	−2.3
New Hampshire	−1.0	−0.2	0.0	0.0	−0.6	0.1	−1.7
New Jersey	2.4	0.0	−0.2	0.0	0.3	−0.1	2.4
New Mexico	0.0	−1.3	−0.6	0.0	0.0	0.0	−1.9
New York	−2.8	−2.3	−0.1	0.0	−0.2	−1.6	−7.0
North Carolina	−2.1	0.0	−0.9	0.0	−0.8	0.2	−3.7
North Dakota	0.0	−6.2	0.0	0.0	0.0	−0.5	−6.8
Ohio	−5.9	−1.1	0.0	0.0	−0.4	0.0	−7.5
Oklahoma	0.0	−9.2	0.0	0.0	0.0	0.1	−9.1
Oregon	0.0	−2.9	0.0	−0.1	0.0	2.9	−0.1
Pennsylvania	−3.8	−2.6	0.0	0.0	−0.4	−0.5	−7.3
Rhode Island	0.0	0.0	0.0	0.0	−0.1	0.0	−0.1
South Carolina	−2.2	0.0	0.0	0.0	−0.4	0.2	−2.5
South Dakota	0.0	−2.3	0.0	0.0	0.0	−0.1	−2.4
Tennessee	−3.7	−0.1	−0.1	0.0	−0.1	−2.6	−6.5
Texas	3.0	−26.6	−0.3	0.0	−0.3	0.4	−23.8
Utah	0.0	−0.5	0.0	−0.2	−0.1	0.1	−0.8
Vermont	2.2	−0.6	−0.1	0.0	−0.5	−1.0	0.0
Virginia	0.9	0.0	0.0	0.0	−0.8	0.0	0.1
Washington	0.4	−4.4	0.0	0.0	0.2	2.2	−1.7
West Virginia	0.0	−1.3	0.0	0.0	0.0	−0.1	−1.5
Wisconsin	0.6	−1.3	0.0	0.0	−0.4	−0.5	−1.5
Wyoming	0.0	−2.8	0.0	0.0	0.0	0.0	−2.8

reduced their overall CO_2 emissions between 2005 and 2015.

Part of these large decreases in state-level CO_2 emissions, however, merely reflect reshuffling of electricity generation to another state (in particular for Indiana, Maryland, Massachusetts, Ohio and Tennessee)—such that on net, these changes in electricity generation across states did not contribute significantly to overall US power sector CO_2 reductions between 2005 and 2015. The net effect across all states is only a 1%-point

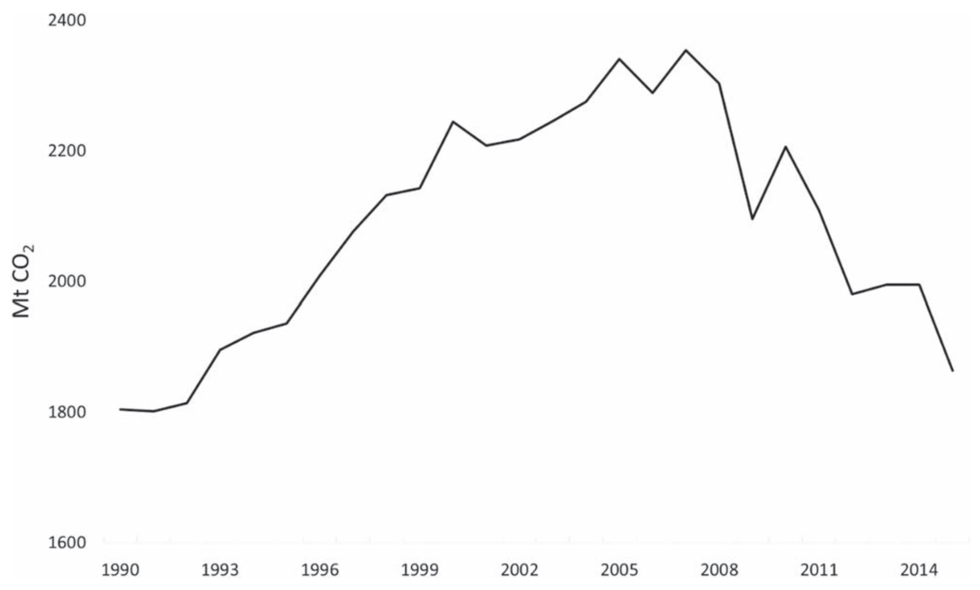

Figure 1. US power sector CO_2 emissions, 1990–2015.

