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The state of the states
Data-driven analysis of the US Clean Power Plan

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ABSTRACT

On August 3, 2015 the US Environmental Protection Agency finalized the Clean Power Plan (CPP) which aims to reduce CO_2 emissions from the electricity generating sector by 32% of their 2005 levels by the year 2030. With the rule now finalized, in order to understand how the impact of this will unfold, we need to understand the factors that may influence how the electricity sector evolves given the targets that must now be met. To both identify and understand these relevant factors, we have completed an analysis of US electricity generation data for the period between 2001 and 2014. The result is a detailed fingerprint of the sector per state based on monthly data at the resolution of individual generators. This analysis demonstrates that several "building blocks" or decarbonization strategies encouraged by the CPP are already being utilized in the period analyzed across US states, resulting in CO_2 emissions that have already dropped 12% in the period studied.

Furthermore, we show how the states exhibit considerable differences due to the complexity of their existing generation portfolios, geography, climate and demand patterns. We also examine to what extent the targets of the CPP may impact the most polluting part of their generation portfolios, and how this relates to developments with shale gas and state policies. We then conclude with an overview of which factors may either enable or hinder how the goals of the Clean Power Plan will be met.

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The US electricity sector emits 2 billion tons of CO_2 yearly,[1] accounting for 38% of the country's total energy related CO_2 emissions [33]. Addressing climate change will clearly require changes to this sector. A challenge is that states vary widely in terms of their mix of natural resources, their power systems, network infrastructures, policies and demand patterns. Decarbonizing requires understanding and navigating the complexity of these factors, and we desire to unravel these further through a data-driven analysis which provides sophisticated fingerprints of the electricity sector per state.

Climate change concerns and the Kyoto Protocol (1997) have stipulated companies, innovators, and individual countries to improve the efficiency of their thermal power plants, shift from coal to natural gas or nuclear, develop systems for combined heat and power, and to develop alternative sources, such as biomass, solar, wind and hydro power. While the US never ratified the Kyoto Protocol, US Presidents have consistently worked on developing decarbonizing capability. The government has consistently monitored the US positions with regard to resources, and committed enormous funds to among others, the US Department of Energy, the EPA and several large government agencies and university-run research programs in the (clean) energy and power domain. In addition to efforts at a national level, several initiatives are underway or in consideration at the state level [15]. These include the Regional Greenhouse Gas Initiative (RGGI)[2] involving the Northeast and Mid-Atlantic states, the Midwestern Greenhouse Gas Reduction Accord, and the California Cap-and-Trade Program.[3]

To encourage decarbonization, on August 3, 2015, the US Environmental Protection Agency (EPA) finalized the Clean Power Plan (CPP) [30], which aims to cut carbon emissions from power plants by 2030 to 32% of their 2005 levels. The plan has been met with mixed responses. Unsurprisingly, environmentalists and the renewable energy sector are largely in favor, while the coal industry and representatives from coal states are generally opposed to it [5,28]. Opponents of the plan are challenging its legal justifications, which hinge on the interpretation of the powers that are given to the EPA by the Clean Air Act [23,48], with others questioning the health claims made in the plan and advocating for greater transparency of the plan's data sources and research [25].

To understand the plan's implications given the complexity of the US electricity sector, we analyzed data published by the Energy Information Administration (EIA),[4] containing monthly data on individual Electricity Generating Units (EGUs) from 2001 until 2014.[5] In examining 1.6 million observations, we uncover important patterns in the development and operational characteristics of the electricity sector, both at national and state levels, and investigate the following questions: How does electricity generation compare across the states, and what important changes have taken place over the last decade? To what degree do we already observe progress towards the targets specified by the plan, and through what changes can we see this being achieved? Furthermore, what does the data reveal about factors which will play a role in how the impacts of the Clean Power Plan unfold?

1. The ongoing decarbonization of the US electricity sector

Over the past decade, US electricity generation has been relatively stable and CO_2 emissions have been decreasing along with the CO_2 intensity of generation (Fig. 1a). A major factor is that generation from natural gas is increasing at the expense of that from coal, largely due to lower gas prices resulting from increased availability of shale gas [32], which has in turn led to lower CO_2 emissions from the power sector [6]. Furthermore, installed capacity for solar and wind has been increasing significantly, although still constituting a small fraction of total generation. A remarkable trend is that solar capacity is increasing so rapidly that generation for the *winters* of 2014, 2013 and 2012 were all greater than or equal to that during the *summers* 18 months previous.

2. Implications of the Clean Power Plan for US states

The CPP proposes a set of state-specific goals expressed in terms of adjusted output-weighted-average CO_2 emission rates. These are determined using a standard formula[6] fed with state and region-specific information, such as the characteristics of the state's current generation portfolio and the technical possibilities for reducing emissions. States would be required to meet the proposed targets by 2030, but would be free to choose from a mix of three strategies or “building blocks”.

The states vary widely in their generation portfolios, and have different opportunities related to factors such as population, geography and economics. Some states have a long history of heavy reliance on renewable energy sources; some have more recently embraced renewables, natural gas and other forms of cleaner energy sources; others have stuck largely with coal-based generation. Change is not always fast as power plants have very large capital costs and long lifetimes. Coal and nuclear plants may be operational for more than forty years, and several operational hydropower plants are over a hundred years old.

Fig. 2 gives a visual overview of the CPP targets by showing the rank of the states in terms of emissions rates and the magnitude of improvements proposed. As shown by the lines for the CO_2 intensity of coal and natural gas, a switch from coal to natural gas would enable many states to reach their goals even without a major focus on renewables.

3. Building blocks of the clean power plan

The three CPP “building blocks” have been used to determine state-specific goals, and states are free to choose from a combination to achieve their targets. The proposed blocks are:

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[1] As of 2013.

[2] http://www.rggi.org/

[3] http://www.arb.ca.gov/cc/capandtrade/capandtrade.htm

[4] http://www.eia.gov/electricity/data/eia923/

[5] The data contains diverse information such as the fuel type and heat input for electricity generation, which we have coupled with fuel emissions factors (in terms of kg CO_2/MMBtu) to calculate the total CO_2 emissions. The net electricity generation is also recorded, so the CO_2 intensity per MWh can also be derived. These do *not* include life-cycle emissions, such as greenhouse gas emissions from coal and (shale) gas extraction or methane leakage.

[6] Described starting on p. 771 of United States Environmental Protection Agency [30].

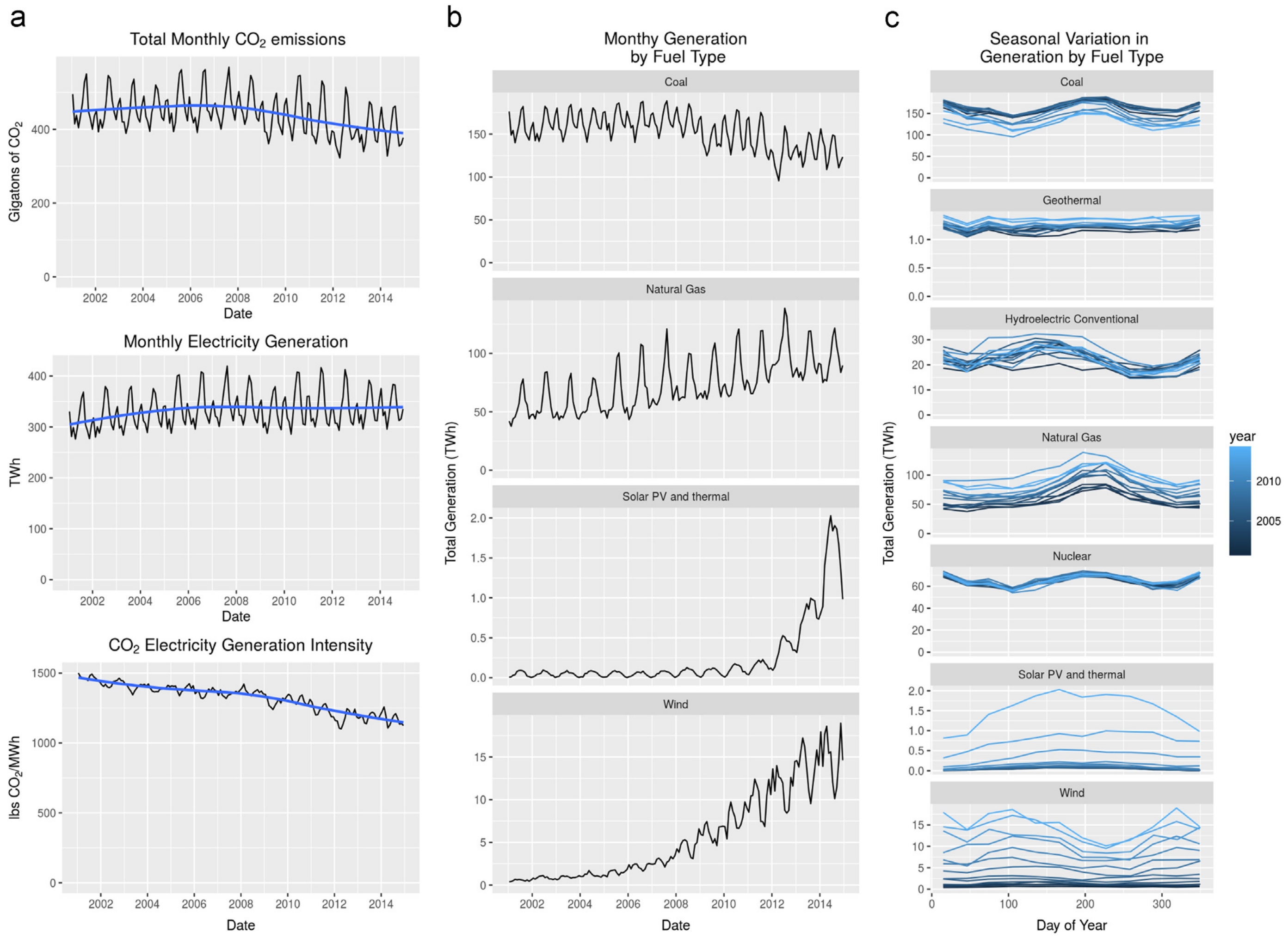

Fig. 1. US total CO_2 emissions and electricity generation.

Increased EGU efficiency: EGUs are made more efficient at converting fuel into electricity.

Dispatching lower-emitting EGUs: EGUs with higher efficiencies, such as natural gas fired combined cycle units, are prioritized over the use of plants with lower efficiencies.

Expanding use of low or zero-emitting generation: The installed base of cleaner generating units is increased.

The proposed version of the CPP from June 2, 2014 also included a fourth block, which has since been removed from the final version of the rule:

Increasing demand-side energy efficiency: Demand for electricity is reduced, which may result in less operation of older inefficient plants with higher CO_2 intensities.

The electrical grid is a complex system where supply and demand are coupled to social, economic and technological factors. A way to understand the rationale behind these building blocks is to view them in light of the merit order (also called the “dispatch order”) of electricity production, which illustrates which power plants will be operational given the demand for electricity (Fig. 3). The merit order shows on the vertical axis the variable operating costs of a power plant, while the horizontal axis shows the cumulative installed capacity of all the power plants, with plants sorted from lowest variable operating cost to highest. A primary factor which determines if a plant will be operating or not is whether the price a plant will receive for generating electricity is above the variable operating costs of the plant, which is based largely on the fuel costs that are needed to generate a given amount of electricity. As demand increases, plants with successively higher variable operating costs are brought online, and in the graph, everything to the left of the demand line indicates power plants which are operating. The sharp up tick on the right tail indicates that older less efficient plants are brought online only during periods of very high demand.