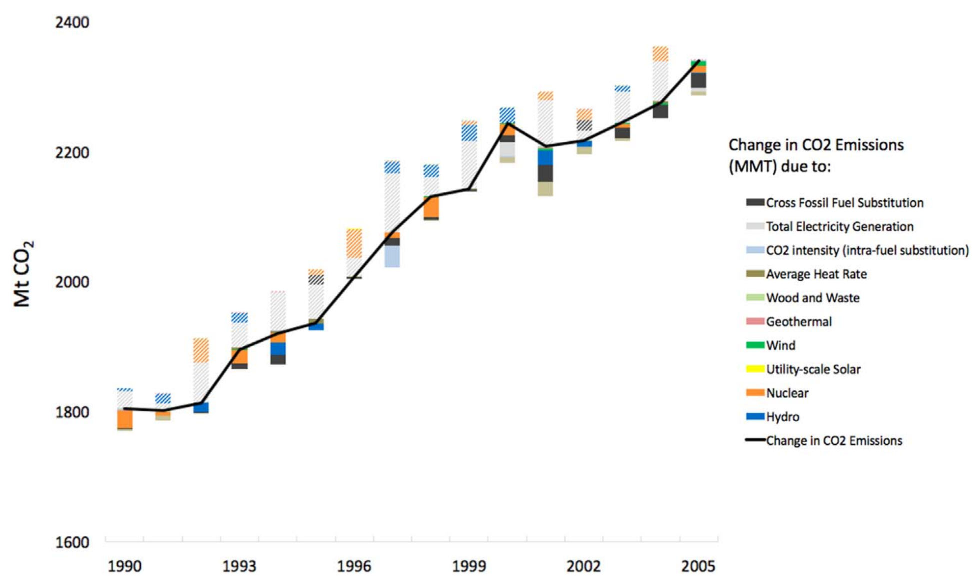

Figure 2. US power sector US CO_2 emissions 1990–2005: decomposition results for the yearly net change in CO_2 emissions from cross fossil fuel substitution (natural gas substituting for coal and petroleum), renewable and nuclear energy, changes in total electricity generation, average heat rates and intra-fuel substitution, aggregated across all 50 states.

reduction in CO_2 emissions through shifts to states with on average slightly cleaner generation mix. In the following sections, we therefore focus on which states made significant contributions to reducing their power sector CO_2 emissions through changes in other factors than total state electricity generation.

The role of natural gas in power sector decarbonization

The total net 12%-point reduction in power sector CO_2 emission between 2005 and 2015 driven by natural gas resulted from increases in the share of electricity from natural gas compared to coal and petroleum. Over this period, natural gas increased its share of the total US electricity generation mix from 18% to 32% at the same time as coal decreased from 51% to 34%. Figure 5 shows how changes in the fossil fuel generation mix reduced power sector CO_2 emissions across the states and ranks them according to their gross CO_2 reductions from natural gas substituting for coal and petroleum. Out of the total gross reduction of 280 Mt from natural gas substitution nationally, more than one third of those reductions (100 Mt) came from only four states—Florida, Pennsylvania, Georgia and Alabama—while another five (Texas, North Carolina, Ohio, New York and Virginia) accounted for much of the remaining reductions (an additional 70 Mt).