We next examine the implications of the CPP's building blocks using results from our data-driven analysis. The graphs included examine a selection of states exhibiting typical patterns. Details of the data sources along with more extensive graphs for all the states are included in the Appendix. Our analysis focuses on data “within the fence” of the power plants, with data on CO_2 emissions derived directly using fuel emission factors provided by the EIA.[7] Fully quantifying the impact of the Clean Power Plan on CO_2 would require a life cycle approach that would consider CO_2 emissions not just from the burning of fuel, but also from upstream processes such as extraction and processing of the fuel [46,44]. A notable example of the importance of this perspective has been the realization that land use change can contribute significantly to CO_2 emissions related to palm oil production [8]. An issue relevant for electricity

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[7] Fuel emission factors are given by the EIA in the spreadsheet at http://www.eia.gov/survey/form/eia_1605/excel/Fuel_Emission_Factors.xls

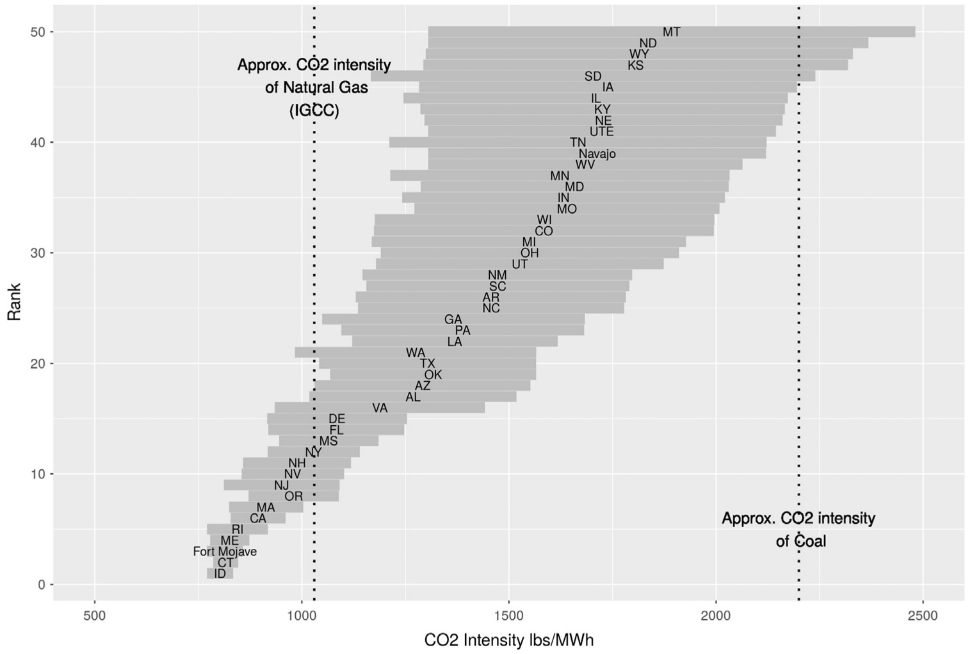

Fig. 2. Required emissions rate improvements per state. The right side of the bars indicates the current emissions rate (based on 2012 EPA data), with the left side showing the required improvement.

production is that while a switch from coal to natural gas is favored by the Clean Power Plan, there has been debate about to what extent using shale gas is actually an improvement over using coal in terms of CO_2 emissions [16,18]. More generally, the issue of methane leaks from natural gas production is also an important factor [1,20], although to some extent this issue is being addressed by other legislation on emissions from the oil and gas industry.[8]

As discussed in the Appendix, the CPP only regulates a selection of total EGUs and excludes those used for industrial purposes, which means that not all of the CO_2 emissions resulting from the production of electricity are regulated. The discussion on which EGUs are to be included under the regulation also highlights the nature of the process of decarbonizing the electricity sector. For most consumers, the specific technology used for electricity production is irrelevant. However, EGUs that are used for industrial purposes may be combined heat and power installations where electricity generation is seen as a byproduct of some larger process, and technologies may not be easily substituted. In some cases the electricity production is a means of utilizing products with low economic value, such as with refineries which generate electricity using residual fuel oil, or electricity generation from coke oven gas as a byproduct of steel production.

For the sake of analyzing historical trends, we analyze *all* of the electricity generators as reported in EIA forms 860, 906 and 923. While we know which current EGUs are likely to be affected by the regulation [41],[9] it is difficult to know which generators in the past would have been covered, as the EPA's selection criteria include aspects such as EGUs which “sell more than one-third of their potential electric output to the grid” [29]. This is not contained within the EIA data. A further distinction is that we analyze all power plants within each state's borders, although for some of the Western states, the CPP creates goals separately for Indian lands existing within those states [30].

3.1. Increased EGU efficiency

The first building block involves increasing the efficiency of the EGUs. Fig. 6a shows improvements in conversion efficiency for generation from coal that have been made across select states over the past decade. Every line represents the cumulative amount of electricity generated for a specific year, using monthly data for each EGU, with EGUs sorted by their efficiency (MMBtu of heat input per MWh of electricity). Many states show a trend towards more efficient generation, however efficiency gains appear to stop around 10 MMBtu per MWh. Illinois, New Jersey, Wisconsin have made large gains in shutting down inefficient plants, and a more extreme case of New York, which shut down many of its power plants, and kept only a few efficient ones. This graph does not track individual EGUs but rather indicates the efficiency of the states' portfolios. As shown in the Appendix, when examining the fifty largest coal EGUs individually, there does not appear to be a clear trend towards greater efficiency.

3.1.1. Rebound effects?

One issue with this strategy, which has been acknowledged by the EPA [30, 334], is that a rebound effect may occur. With efficiency improvements, the marginal costs of electricity generation for an EGU go down. Since it can produce electricity cheaper and will likely be favored in the dispatch order, it may actually run more than previously to such an extent that its total CO_2 emitted would be greater despite less CO_2 emitted per MWh. While this can conceivably happen, and Grant et al. [12] claim to find evidence of rebound effects using aggregated data from EGUs for the years 2005 and 2010, we argue that due to the reasons discussed below, when examining the data it is actually quite difficult to separate out false positives due to the types of factors that need to be considered.

First, a more efficient EGU with more electricity generation and higher total CO_2 emissions (although at a lower rate of CO_2/MWh of electricity generation) does not explicitly mean that a rebound effect has occurred. If the EGU does operate more, then assuming the same electricity demand, that implies a shift in the merit order, where the more efficient EGU is now being favored over another EGU which

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[8] http://www.epa.gov/airquality/oilandgas/actions.html

[9] An overview of which EGUs are included or excluded is in http://www.epa.gov/airquality/cpp/tsd-cpp-emission-performance-rate-goal-computation-appendix-1-5.xlsx

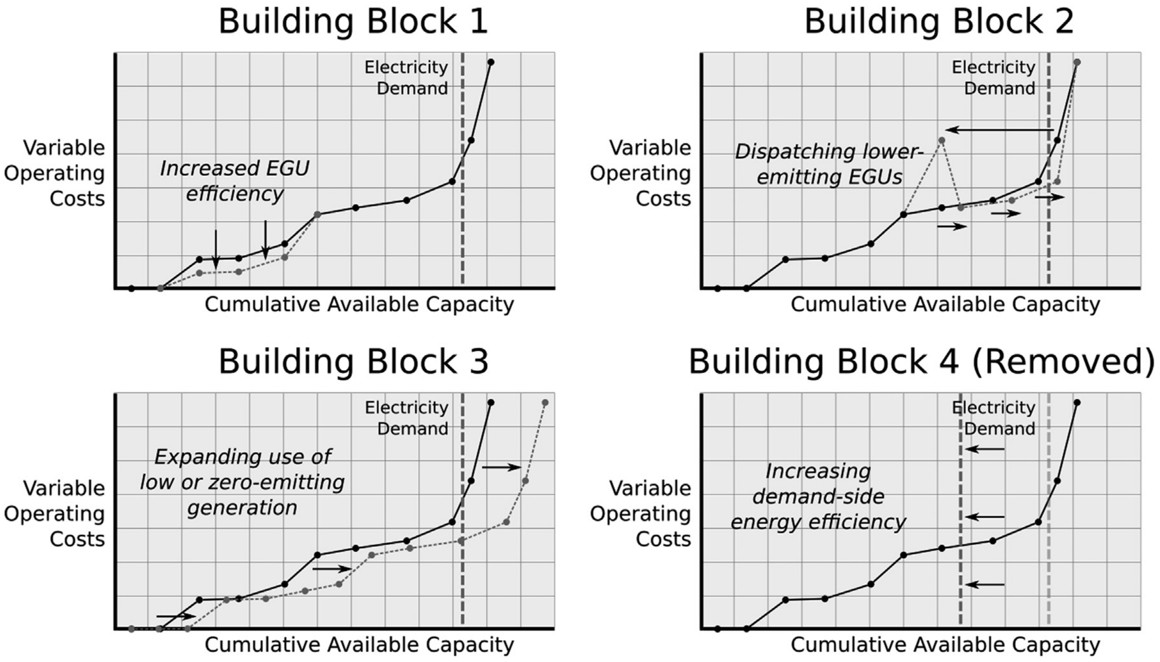

Fig. 3. "Building Blocks" specified within the Clean Power Plan. Four were included in the 2014 proposal, and only the first three were retained for the final version of the CPP in 2015.

will now be operating less. In order to quantify how much additional CO_2 is generated, we cannot simply measure how much additional CO_2 is released by the EGU, but we have to compare this to the amount of CO_2 that would have been emitted if the other EGU was operating in its place. In other words, if a more efficient EGU is emitting more total CO_2 at a system level this still may be less than would be emitted if the other EGU was operating, meaning that although emissions from one EGU have increased, the overall emissions from the power system have actually decreased. Given this situation, while technically there may be a rebound effect at the level of the EGU, there is not one from the point of view of the overall system, which is what matters for the CPP and ultimately the climate.

Concerns about rebound effects also need to consider that EGUs *already* become more efficient with higher amounts of electricity generation. This means that by their very nature, there already is an incentive for them to operate more, without any modifications being made. Before concluding that a rebound effect is actually happening, we need to know if an efficiency improvement has actually been made or if we are only looking at normal operation given a situation of increased electricity demand or an increased number of other EGUs which are offline for maintenance. Fig. 4 uses detailed hourly data from the EPA Air Markets Program Data (AMPD)[10] for the year 2014 and shows for every coal EGU in Texas the heat rate (mmBtu/MWh) and the amount of electricity generated within that hour. While some variation between the plants can be seen, they do all exhibit a trend of higher efficiency given higher output.

The flip side of this discussion is that the emissions rate of EGUs increases when they produce less electricity, as illustrated in Fig. 5. This means that the second and third blocks mentioned below may, if not employed correctly, negate gains made under this block. Coal plants are most efficient when they are continuously operating and supplying base load electricity. If the plants have to shut down production frequently due to a large amount of generation from renewables or other fuel types such as gas, they will be less efficient overall due to the need to reheat the boiler and bring the plant back into operation [9,27]. This means that we cannot look at the operation of a single EGU and conclude if this is leading to positive or negative results, but we have to evaluate the interplay of the generation portfolio.

Furthermore, coal EGUs are already facing pressure to operate less due to competition from gas EGUs which are currently enjoying lower fuel costs. Given the current economic situation, this means that the EGU displaced by the more efficient coal EGU would likely be a less efficient coal-fired EGU. Along with Building Block 2 which aims to dispatch lower-emitting EGUs, it is doubtful that increasing the efficiency of a coal EGU will play a large role in negating the effectiveness of the CPP. Even if electricity demand actually increases leading to more operation of the EGU, the answer to whether or not there is a rebound effect still hinges on the operation of the rest of the EGUs in the system.

3.2. *Dispatching lower-emitting EGUs*

The second building block involves favoring generation from EGUs with lower emissions, thus changing the order in which they are dispatched. We visualize how this might apply to the current situation by constructing a "CO_2 merit order" where CO_2 intensity is plotted instead of variable operating costs (Fig. 6b). This figure shows per state a cumulative sum of the total monthly generation for all EGUs over the course of a year, sorted by its corresponding CO_2 intensity, thus giving a profile per state of the CO_2 intensity of its generation portfolio. The vertical "steps" in the graphs representing various fuel types such as renewables and nuclear (0 lb CO_2/MWh), natural gas (~1000 lb CO_2/MWh) and coal (~2200 lb CO_2/MWh). The slope of the steps indicates the range of generation efficiencies of EGUs using particular fuels. This range is due to differences between EGUs and also due to differing efficiencies that occur during the operation of a single EGU over the course of a year, similar to what has already been shown in Fig. 5.