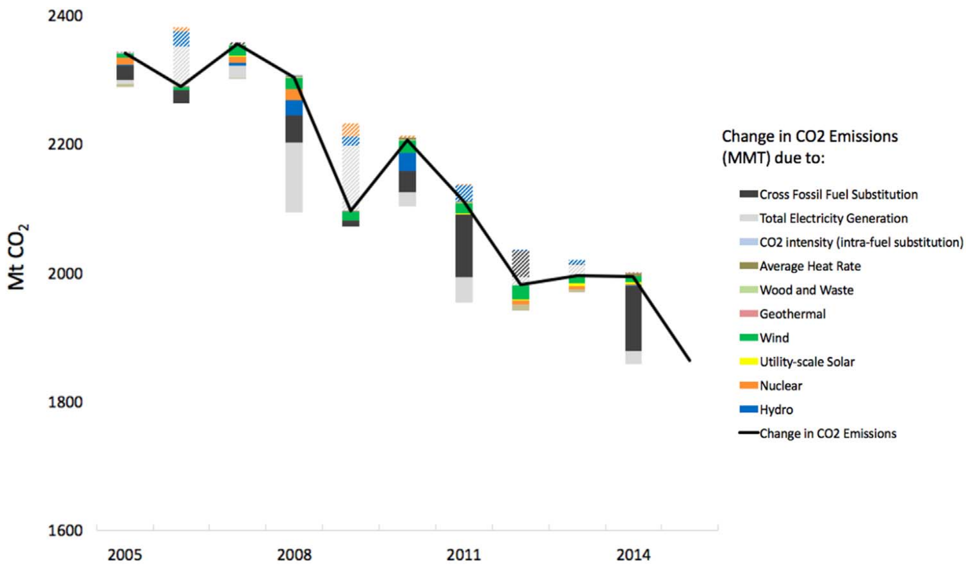

Figure 3. US power sector CO_2 emissions 2005–2015: decomposition results for the yearly net change in CO_2 emissions from cross fossil fuel substitution (natural gas substituting for coal and petroleum), renewable and nuclear energy, changes in total electricity generation, average heat rates and intra-fuel substitution, aggregated across all 50 states.

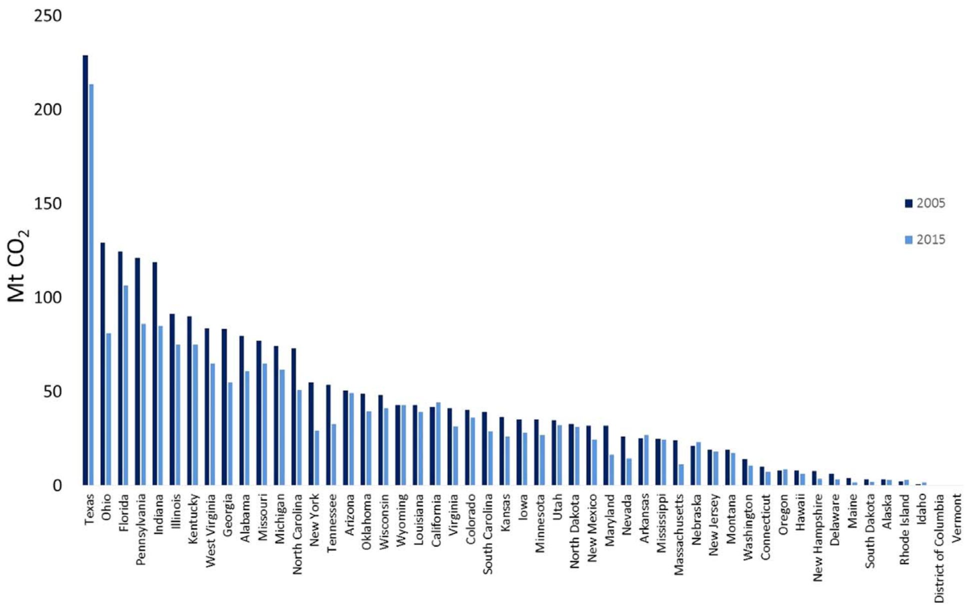

Figure 4. State contributions to US power sector CO_2 emissions in 2005 and 2015.