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[10] http://ampd.epa.gov/ampd/, ftp://ftp.epa.gov/dmdnload/emissions/hourly/monthly/

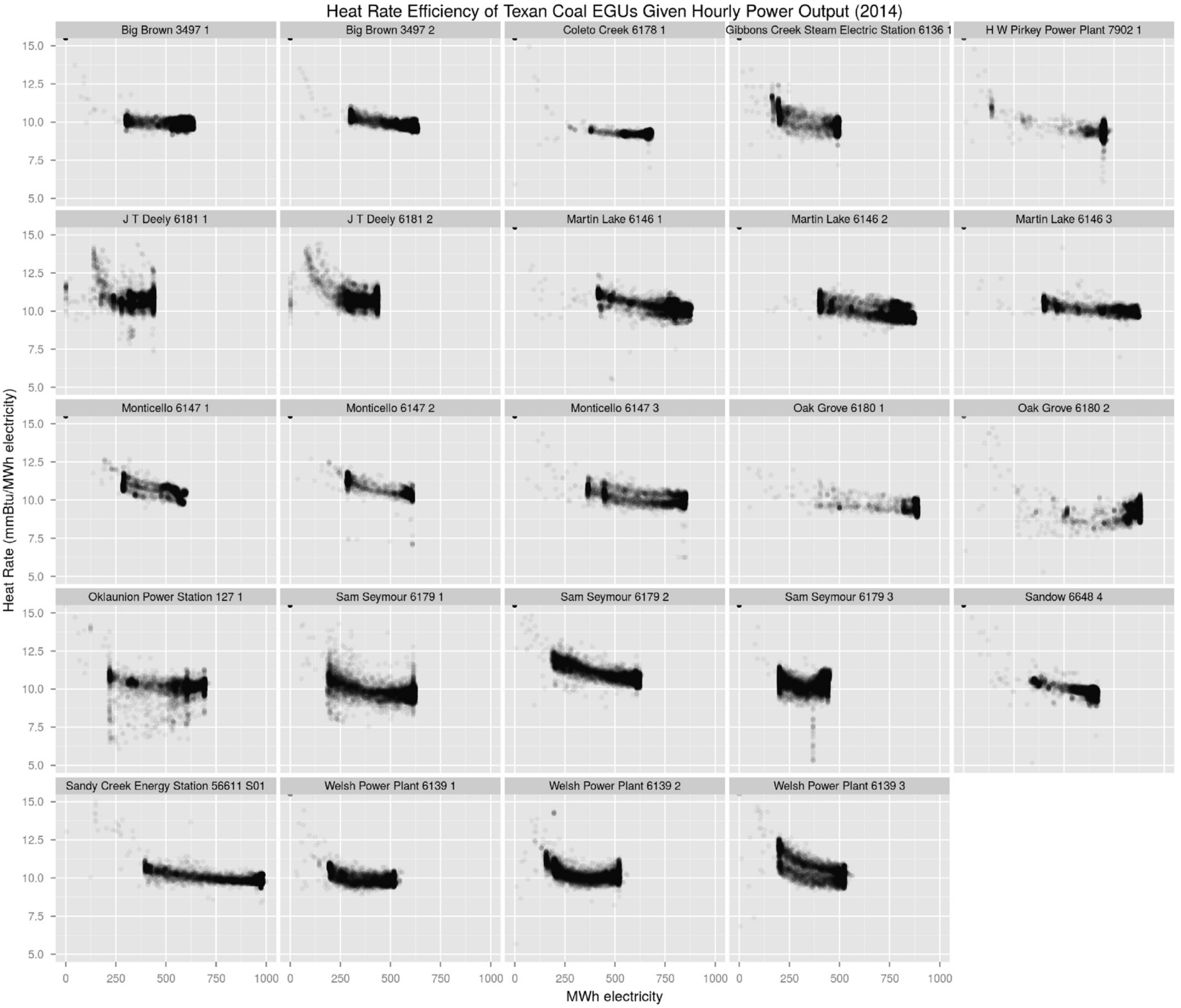

Fig. 4. Heat Rate Efficiency (mmBtu of Heat/MWh of electricity) for Texan Coal EGUs in 2014. First number after the name is the ORISPL code and second number is the unit ID.

Based on the color of the lines representing specific years, we can see how each state has shifted its production portfolio since the start of the millennium, thus giving an indication of how much the CO_2 intensity of their portfolio has changed over the past decade. The EPA Clean Power Plan targets are shown as well, with the interim and final CO_2 intensity targets shown in yellow and red respectively. It should be kept in mind that the targets for the final version of the CPP are calculated based on the fossil fuel generation portfolio, and in the figure generation from renewables is included as well for the point of illustration of the entire portfolio, meaning that the impact of these targets on each state's generation portfolio is most clear for states with large amounts of generation from fossil fuels. In addition to emissions rate targets, the CPP also specifies mass targets. All generation to the left of the black curve results in less CO_2 than this target (using data on generation from 2014). This gives an indication of how much generation would have to be curtailed through demand side reduction or offset through increased generation from renewables.

The trends in four states are shown as examples of common patterns and the impacts the targets may have, with the graphs for the rest of the states included in the Appendix. Wyoming has increased its installed wind capacity, but their continued reliance on coal means that most of their generation is above the target. Iowa has a similar condition to Wyoming, but has installed significantly more wind capacity over the same period. North Carolina has maintained roughly the same amount of generation as previous years, while relying on less generation from coal and switching to more generation from less CO_2 intensive sources, as evidenced by the middle of the line shifting to the right with a series of steps now appearing. Texas has maintained a diverse portfolio augmented by increasing wind capacity. Generally across the US, a change in the dispatch order has already been observed due to falling prices of natural gas [32].

A question that needs to be addressed relates to how this building block will influence the economics of the electricity market. In certain cases, changing the dispatch order many mean that EGUs with higher generation costs are favored, although this depends on factors such as the economics of fuel costs and CO_2 pricing. It is interesting to note that the first building block (increasing EGU efficiency) can be seen as a subset of the second building block. A more efficient EGU may have lower marginal operating costs, meaning that it would be economically favorable for it to operate more often.

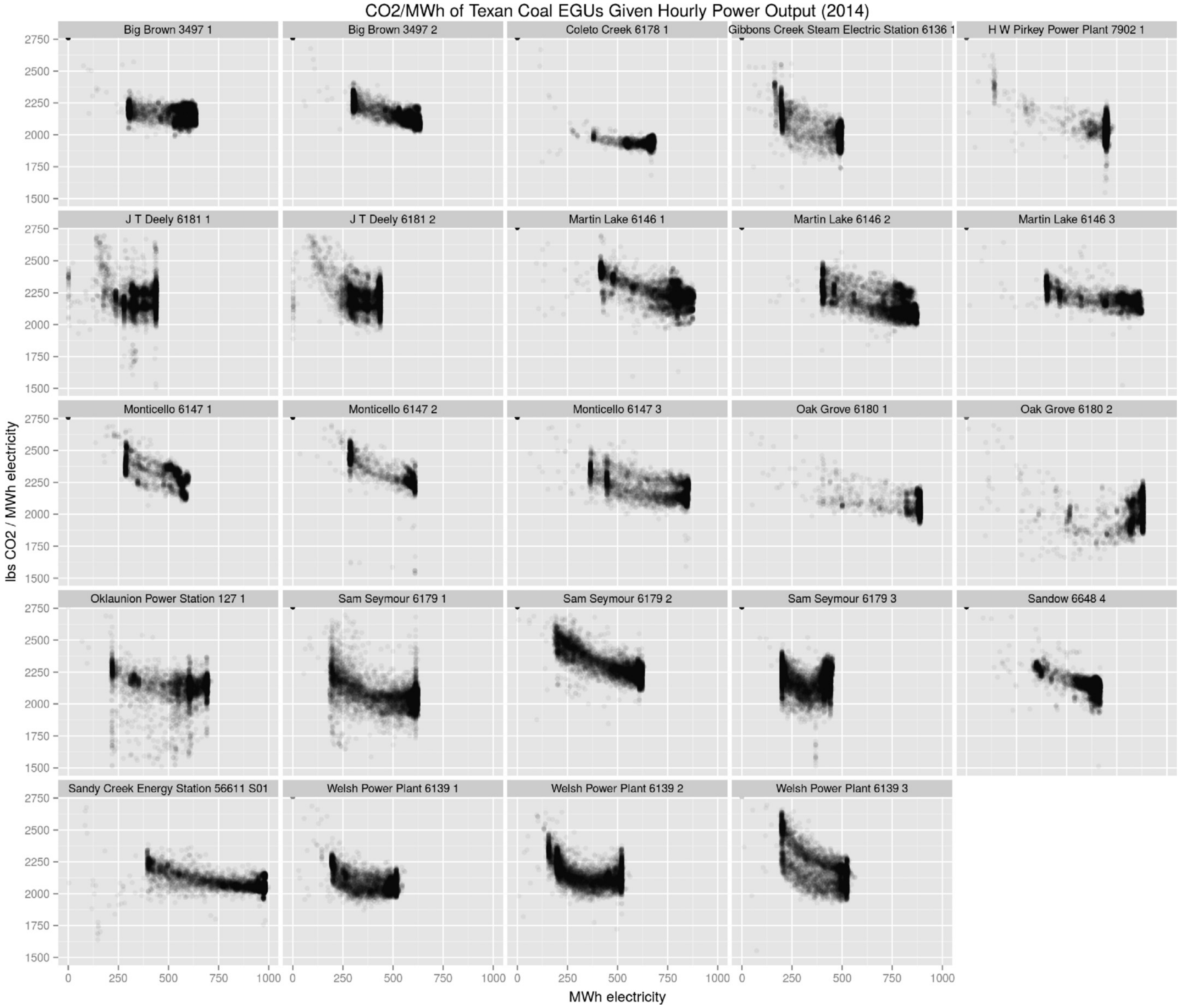

Fig. 5. Pounds of CO_2/MWh of electricity generation for Texan Coal EGUs in 2014. First number after the name is the ORISPL code and second number is the unit ID.

3.3. *Expanding use of low or zero-emitting generation*

The third building block involves adding new EGUs to a states' generation portfolio. Historical changes can be observed when examining electricity generation by fuel type (Fig. 6c). Most states produce a majority of electricity from fossil resources. Some states that largely relied on coal at the start of the millennium have since significantly diversified their generation with natural gas (Pennsylvania). In many Midwestern states, generation from wind is increasing without a noticeable substitution of fossil fuel.

Seasonal variation of supply and demand is an important consideration for this building block. Showing the trend lines for several major fuel types, Fig. 1c exposes these variations. Renewables (except pumped-storage hydroelectricity and geothermal) are largely supply-driven, while generation from fossil fuels (and to some extent nuclear) is generally demand-driven. While changes in the seasons provide us with renewable resources that can be used for the generation of electricity, they also impact the drivers of electricity demand. Demand for air conditioning occurs in the summer, while in winter demand increases, especially in the northern states, due to factors such as fewer hours of daylight, more time spent indoors, and electric heating. The drivers of electricity supply and demand do not always coincide, and strategies must be employed to address the ensuing imbalance. This is seen in Western states (Oregon) that rely largely on hydroelectricity, which experiences an annual surge in generation due to snowmelt. In some cases, supply and demand do coincide as with hotter summer temperatures being accompanied by both increased cooling demand and increased generation from solar. The rest of the year, generation from fossil fuels is brought online to fill in the production gap. The effects of fuel economics are visible as well. Coal plants generally run most of the year, with gas plants brought online to provide extra base load for higher demand in summer.

The trends also show the evolution of the electricity sector in many states. The recent growth of the wind industry is especially visible in the Midwest states, although unlike with the case of natural gas, in many of the states, except Minnesota, the total amount of generation is increasing, without a noticeable fuel substitution occurring. A challenge related to this trend is the geographical mismatch of supply and demand. While generation from wind has expanded to a large extent in the Midwest and the Great Plains, these are areas of low population density, while much of the population resides near the coasts.

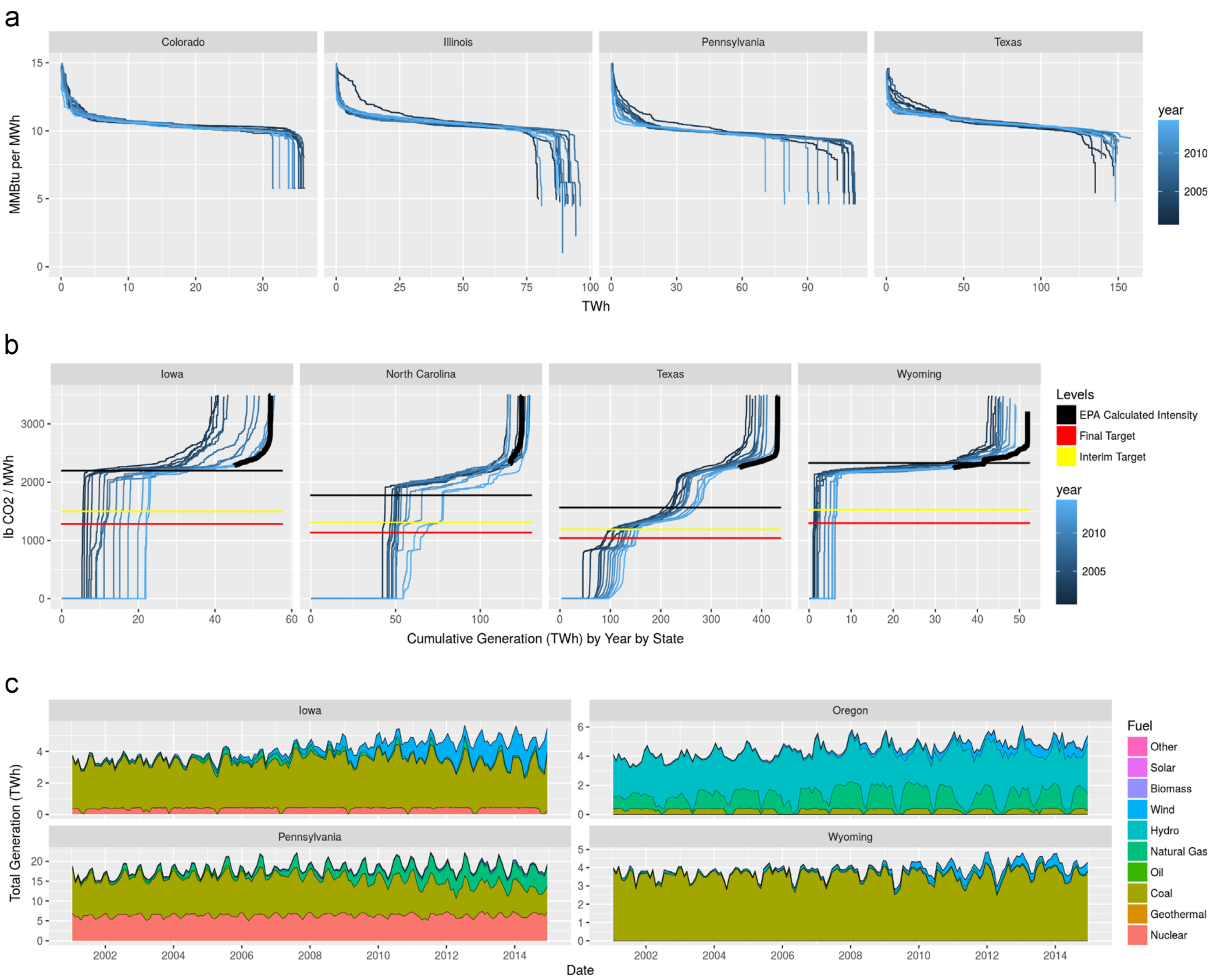

Fig. 6. (a) Total yearly generation by coal EGUs, sorted by efficiency and (b) CO_2 intensity per cumulative generation. Generation to the left of the black curve results in CO_2 emissions below the 2030 mass targets and (c) monthly generation by fuel type.

Transmission network expansion will be needed to better link areas of supply and demand [19].

One of the most significant changes seen is that the aforementioned impact of shale gas is reflected in a general increase in the use of natural gas, with less generation occurring from coal. In the Appendix, Fig. A8 gives an overview of the changes per state in generation from coal and natural gas since 2001. In many of the eastern states a substitution can be seen, although in other states this is not as clear, likely due to competition in the merit order from growing amounts of renewables.

Questions about whether the shale gas revolution will continue have been raised [45,17,22,43], and the ultimate answer to this will have a large impact on the success of the CPP. Fig. 7 summarizes historical and projected data on natural gas production and consumption based on EIA data [37–39]. As can be seen, several projections are given based on factors such as the oil prices and the amount of gas resources available.

The electricity sector currently consumes about 1/3 of the total production of natural gas in the US, and only modest changes in the volume consumed are predicted by the CPP deadline of 2030, while the overall production of gas is forecast to steadily increase. As can be seen in Fig. 2, several states could meet their targets or significantly improve their emissions rate through a switch to natural gas. To evaluate an upper bound on how much additional consumption this could represent, we take generation data from 2014 and successively replace generation from the most CO_2 intense coal plants until the state mass target is met or all generation from coal has been replaced. The value of the total gas consumed in this scenario is reflected in the “Total gas consumption to meet targets” line. If this occurs, then natural gas consumption by the electricity sector would more than double, although would still be less than the total amount produced. While this provides an extreme example as no additional renewable capacity is assumed to be installed, the forecast indicates that there would be enough supply to enable this.

There are still serious concerns though. What should be noted is that production from shale gas is already greater than that of gas from conventional sources, which has declined by over a third in under a decade. If shale gas production forecasts prove to be too optimistic, the electricity sector could find itself in a situation where the economic advantage enjoyed by electricity generation from gas disappears while the main fossil alternative, coal, is being phased out due to the targets set by the CPP. Such a situation highlights the danger of relying too much on natural gas to reach

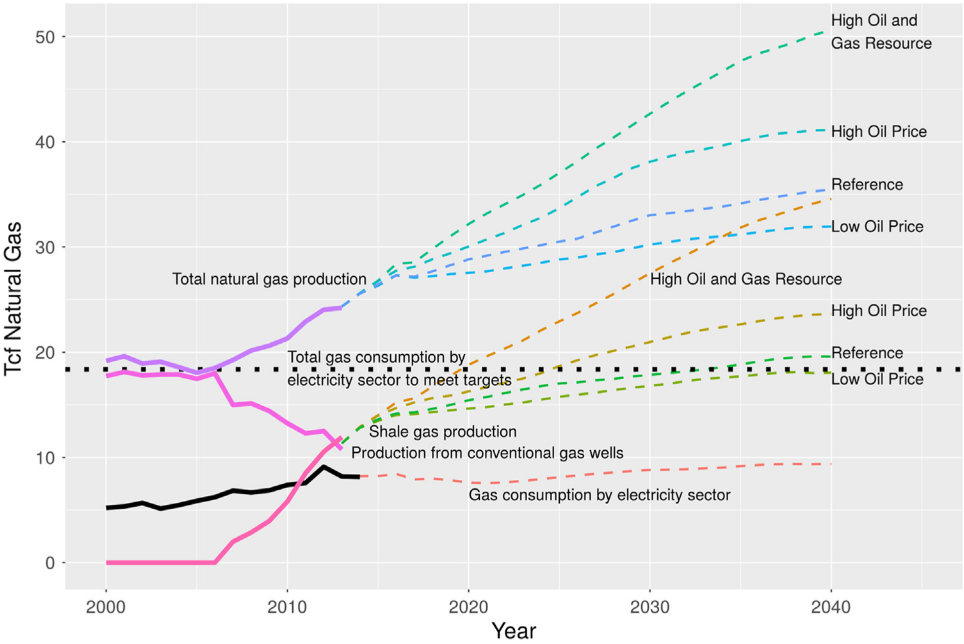

Fig. 7. Historical and projected trends in natural gas production and consumption.

the targets, and the importance of diversifying among renewable technologies.

3.4. Increasing demand-side energy efficiency

The proposed version of the Clean Power Plan from 2014 included a fourth building block, now removed from the final version in 2015, which aimed to reduce electricity demand. In the dispatch order, the most inefficient plants only operate during periods of high demand, meaning that the timing of the reduction in demand could have different effects. A reduction in demand during times of peak demand would have a larger impact on CO_2 emissions than would an equivalent reduction during a period of lower demand, since this could cause the least-efficient peak-shaving plants not to operate. Economics also play a role – if generation from coal is cheaper than from gas, a reduction in demand may mean that gas-fired plants run less, resulting in a higher overall CO_2 intensity of generation. Even though overall CO_2 emissions may decrease, a state may be worse off in meeting its targets due to situations such as this.

A further uncertainty relates to an increase in the use of electric vehicles. Instead of cars charging directly when the owner plugs them in, other strategies may be employed to distribute the charging to smooth out peaks in overall electricity demand [10,42]. While electric vehicles may actually increase overall demand, to understand their impact on CO_2 emissions, we have to understand how they may increase (or decrease) demand during specific points in time.

There are also deeper aspects of energy efficiency and the nature of the states' economies. Fig. 8 illustrates the amount of CO_2 generated per person per year versus the amount of energy consumed for every dollar of GDP. The size of the text indicates the total CO_2 emissions for 2010. States such as California and New York, whose economies have large technology and financial sectors, have by far some of the lowest per capita CO_2 emissions, and are remarkably efficient in terms of energy use per dollar of GDP. States, such as Wyoming that rely to a large extent on natural resources, rank worst in the nation by both of these measures.

4. Role of state policies

The CPP gives states freedom in terms of how they meet the goals that have been set. Many of the states have created their own policies to support the development of renewable energy given the previous lack of leadership at a national scale. It remains to be seen how these may be adapted in complying with the CPP as states are faced with a firm target to meet by 2030.

One of the policy tools that states have used in encouraging renewable energy is Renewable Portfolio Standards (RPS) which specify the amount of generation that must come from renewables by a particular year. Currently 29 states have mandatory RPS targets, 8 have voluntary targets, and 13 have not implemented any [4]. The exact details of the RPS targets vary by state in terms of compliance rules and enforcement.

Fig. 9 gives an estimate of how much each state's RPS contributes to meeting its CPP targets, and how this compares to the current amount of generation from non-hydro renewables. This assumes that the RPS addresses non-hydro renewable energy generation, and is based on monthly EIA power plant generation statistics from 2014. The amount of generation from non-hydro renewables needed to meet the CPP is determined per state by replacing the most CO_2 intense generation with renewable generation until the mass-based target is met. This does give an extreme value as it only considers the addition of renewables and not the implementation of the other CPP building blocks. This value is then added to the amount of already existing non-hydro renewables. Given this, we can then determine how close the RPS gets the state to meeting its CPP targets, and how close it already is based on existing generation. Values above the vertical line indicate that the states' RPS is more ambitious than that required by the CPP, while those below will likely need to employ other measures. The horizontal axis indicates the amount of progress that the states have made toward their CPP mass targets, irregardless of whether goals are set or not. A logarithmic scale is used for the vertical scale, as some of the states' RPS goals far exceed that required by the CPP, especially if it results in the most CO_2 intense generation being brought offline.

By comparing the horizontal and vertical axes, it becomes clear that a weak RPS is not necessarily a sign of a lack of progress. For example, Iowa has 5667 MW of installed wind capacity as of 2014 [36], which is over 50 × greater than the 110 MW requirement in its Renewable Portfolio Standard (RPS) [14]. With the exception of California and Hawaii, all of the states' Renewable Portfolio Standards will expire before 2030, and as many states have RPS targets below that needed for the CPP, a new wave of legislation can be expected.

Analyzing the effectiveness of state policies in achieving increased generation from renewables is difficult as policies are often designed to address local circumstances. These particular implementation details make it challenging to consistently compare the policies across multiple states. Properly answering this question requires a detailed examination on a state-by-state basis, and studies are emerging such as that by Wiser et al. [47], which is a multi-year effort to analyze the costs, benefits and impacts of states' RPS with estimates of displaced fossil generation.

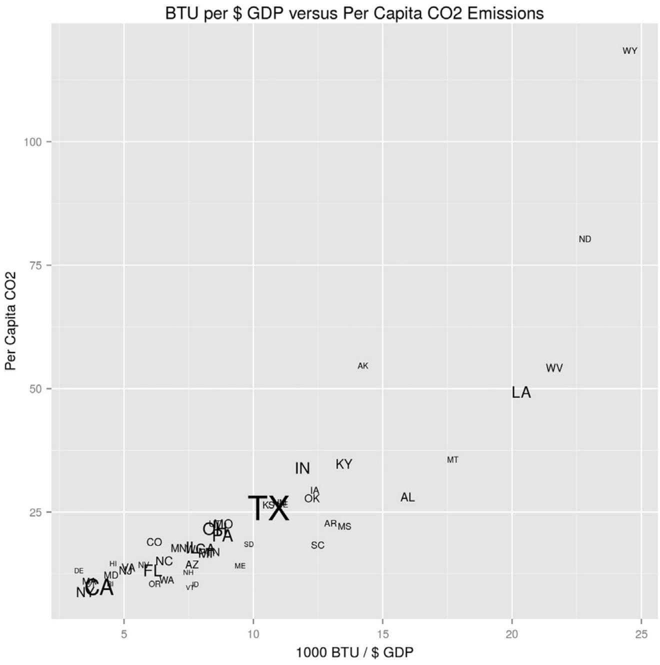

Fig. 8. Energy Use per $ GDP versus CO_2 per capita, size relates to total CO_2 emissions.

Wiser et al. [47] show that renewable energy installed since the enactment of RPS in the states had by 2013 had resulted in 98 TWh of generation from renewables, accounting for 2.4% of the total US electricity generation, and a reduction of 61 million metric tonnes of CO_2 from direct combustion. Most reductions had occurred in the Great Lakes and Mid-Atlantic regions, in addition to Texas, California, Colorado, Washington. This reflects areas that have both high RPS targets and where the most CO_2 intensive generation from coal plants is likely to be displaced.

Many previous efforts [21,3,7,24,11] fit regression models to a variety of factors for each of the states related to the presence and age of certain types of policies along with indicators aiming to capture aspects such as the political party in power and the prevalence of environmental attitudes. These studies all come to mixed conclusions, which we argue is due to several reasons. First, summarizing the conditions in each state through the use of categorical variables is useful although it still obscures relevant details. For someone facing the choice of whether to invest in a new renewable energy facility, the ultimate question is whether the numerical magnitude of factors such as tax incentives and feed-in tariffs are sufficient for a positive business case. In other words, this is not so much about the presence or absence of factors, but rather whether the sum of any combination of incentives can lead to a positive IRR.