A closer look at state-level results reveals that the coal to natural gas switch was the primary driver (substitution for petroleum played a relatively minor role). However, this transition unfolded in very different ways across the states. Some states primarily added new natural gas capacity (Florida and Texas) while dispatching less coal and petroleum-fired generation; some primarily retired existing coal capacity (Ohio, Pennsylvania, and Alabama) and ramped up gas-fired generation; and some relied on a combination of the two (Georgia, North Carolina, Virginia, and New York). The retirement of coal plants accelerated near the end of our study period, with 11 000 megawatts (MW) of retired capacity in 2012 and 16 000 MW in 2015. In total, 48 000 MW of coal capacity was retired between 2005 and 2015 corresponding to 17% of existing coal capacity in 2005 (EIA—US Energy Information Administration 2018b). In general, the states with the largest combined new gas capacity and retired coal capacity, such as Florida, Pennsylvania, Georgia, and Alabama (the third, fourth, 9th and 10th largest contributor to US power sector CO_2 emissions in 2005) showed the greatest reductions in CO_2 emissions from fossil fuel switching.

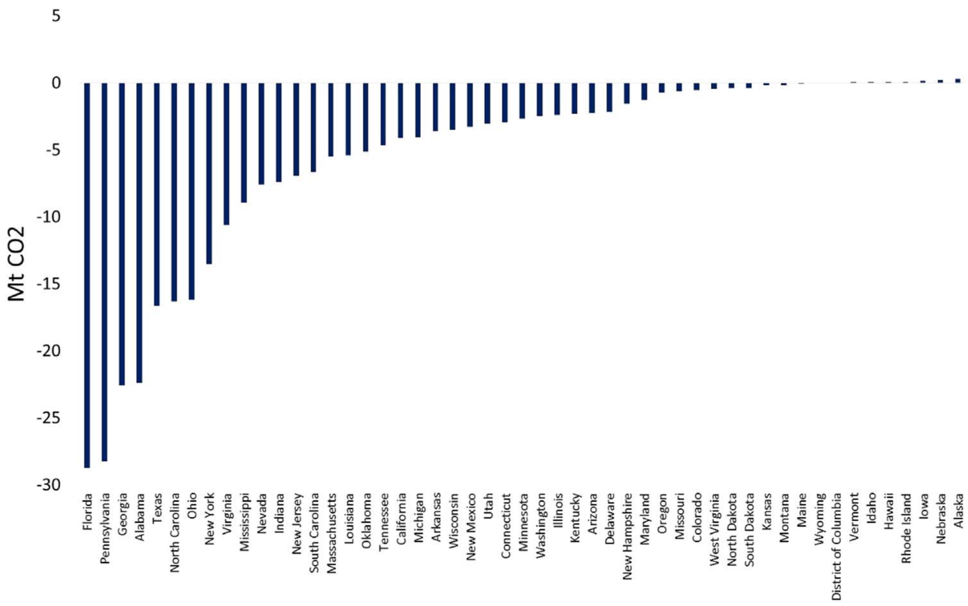

Figure 5. State ranking according to their gross CO_2 reductions from natural gas substituting for coal and petroleum.