A second issue is that these studies do not examine cross-border effects. An example of why this matters is the case of Iowa, whose neighbors support its large amount of wind generation as a means to meet their own RPS goals [14]. This leads to an interesting situation where the presence of an RPS for Iowa is not very informative as the state has far exceeded its goals. The presence of an RPS for surrounding states may not seem to have led to much of an impact until one realizes that the decarbonization may be happening outside of the state borders.

A similar situation can be seen in the northeast of the US where several states are part of the Regional Greenhouse Gas Initiative (RGGI). After the policy was implemented, we do indeed see less generation from coal and oil, with more generation from natural gas. However, the policy has also led to increased electricity imports from Canada [13]. From an emissions perspective, this is still beneficial as most of the

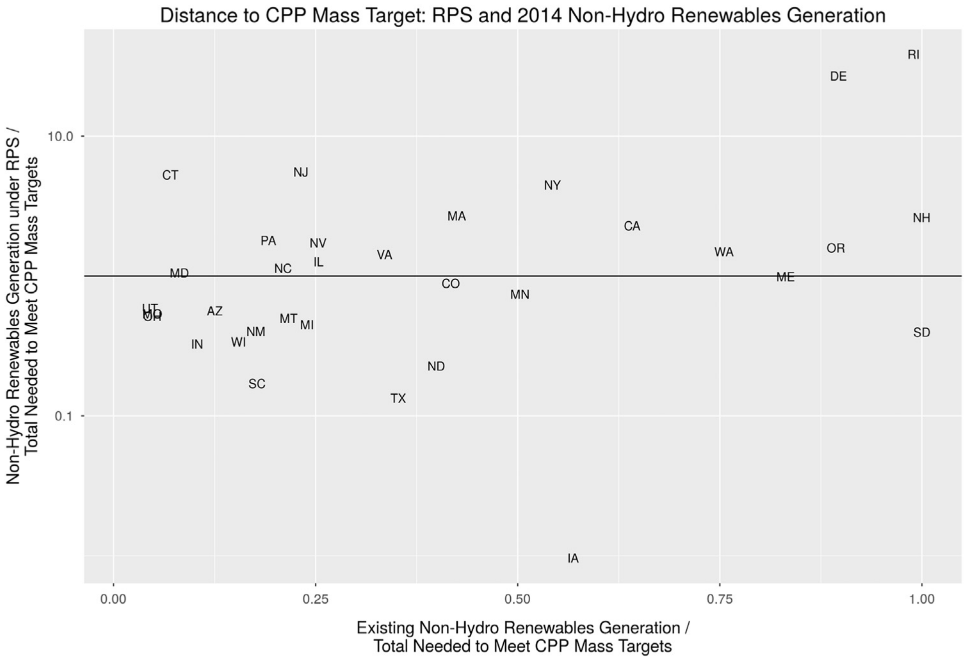

Fig. 9. Distance to CPP mass target.

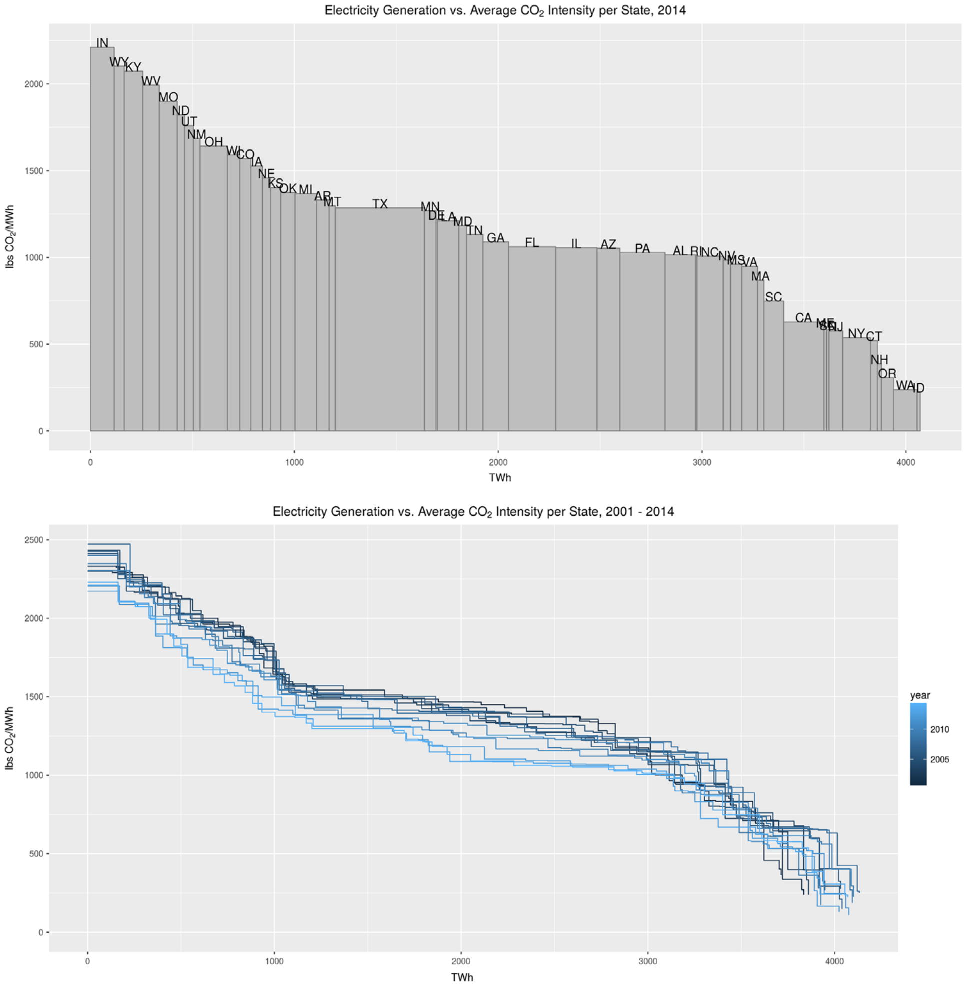

Fig. 10. Electricity generation vs. average CO_2 intensity per state, 2014.

electricity is being generated from existing hydropower plants. Similarly, California imports over 25% of its electricity from other states [31,35]. A large portion of this is from hydropower, although California still has long-term contracts with several coal plants in the Southwest US, which it is aiming to phase out by 2026 [2].

A third issue is that these studies use data that is several years old and before much of the growth in renewables occurred. Carley [3] notes an interesting situation where the renewable potential is not significant in predicting investments in renewables. This is noticeable particularly around the Midwest, although recent data shows that this situation has changed as the amount of installed wind capacity has increased significantly in these areas, even in places such as Wyoming which is dominated by coal and still does not have an RPS in place. As of 2014, 9% of Wyoming's electricity comes from wind, although there are no state-level incentives for wind farms, aside from a generation tax credit that expired in 2013. News articles from the state are claiming that developers are moving ahead with projects even without government incentives since wind has become so economically attractive, although they are currently facing roadblocks of transmission capacity and a lengthy permitting process [26]. This situation is in line with recent estimates [38] showing that the US average total system levelized cost of energy (LCOE) for wind is the same as with natural gas combined cycle plants and is better than coal. The US average LCOE for solar is still higher than that for coal, although the price of solar has been consistently dropping, and just as with wind, large changes can be expected as it becomes cost competitive with its fossil alternatives.

While state policies will be relevant for meeting the CPP targets, we will likely see large changes in the next few years in their implementation. States currently face the question of whether to meet the targets on their own or to set up cooperation with other states in a way that can leverage the different distribution of renewable potentials and economic factors. Additionally, with the improving economics of renewables, we will likely see the importance of renewables policy shift from providing incentives to improving operational aspects related to transmission capacity and managing intermittency of generation.

5. Future concerns

While we have not aimed to predict the effectiveness of each building block of the CPP, the data has shown that these mechanisms have led to meaningful reductions of CO_2 emissions in the past. Although many states still have room for improvement, each building block has limits dependent on the states' characteristics. To get a view into the trends in CO_2 intensity changes, we first refer to Fig. 10a, which shows how each of the states contributes to the overall CO_2 emissions of the US. The horizontal axis shows the total US generation broken down into segments per state in 2014, with the bar height indicating CO_2 intensity of generation. The area under the curve shows the total CO_2 emissions per state.

Plotting this profile for the years 2001–2014 (Fig. 10b) shows that not only has the CO_2 intensity been dropping, but also by examining the area under the curve, the total amount of

CO_2 emissions has dropped as well. The most CO_2 intensive state is now emitting 2200 lbs/MWh as to 2500 lbs/MWh in 2001, and the curve shift to the right shows that demand reduction is not apparent, and the biggest reduction has likely been achieved by shifting to natural gas (the big plateau at 1100 lbs/MWh), which has taken over coal operating hours.

While these trends may be interpreted as positive or negative with regard to the effectiveness of the CPP targets, there are several factors that must overall be considered:

Change is fast, change is slow: The growth in natural gas and wind shows that large changes can happen within a decade. The data also may indicate that we have picked "the low-hanging fruit" for efficiency improvement of generation from coal by revamping installations or taking them out of service. This may imply that future improvements in areas without large potential for renewables will be slow because of the long operational lifetimes of power plants.

The future of shale gas: Electricity sector CO_2 reductions in some states have been enabled to a large extent by shale gas, and as shown in Fig. 2 many states may meet their targets mainly by switching to gas. However, there are questions about the life cycle emissions of shale gas [16] and to what extent emissions "outside the fence" of power plants, such as methane leakage from pipes, could reduce CO_2 emissions reductions due to a switch to natural gas from coal.

A key uncertainty that needs to be investigated further is that if concerns that shale gas production forecasts are too optimistic [45,17,22,43] turn out to be true, this could negatively effect the economics of meeting the CPP targets. As shown in Fig. 7, production from conventional gas fields has declined by a third within the last decade, with shale gas now being the dominant source of gas production in the US. Increased generation from natural gas will help the states meet their CPP targets, although if shale gas production decreases, states will face higher fuel costs at a time when coal plants are being decommissioned, which emphasizes the urgency of transitioning to renewables.

The growth of solar and wind: Increased generation from wind is already noticeable primarily in the Midwest. While solar has been doubling in generation for the past several years, it is still a nearly imperceptible part of the generation mix. The national average LCOE of wind is already on par with gas plants and is more favorable than coal, while solar is not as attractive, but continues to decrease in price. If prices continue to fall and manufacturing capacity is able to grow quick enough, large changes in the generating portfolio of the states may be possible. However, seasonality and intermittency must be managed.

Upgrading the grid: Locations with large renewable energy potential do not necessarily coincide with the areas of large electricity demand, as shown by the growth of wind in the Midwest. The grid will need to be updated to harvest stranded renewable resources.

Electric vehicles: These will increase demand, although vehicle-to-grid implementations that distribute charging times can smooth out peaks in demand and influence the merit order in ways that impact (positively or negatively) the CO_2 intensity of generation [42].

Local actions, national impacts: Given the previous absence of a national climate policy for the electricity sector, many states took the initiative to create their own policies. In a survey of these, the EPA has stated that "[t]heir leadership and experiences provided the EPA with important information about best practices to build upon in the proposed rule" [40]. As the impacts of the CPP unfold over time, we cannot simply extrapolate the impact of these state policies forward, but a key aspect to watch is how policies that have worked at a state level will now have impacts when applied at a national level. These existing state policies give some states a path to reach their targets, but with pressure now coming from a national level and options such as interstate emissions trading being mentioned (beyond its current limited scale), we may see significant changes as new policies are implemented and states with weaker policies have to find viable means to meet their targets.

National actions, local impacts: Some opposition to the CPP relates to the importance of fuel exports to state economies. In 2012, Wyoming produced 39% of all the coal mined in the US, and has over a third of recoverable coal reserves at mines that are currently producing [34]. A national reduction in coal use will have local economic impacts, but also may impact global coal prices and use.

6. Conclusion

We have completed an analysis using detailed US electricity generation data of the period between 2001 and 2014. On the upside, our analysis reveals that there clearly is momentum towards decarbonization. Several CPP building blocks already are being utilized in the period analyzed – though to different degrees and in different ways across the states. Less efficient coal EGUs are disappearing from the generation portfolios of many states. Across the Eastern states, a main factor explaining the observed decarbonization is dispatching lower-emitting generation units due to the falling prices of natural gas. In select states such as in the Midwest has the use of low-/zero-emitting generation such as wind been noticeably expanded.

Throughout the CPP, the EPA has emphasized flexibility in allowing states to achieve the emissions targets, and we can see the importance of this through the diversity of factors at work across each of the states. Extreme examples exist such as Oregon, which during the course of a year alternates between virtually nonexistent CO_2 emissions from power generation, to nearly half their generation coming from fossil sources. There is no one-size-fits-all solution, and what remains to be seen is how the combination of factors such as the long lifetimes of fossil power plants and associated interests, the seasonality and intermittency of renewable generation, along with possibilities such as a greater than expected deployment of electric vehicles and congestion due to a lack of grid investments may impact the routes through which further decarbonization is achieved.

Conflict of interest statement

None declared.

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Appendix A

A.1. Data sources and processing

Figs. 1, 6 and 10 are sourced from EIA Form 906 and 923, specifically the "Page 1 Generation and Fuel Data" worksheets. CO_2 emissions are derived given information about fuel consumption, combined with fuel emissions factors specified by the EPA (http://www.eia.gov/survey/form/eia_1605/excel/Fuel_Emission_Factors.xls). Data on state CO_2 intensity targets, along with

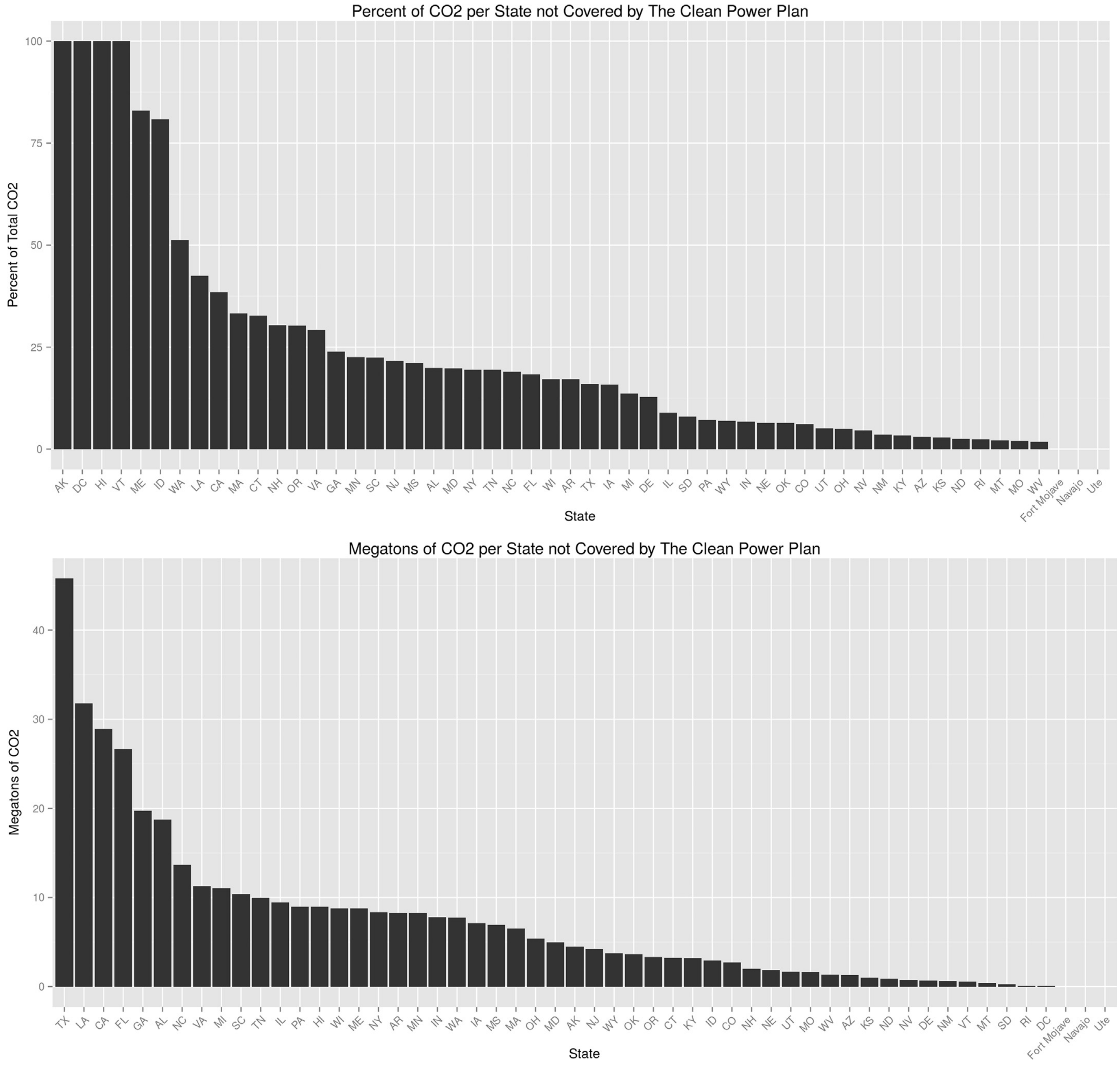

Fig. A1. CO_2 emissions not covered by the Clean Power Plan, in absolute and relative terms. Calculations based on spreadsheet indicating which EGUs are included or excluded when calculating the CPP targets (Goal Computation Appendix 1–5 in http://www.epa.gov/airquality/cpp/tsd-cpp-emission-performance-rate-goal-computation-appendix-1-5.xlsx).

CO_2 emissions and electricity generation of EGUs covered by the Clean Power Plan, are documented in http://www2.epa.gov/sites/production/files/2014-06/20140602-state-data-summary.xlsx. This same spreadsheet is the source of the data in Fig. 2.

Figs. 4 and 5 use hourly data from the EPA's Air Markets Program Data.[11] Fig. 7 is generated using data from http://www.eia.gov/environment/emissions/state/analysis/, specifically “Table 1. State energy-related carbon dioxide emissions by year (2000–2011)” (http://www.eia.gov/environment/emissions/state/analysis/excel/table1.xls), “Table 6. Energy intensity by State (2000–2011)” (http://www.eia.gov/environment/emissions/state/analysis/excel/table6.xls) and “Table 5. Per capita energy-related carbon dioxide emissions by State (2000–2011)” (http://www.eia.gov/environment/emissions/state/analysis/excel/table5.xls).

All data is processed in R, using XLConnect[12] to read Excel files, the sqldf package[13] for querying the data, and the ggplot2 package[14] for visualizations.

The importance of how the EIA has prepared this data cannot be understated. In Europe, the type of analysis shown in this paper simply could not be done, as there is no central database that consistently describes power generation, especially at the

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[11] http://ampd.epa.gov/ampd/

[12] http://cran.r-project.org/web/packages/XLConnect/index.html

[13] https://code.google.com/p/sqldf/

[14] http://ggplot2.org/

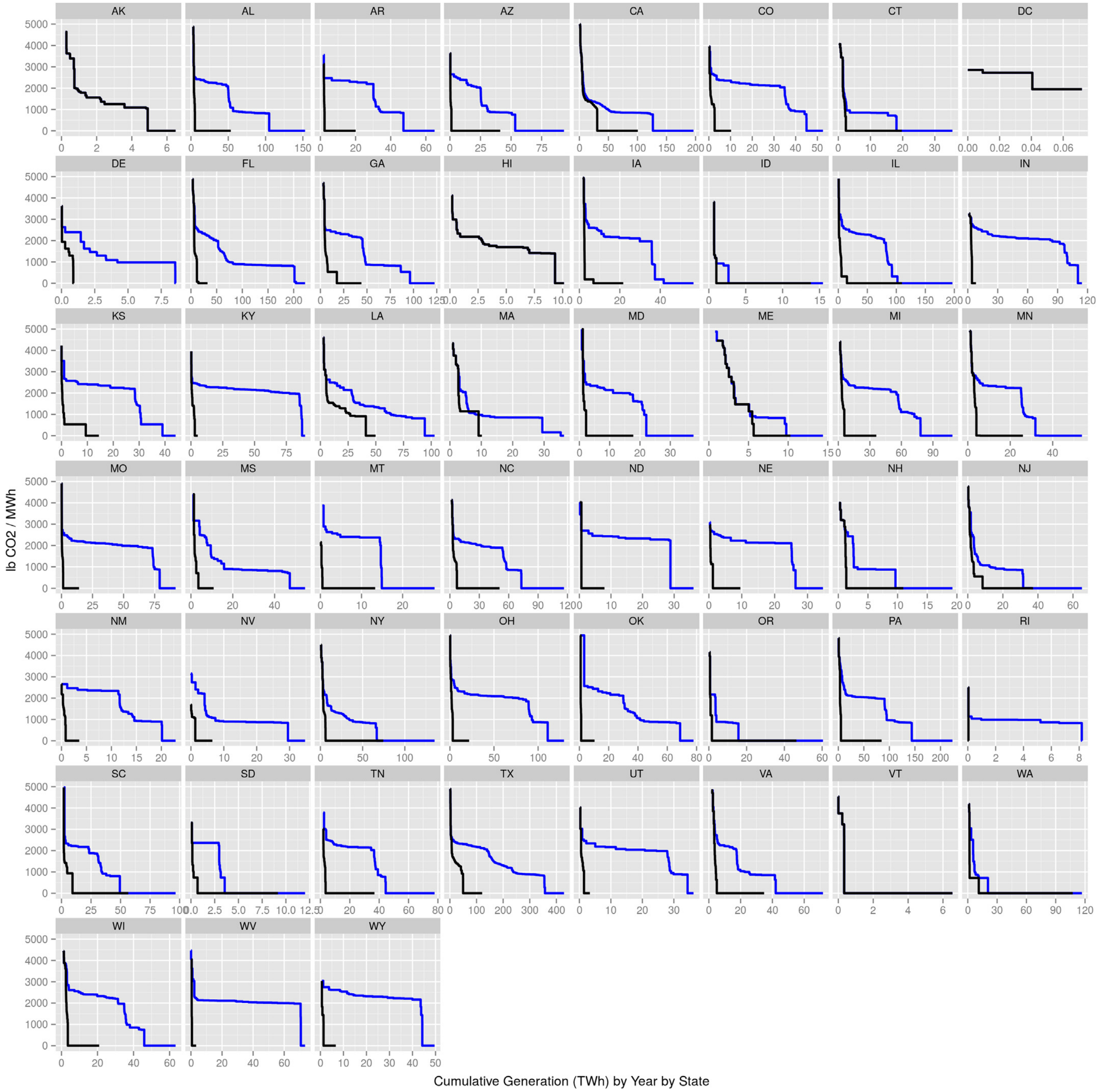

Fig. A2. Cumulative generation per state sorted by CO_2 intensity. Blue represents all EGUs, while black indicates EGUs excluded from the Clean Power Plan. Based on data in Goal Computation Appendix 1–5 in http://www.epa.gov/airquality/cpp/tsd-cpp-emission-performance-rate-goal-computation-appendix-1-5.xlsx). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

EGU level and with monthly observations. We are not aware of any other dataset around the world that covers such a large power system with this level of spatial and temporal granularity. The data is very well structured for several reasons. First, the data columns are consistent across the years 2001–2014, which makes it straightforward to merge them together. Furthermore, unique identifiers are consistently used for power plants, states, regions, etc. This allows us to very easily write queries to analyze slices of the data at various system levels.