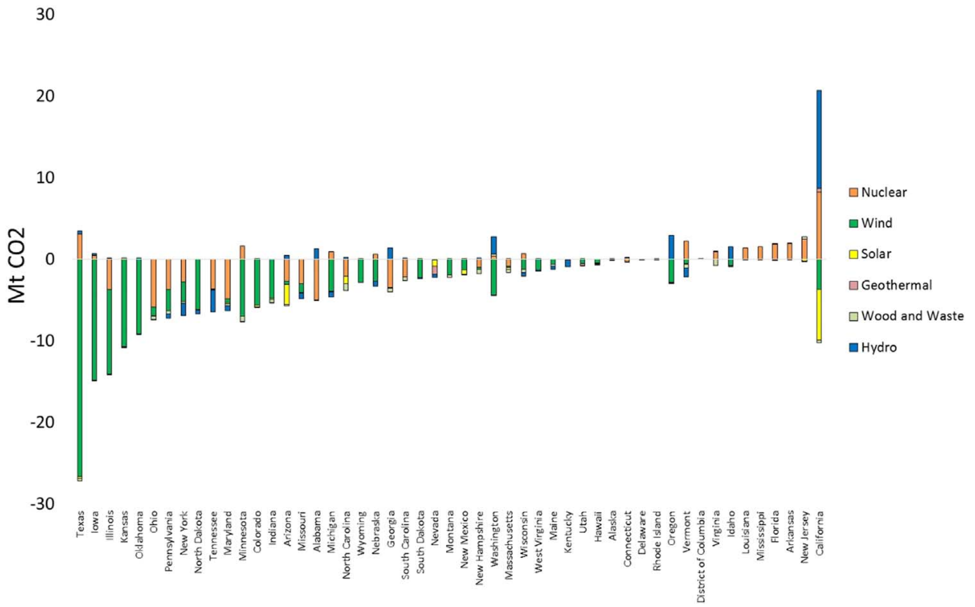

Figure 6. Contributions from renewable and nuclear energy to state level CO_2 reductions between 2005 and 2015.

The role of renewable and nuclear energy in power sector decarbonization

The expansion of renewable energy also played a major role in decreasing US power sector emissions between 2005 and 2015. Wind generation was the primary driver behind the growth in renewable electricity generation, increasing more than 10-fold from 18 terawatt-hours (TWh) to 190 TWh over this 10 year period. Utility-scale solar thermal and photovoltaic generation increased 40-fold over the same time-period, although it grew from a much smaller base, from 0.6 to 25 TWh. In 2015, renewable sources (hydro and pumped storage, biomass, wind, solar, geothermal) comprised 12% of total US utility scale electricity generation, compared to 8% in 2005, with the increase almost exclusively driven by wind energy (EIA—US Energy Information Administration 2019). During this period, many states had RPSs in place and the federal government offered a (mutually exclusive) production tax credit (\$0.023/kWh) and investment tax credit of 30% for renewable energy (see e.g., DSIRE 2019).

Figure 6 shows in which states the largest reductions in CO_2 emissions are attributed to changes in renewable and nuclear electricity generation. As can be seen from the green bars, wind is the dominant resource in driving emission reductions among the renewable resources. Most of the renewable impact came from the states in the Midwest with advantageous wind conditions, as well as Texas, which played a dominant role with gross reductions from wind energy of 27 Mt corresponding to 1%-point of the US total net reduction in power sector CO_2 emissions. In fact, Texas achieved its final RPS target of 5880 MW of renewable generation by 2015 in 2008, seven years ahead of schedule. Factors such as reduced costs of wind turbine technologies (see e.g. Wagner *et al* 2015), federal tax credits, and advantageous wind conditions (see e.g. Barbose 2017) likely played a significant role.

The four states with the largest gross emissions decreases attributed to renewables after Texas are Iowa, Kansas, Illinois and Oklahoma. Together these states contributed half of the renewables related emission reductions (equivalent to 70 Mt or 3%-points of the US total reduction)—all driven by increases in wind generation.

Also illustrated in figure 6, hydroelectric generation (blue bars) was lower in 2015 compared to 2005 in states such as Alabama, Georgia, Washington and California, which contributed to higher emissions—counteracting reductions driven by increases in other non-emitting resources in those states. Overall, across all the states, a decrease in hydroelectric generation between 2005 and 2015 was associated with a 12 Mt gross increase in CO_2 emissions, as seen in figure 3. Meanwhile, increased utility-scale solar thermal and PV electric generation only made significant contributions to gross CO_2 reductions in the sun-rich states of California, Arizona, Nevada and New Mexico as well as in North Carolina.

As illustrated in figure 3, nuclear energy played only a marginal role in decreasing CO_2 emissions over the period, resulting in an emissions decrease of 17.6 Mt CO_2. As can be seen in figure 6, an increased share of nuclear generation in some states was offset by a decreased share in others—resulting in an only modest net contribution to CO_2 reductions over this time period at the national level. However, as illustrated by the example of California in the next section, nuclear energy nevertheless plays an important role in keeping CO_2 emissions down.

A tale of two states' power sector CO_2 emissions

California and Texas offer two particularly interesting case studies, as two large states with differing approaches to climate and energy policy. California has long been a leader when it comes to renewable energy and climate policy. With the passage of the Global Warming Solutions Act (AB32) in 2006, California began developing a suite of programs designed to take a comprehensive approach to addressing climate change. Today, the state's expansive portfolio of policy approaches includes a cap and trade program that launched in 2013 and now covers 85% of the state's greenhouse gas emissions, a recently updated requirement to generate 60% of the state's electricity from renewable sources by 2030 and a goal of achieving carbon neutrality by 2045. In contrast, Texas does not have specific climate policies with emission reduction mandates in place, but it has an RPS that took effect beginning in the year 2000 as well as voluntary targets for renewable energy. In 2005, Texas generated twice as much electricity as California and emitted more than five times as much CO_2 from power generation. By 2015, California's generation level was still the same as in 2005 but CO_2 emissions from the power sector were up by more than 5%. At the same time, Texas had increased its electricity generation by 14% while reducing its CO_2 emissions by more than 6%.

An in-depth look highlights the role of each factor in explaining these diverging patterns for the two states: the coal to natural gas switch, the substitution of renewables, and the substitution of nuclear energy.

Whereas the coal to natural gas switch was the main driver for emissions reductions in most states, there was very limited potential for this to occur in California since coal accounted for only 1% of capacity and generation in 2005. Furthermore, the small net increase in CO_2 emissions from renewables substitution for California seen in figure 6 obscures the 3-fold increase in wind generation (from 4 to 12 TWh) and an increase in utility scale solar generation from 0.5 to 15 TWh. As illustrated in figure 7 which shows the year-by-year decomposition results between 2005 and 2015 for California, the emission reducing impacts of the growth in utility scale solar and wind generation were offset by a 65% decrease in hydro generation, from 40 to 14 TWh, due to a severe five-year drought spanning 2012–2016. Hydropower supplied less than 7% of California's electricity in 2015, versus an average of 17% from 2001 to 2005. The emission reducing impact from renewables is a lower bound because the exponential increase in distributed solar PV capacity in California by 3.3 GW between 2005 and 2015 (CDGS 2018) is not reflected in our data and results—such behind-the-meter resources only serve to reduce net electricity demand and does not show up in the statistics on renewable electricity generation. The increase in distributed solar generation likely replaced gas-fired electricity generation and thereby served to avoid further CO_2 emission increases.[10]

Most significant, however, for the increase in California emissions from 2005 to 2015 was the shutdown of the San Onofre Nuclear Generating Station (SONGS) in February 2012. While in operation, SONGS

[10] Assuming a capacity factor of 15% (see e.g. California Energy Commission 2018), these behind-the-meter resources represented an approximate 4 TWh of electricity generation in 2015. Assuming that electricity would otherwise have been provided by gas-fired generators with a CO_2 emission factor of 0.5 tonne CO_2 per MWh, avoided emissions would be approximately 2 million tonnes of CO_2 in 2015. I.e. close to 5% of California total power sector emissions in 2015.