For the EIA Form 906 and 923 data, the main processing involves merging together data from the “Page 1 Generation and Fuel Data” worksheets into a single table. In the original data, the monthly observations are recorded in columns. The table is reshaped so that monthly data is recorded in rows, meaning that there is now a single column for monthly generation, a single column for heat input, etc. An additional column is added to the table to record the date of the observation. This processing results in approximately 1.4 million rows of data. With the data in a large table, most of the analysis is done in a similar fashion to that shown in the code below. First a SQL query is performed on the table to extract the relevant slice or aggregation of the data, and this data is directly used within a

```
# Query the data for total generation and CO2 emissions per date
# This is aggregated for the entire US
df = sqldf(”SELECT dayOfyear, year, date,
           SUM(netgen) AS totalGeneration,
           SUM(kg_CO2_emissions_calculated_using_fuel_emissions_factors)
                AS totalCO2kg
           FROM generationAndFuelData GROUP by date”)

# Plot the data, convert kg to Gigatons

ggplot(df, aes(x=date, y=(totalCO2kg*2.2)/1e9, ymin=0)) +
     geom_line() +
     ggtitle(expression(paste(”Total Monthly ”, CO[2], ” emissions”), sep=””)) +
     geom_smooth(se=FALSE) +
     xlab(”Date”) +
     ylab(expression(paste(”Gigatons of ”, CO[2], sep=””)))
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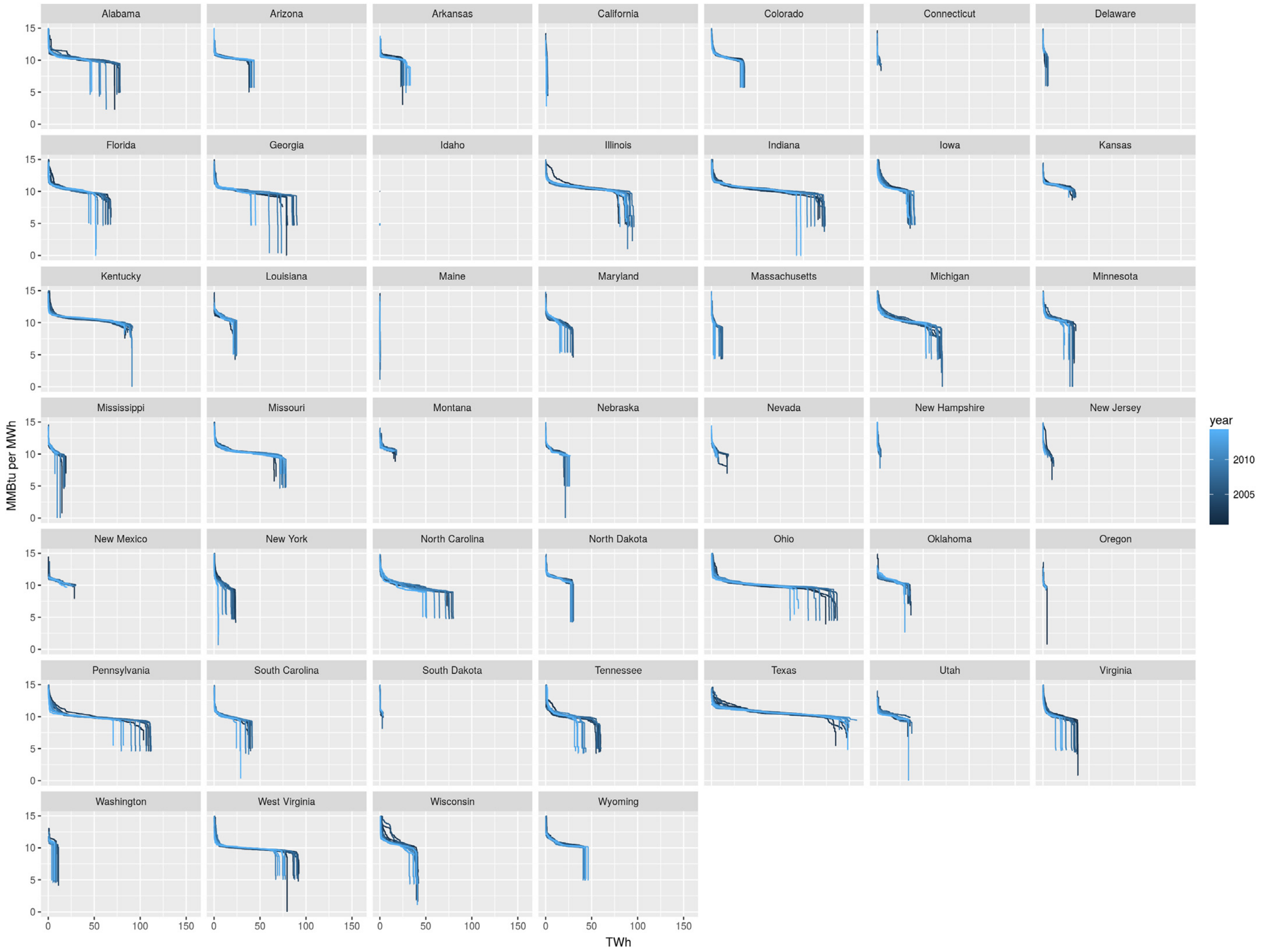

Fig. A3. Electricity generation by coal plants, sorted by conversion efficiency.

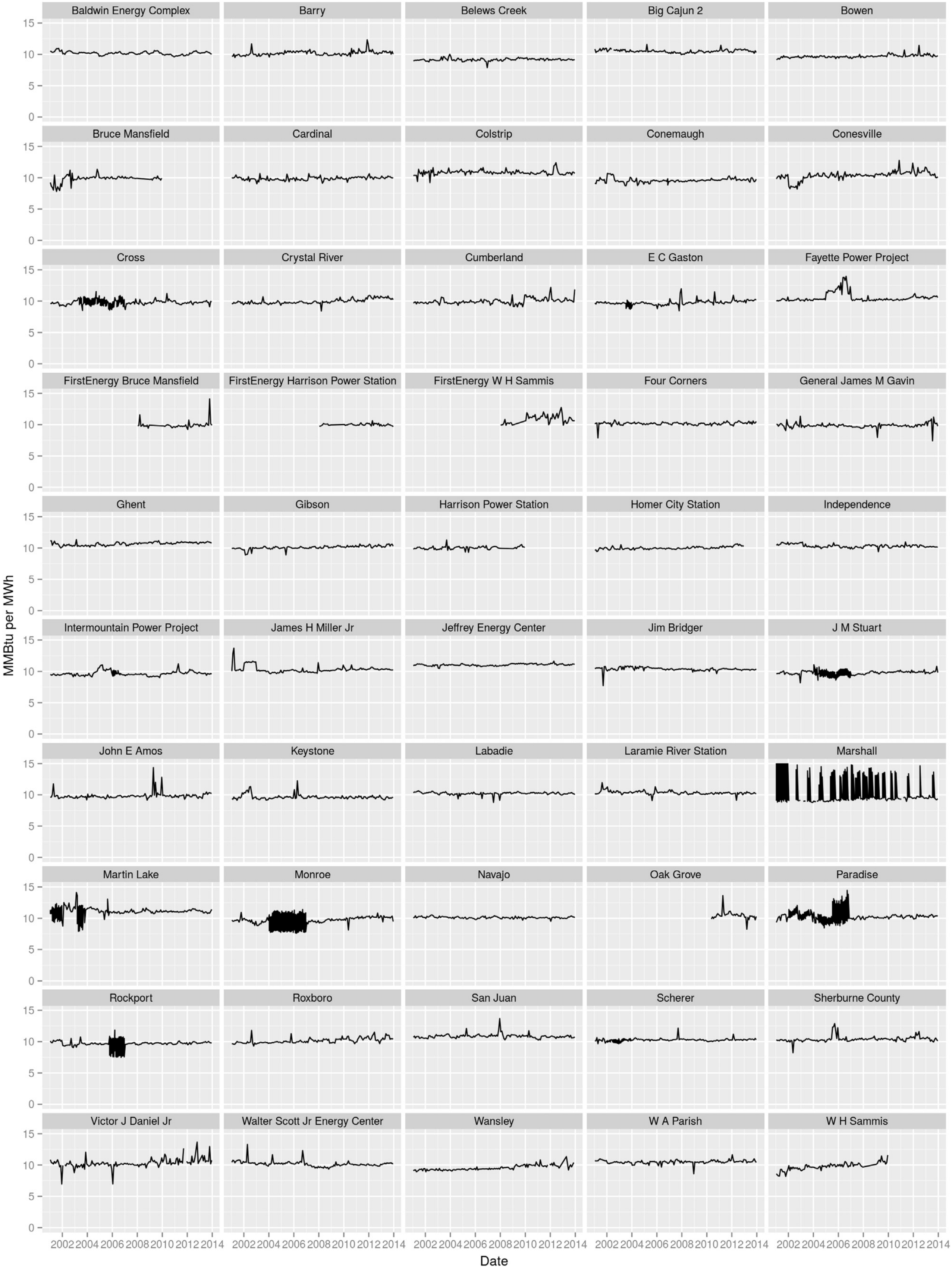

Fig. A4. Monthly conversion efficiency of top 50 coal-fired power plants.

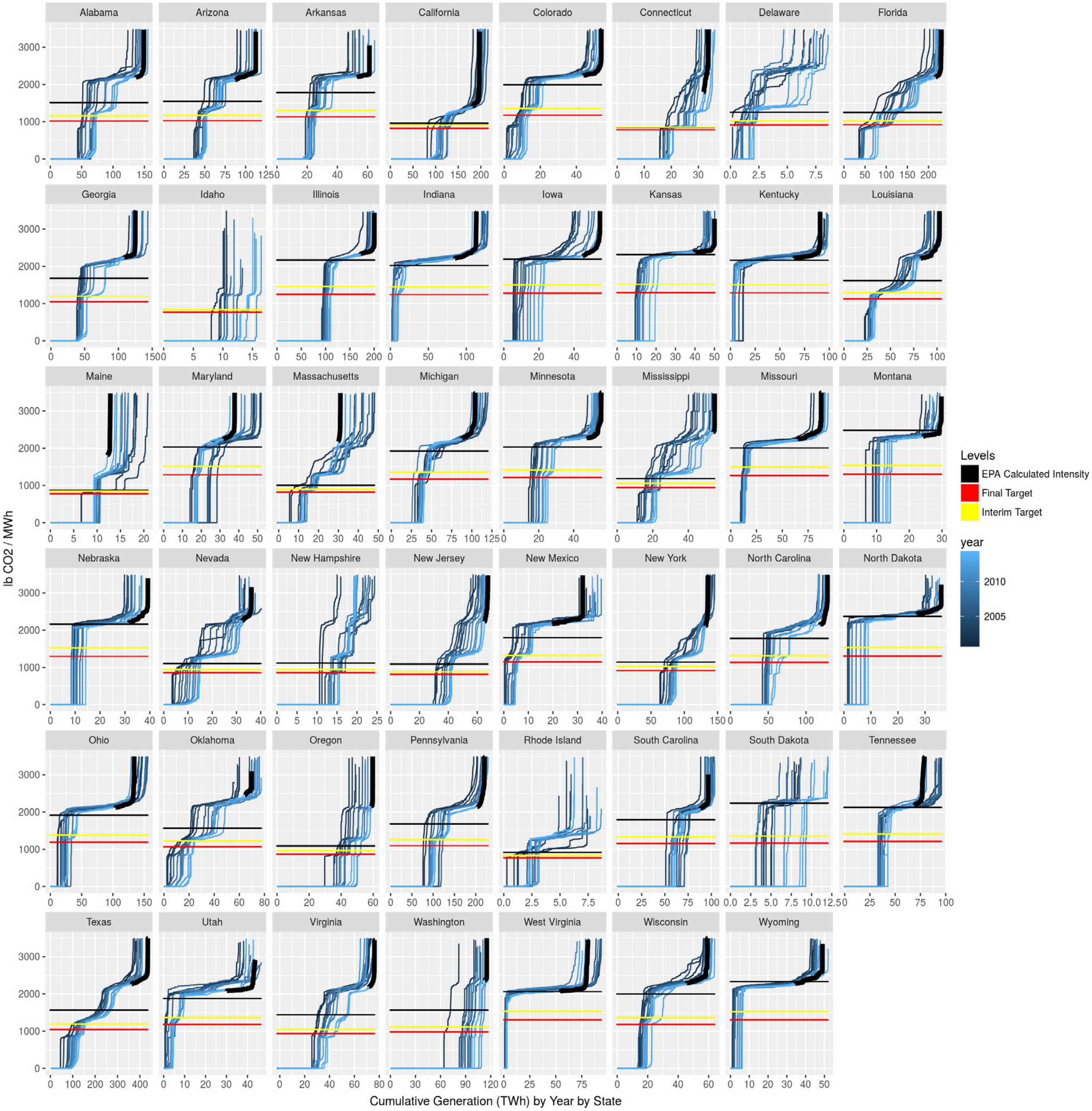

Fig. A5. Electricity generation sorted by CO_2 intensity. Black lines represent the amount of generation which exceeds the 2030 CO_2 mass targets.

visualization, with relevant unit conversions being performed where necessary.

A.2. Impact of EGU selection criteria

The Clean Power Plan targets are set per state based on a measure of the emissions rate of power generation (lb CO_2/MWh). In the paper, we analyze all of the generation documented by the EIA in Form 906 and Form 923. In setting the targets per state, the US EPA only considers a subset of the EGUs within a state. EGUs used by industry are excluded, and generation from hydroelectric power is not included in the development of the states' targets.

Overall, 84.8% of total electricity related CO_2 emissions are covered, with 390 Megatons out of 2569 Megatons of CO_2 not included.[15] Fig. A1 gives an overview of the CO_2 emissions per state that are not covered by the Clean Power Plan. Vermont and the District of Columbia do not have affected EGUs and therefore do not have any targets set for them. While Hawaii and Alaska do have EGUs which are included due to the selection criteria, the EPA lacks the appropriate