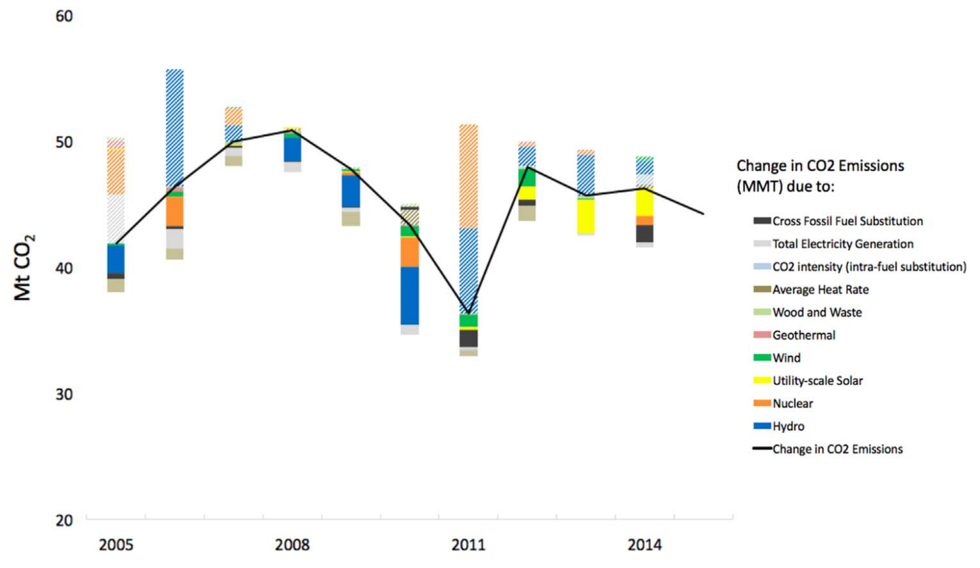

Figure 7. Factor contributions to California power sector CO_2 emission changes between 2005 and 2015.

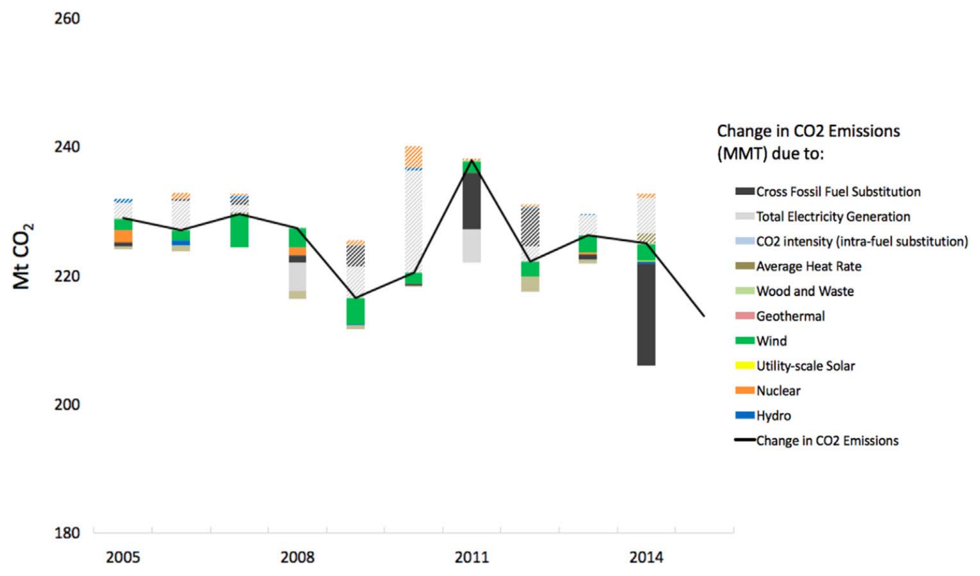

Figure 8. Factor contributions to Texas power sector CO_2 emission changes between 2005 and 2015.

generated 16 TWh annually or around 8% of California's total electricity generation (Davis and Hausman 2016). There was also a sharp increase in new natural gas capacity in 2013, a year after the SONGS shutdown. As illustrated in figure 7, the change in CO_2 emissions between 2011 and 2012 were due to SONGS and hydro generation being replaced by natural gas, leading to increased net emissions—and illustrating the important role nuclear energy can play in keeping down power sector emissions. It also worth noting, as mentioned in the methods section, that any emissions related to changes in imports to California e.g. leading to increases in CO_2 emissions in neighboring states is instead captured in the CO_2 emissions in the exporting state where the electricity was generated.

Like California, Texas saw a decrease in electric generation from nuclear over this time period but also experienced a very large increase in wind generation (from 4 to 45 TWh, as discussed earlier). Together with natural gas substituting for coal and improvements in heat rates of its thermal plant fleet, Texas more than compensated for the 14% increase in total electricity generation (see figure 8 which illustrates the year-by-year decomposition results for Texas) and was thus able to reduce its power sector emissions in 2015 by more than 6% compared to 2005.

Partially due to its starting point in 2005 as the largest emitter of US power sector CO_2 emissions and thus its large reduction potential, Texas is the most prominent example of a state where the combination of increased wind energy and natural gas substitution for coal drove significant reductions in power sector emissions. In comparison, California's reduction potential during this period was more limited and it faced challenges to decreasing its emissions stemming from a key nuclear retirement and a drastic drop in hydro generation due to severe drought.

Discussion and conclusions

Our analysis shows that many states have been on a path of declining power sector CO_2 emissions despite a lack of comprehensive federal US climate policy. The transition from coal to natural gas, and increased deployment of renewable energy—wind energy, in particular—primarily drove this decline.

The coal-to-natural gas switch was concentrated in states with a historically heavy reliance on coal, such as Pennsylvania, Georgia, Alabama and Florida, where the low relative price of gas in recent years made these states somewhat unexpected leaders of US power sector CO_2 emission reductions—together they accounted for more than a fifth of the nation's reductions since 2005.

While natural gas has made a significant contribution towards reducing US power sector CO_2 emissions in the past decade, it is also associated with significant emissions of methane due to leakage across the natural gas supply chain (see e.g. Alvarez *et al* 2018). This analysis does not take these methane emissions into account, which means the overall net GHG benefit from natural gas expansion is lower—potentially considerably lower, depending on the magnitude of methane leaks—than indicated here. In order to drive significant progress toward GHG reductions across all US sectors, a dramatic expansion of renewable and other low and zero carbon technologies will be required going forward in addition to reduced methane leakage and flaring from the natural gas supply chain.

The role of renewable generation as a driver of reduced CO_2 emissions during this period has often been overshadowed by the impact of the natural gas boom—but this analysis illustrates its important contributions. Renewables—primarily wind—played a particularly prominent role in driving CO_2 reductions in Texas and the Midwest. It is notable that Texas was a leading state in renewable energy expansion during this period and has performed above and beyond its renewables portfolio standard. This suggests that a combination of decreasing costs of wind energy, federal tax credits and advantageous wind conditions were important drivers.

These two factors—the combination of natural gas substitution and renewables deployment—led to significant reductions in US CO_2 emissions in the decade from 2005 to 2015. These trends were driven by favorable market conditions during this period of time, as well as policies such as state RPSs, the federal renewable energy tax credits, and federal air quality regulations.

When drawing policy conclusions from our analysis, it is worth noting our research focuses on supply side drivers of power sector decarbonization. Without energy efficiency improvements, which contributed to keeping demand flat over this period, electricity generation and thus CO_2 emissions would have been higher. The reason for not including energy efficiency as a specific driver in our analysis is that the relevant data to incorporate energy efficiency into our state-level analysis are unavailable since it would require a robust index of electricity service demand. However, it is possible to ascertain an upper bound for the economy-wide effect of energy efficiency measures on power sector CO_2 emissions. Estimates for the whole US for our time period suggest that energy efficiency overall might have been responsible for reducing power sector CO_2 emissions by up to as much as the supply-side factors (EIA—US Energy Information Administration 2018c), with individual states' actual CO_2 emissions ranging from 35% to 70% compared to counterfactual projections for a scenario without the past years' energy efficiency improvements (EPA—United States Environmental Protection Agency 2015a, 2015b). These estimates are based on counterfactual demand growth estimates, and it is therefore worth noting that other factors affecting demand growth, e.g. improved grid balancing, could have led to the drop in demand and, therefore, CO_2 emissions.

Looking ahead, while the cost of renewables continues to decline, and a growing number of states are taking crucial action to cut emissions, US power sector CO_2 emissions are projected to remain relatively flat over the next decade and rise slowly after that absent new policy (EIA—US Energy Information Administration 2018d). The past trends identified in this analysis thus cannot be relied upon to achieve the deep emissions reductions needed in the decades ahead. Ultimately, new policy interventions will be necessary—not only in the power sector, but across the economy—to drive reductions at the pace and scale needed for the US to reach net-zero GHG emissions by midcentury.

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