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[15] Based on data from http://www.epa.gov/airquality/cpp/tsd-cpp-emission-performance-rate-goal-computation-appendix-1-5.xlsx

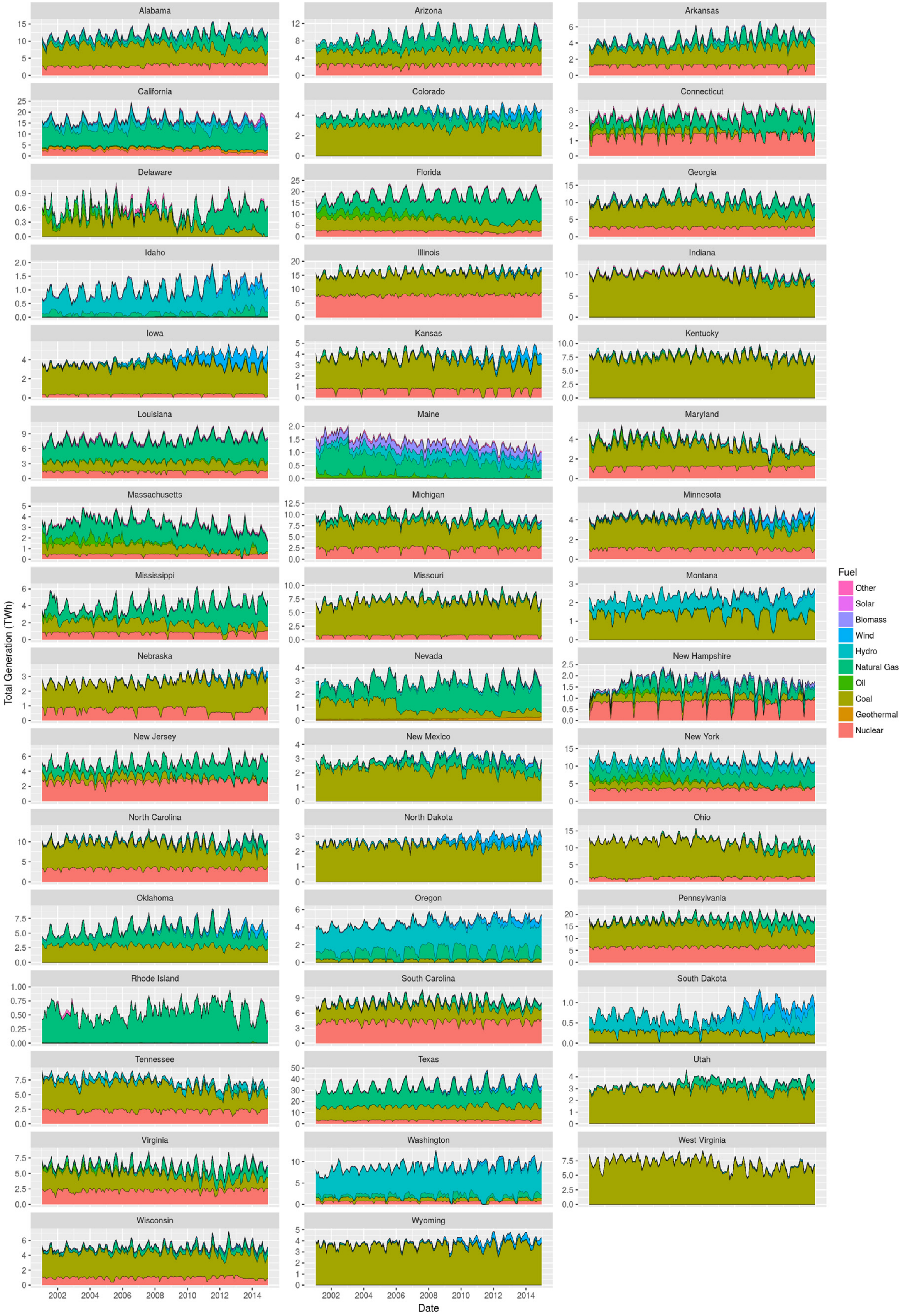

Fig. A6. Generation per fuel per state.

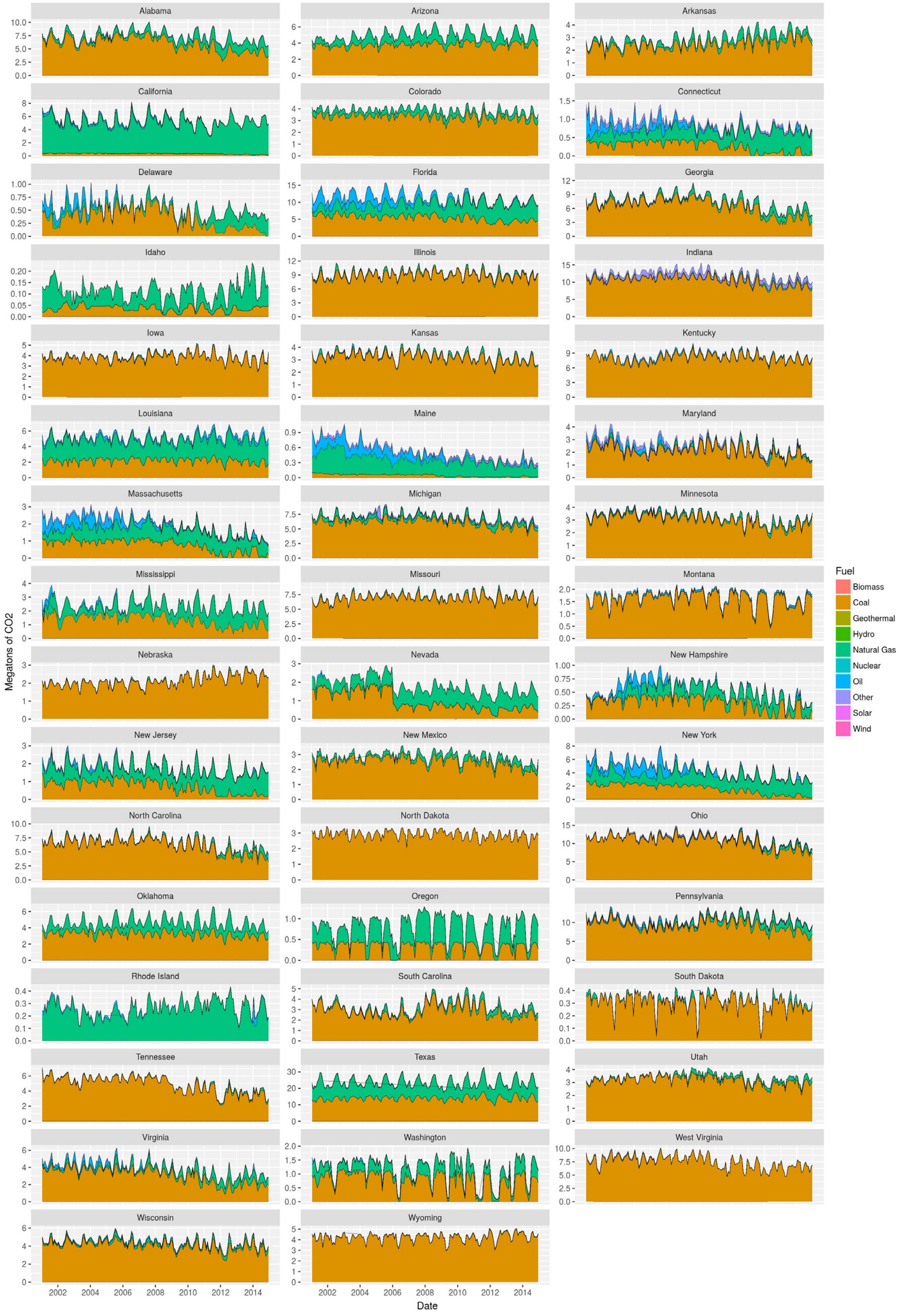

Fig. A7. CO_2 emissions per fuel per state.

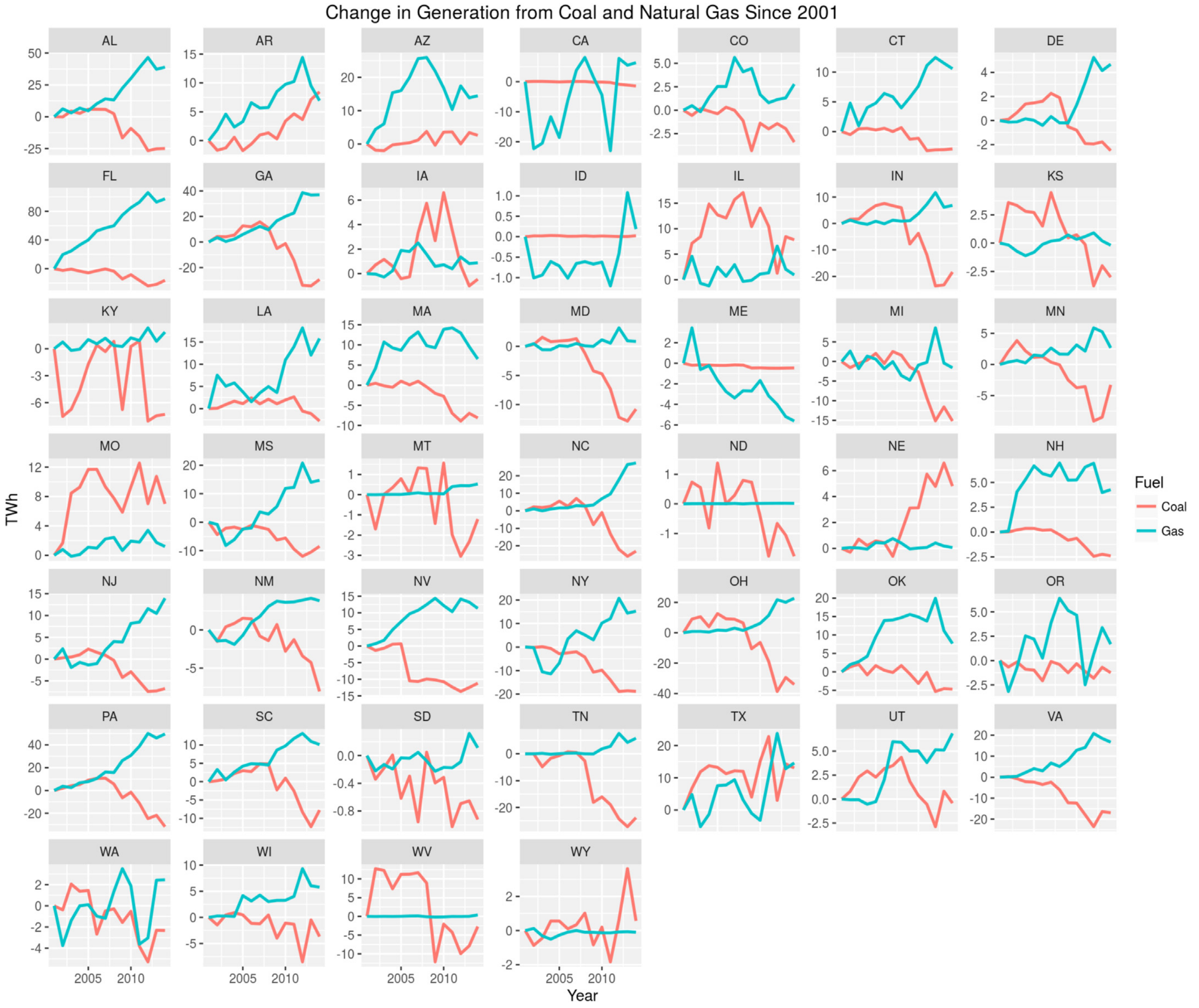

Fig. A8. Change in electricity generation from coal and natural gas since 2001.

information necessary about these EGUs needed to quantify appropriate targets. While Texas has the most total CO_2 emissions that are not covered, this is about 15.9% of its total emissions.

Fig. A2 gives an overview of the CO_2 intensity and electricity generation of EGUs within each state (blue) and the CO_2 intensity profile of the EGUs which are excluded from the CPP (black). The horizontal axis shows the total cumulative generation for 2012, while the vertical axis shows the sorted CO_2 intensity of the individual EGUs. The area under the curves represent the total CO_2 emissions per state (blue) and the total CO_2 emissions not regulated by the CPP (black).

A.3. Full figures including all US states

Due to space constraints, several of the visualizations in the paper only showed data for a select sample of the fifty states. The figures here show the same visualizations, but include all of the states.

A.3.1. Coal plant conversion efficiency

Fig. A3 shows the full version of Fig. 6a and gives an overview of the efficiency of the coal generation per state, where generation is sorted by plant efficiency (MMBtu/MWh). The average expected efficiency is around (10 MMBtu/MWh). Values lower than this (around 5 MMBtu/MWh) are seen in the data, although this is unexpected. In examining the data for individual coal plants, deviations between 5 and 15 MMBtu/MWh are sometimes seen although this does not seem to correlate with factors such as the amount of generation. Fig. A4 shows a sample of the data per month per plant. The top 50 plants are selected based on the greatest amount of net electricity generation in a month during the period 2001–2014.

A.3.2. Yearly Generation by State Sorted by CO_2 Intensity

Fig. A5 is the full version of Fig. 6b and shows the CO_2 intensity of all generation per state over the years 2001 through 2014.

A.3.3. Monthly generation by fuel type per state

Fig. A6 is the full version of Fig. 6c and shows electricity generation by month, per fuel type.

A.3.4. Monthly CO_2 emissions by fuel type per state

Fig. A7 shows the amount of CO_2 emissions resulting from specific fuel types for each state.

A.3.5. Change in electricity generation from coal and natural gas since 2001

See Fig. A8.

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