Tracking emissions in the US electricity system

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Understanding electricity consumption and production patterns is a necessary first step toward reducing the health and climate impacts of associated emissions. In this work, the economic input–output model is adapted to track emissions flows through electric grids and quantify the pollution embodied in electricity production, exchanges, and, ultimately, consumption for the 66 continental US Balancing Authorities (BAs). The hourly and BA-level dataset we generate and release leverages multiple publicly available datasets for the year 2016. Our analysis demonstrates the importance of considering location and temporal effects as well as electricity exchanges in estimating emissions footprints. While increasing electricity exchanges makes the integration of renewable electricity easier, importing electricity may also run counter to climate-change goals, and citizens in regions exporting electricity from high-emission-generating sources bear a disproportionate air-pollution burden. For example, 40% of the carbon emissions related to electricity consumption in California's main BA were produced in a different region. From 30 to 50% of the sulfur dioxide and nitrogen oxides released in some of the coal-heavy Rocky Mountain regions were related to electricity produced that was then exported. Whether for policymakers designing energy efficiency and renewable programs, regulators enforcing emissions standards, or large electricity consumers greening their supply, greater resolution is needed for electric-sector emissions indices to evaluate progress against current and future goals.

carbon intensity of electricity | renewable energy policy | electricity system emissions factors | emissions embodied in electricity exchanges

Power grids transport electrical energy between many different locations, often over large distances. As a result, linking changes in production and consumption at different points of an electric grid is challenging. Accounting for and monitoring pollutants emitted during electricity production and subsequently embodied in electricity trade and consumption is even more complex, difficult, and data-intensive.

Yet, electricity represents a large fraction of emissions from fossil-fuel consumption: in the United States, 28% of 2016 greenhouse gas (GHG) emissions (1). To achieve climate goals (2), massive electrification will very likely be needed, upping the stakes for effectively decarbonizing the electricity sector (3). The climate and health impacts associated with producing, consuming, and exchanging electricity should therefore be the subject of close attention. Ensuring that emissions accounting methods for our electricity systems accurately capture when, where, and why emissions are occurring is especially critical as they become more connected and as the role of renewables grows. Accurate monitoring will help prevent the outsourcing of pollution (carbon leakage), and neglecting the consumption-based perspective may have undesired consequences for social equity and environmental justice.

The emissions impact of electricity can be measured through Emissions Factors (EFs; mass of pollutant per unit electrical energy). According to a compilation of life-cycle analysis estimates for carbon EFs (4), coal emits 2 times more carbon dioxide (CO_2) than natural gas, which emits an order of magnitude more than electricity from the sun, wind, or water. Recent direct emissions estimates (5) show that the carbon intensity of the US grid as a whole decreased by 30% from 2001 to 2017 as gas and renewables displaced coal.

Capturing heterogeneity matters when considering the climate and health impacts of the electric grid. Previous studies have compared the use of average and marginal EFs (6, 7) to estimate the impact of policy interventions in the short-term; shown how EFs can vary by location, season, or time of day (8, 9); and can use consumption or production of electricity as the accounting basis (10–13).

The impact of GHG emissions is global and only depends on time path and total volume, not on geographic location. Not so for air pollutants such as sulfur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter, where damages are more localized. While distant electricity consumers get the benefits of reliable electricity, the associated pollutant burden is borne by communities near the generating units. Whether their impact is global or local, understanding how electricity consumption drives the emission of different pollutants is critical and will be needed by policymakers to develop sound and durable shared-responsibility models between producers and consumers.

The need to capture heterogeneity becomes more pressing as electric grids absorb greater amounts of renewable energy, whose availability typically varies in time and space (14). In such grids, demand will need to become more responsive (15). Understanding embodied emissions flows will be especially important in networks with high levels of trade, e.g., in the US system's western interconnect. As the fraction of renewable generation

Significance

The environmental quality of the electricity flowing through electric grids varies by location, season, and time of day. Data from 3 publicly available sources have been combined to produce an hourly emissions dataset for the 66 balancing authorities in the United States. The environmental quality of electricity varies greatly. Electricity transfers are especially important in the western United States and can be responsible for more than 20 to 40% of emissions. They play a much smaller role in the eastern United States. In a number of regions, a large fraction of pollutant-intensive electricity is exported, resulting in local communities bearing the pollution burden of electricity generation without the benefits of consuming the electricity.

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Data deposition: The code and data have been deposited on GitHub and are available at https://github.com/jdechalendar/tracking_emissions.

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increases, greater amounts of trade are beneficial for reducing costs and helping to balance excess and deficits of electricity supply (16).

In this paper, we trace the flow of electricity through the electric grid and calculate hourly embodied pollutant flows. As in previous work (10–13), we use a fully coupled economic multiregional input–output model (MRIO) of the electricity system. MRIO models have been used to quantify emissions embodied in trade of goods and services between countries (17, 18), but also to assess other footprints, e.g., water, land, or biodiversity (*SI Appendix*, refs. 3–5).

Often constrained by the lack of appropriate data, previous assessments of electricity grids present results that use monthly resolution at best, or do not properly account for the impact of trade (a more detailed literature review can be found in *SI Appendix*). In this work, we built and solved a linear system for each hour of 2016 corresponding to the full exchange network for the 66 continental US balancing areas, as described in Materials and Methods. The high spatial and temporal resolution of the dataset we generated and released represents a significant advance and was obtained by solving a fully coupled MRIO model. This allowed us to perform an exhaustive analysis of the US electricity system and, in particular, of the role played by electricity transfers in the flow of embodied pollution through the electric grid.

We show why emissions accounting systems should consider subdaily, local, and exchange data, in that they would more closely align with the operation of modern electricity markets. As these data on the electric system become routinely available, we can now compute more precise emissions footprints for different components of the electricity system.

Results

The most recent databases available with appropriate resolution describe the state of the US electricity system in 2016, and, accordingly, all results in this paper apply to the year 2016. We computed and reported electric-sector emissions for the 66 balancing authorities (BAs) in the continental United States by combining hourly data on BA-level electricity production, consumption, and trade with hourly data on plant-level emissions produced. Exhaustive, BA-by-BA, hourly reports from this work are provided in *SI Appendix*, while the main text focuses on key findings and insights.

We report both production- and consumption-based emissions, taking the MRIO view that pollution is embodied in generated electricity and subsequently flows through the electricity network. Produced emissions are defined by the administrative territory in which they are physically emitted. Consumption-based emissions are defined by the administrative territory in which electricity is consumed, and we will refer to them as "consumed" emissions. We will similarly refer to "traded" emissions as the emissions embodied in hourly electricity exchanges. In the remainder of the paper, BAs will be referred to as "regions" to simplify language. A full table for abbreviations for the different regions can be found in *SI Appendix*, Table S1; additionally, Figs. 1 and 2 can be used to provide an indication for location and a reference for frequently used abbreviations, respectively.

Carbon Footprint of Electricity Consumption. In 2016, 1.83 Gtons of CO_2 were emitted in the United States to meet 4 PWh (4 million MWh) of electricity consumption. Tracking emissions at the BA level is natural because they correspond to the physical organization of the electricity system, where control-room operators must continually monitor the state of the electric grid to ensure that supply can meet demand and line flows remain technically acceptable. The consumption-based carbon intensity of electricity varies by almost an order of magnitude across the different regions in the US electricity system, as shown in Fig. 1. In these maps, the size of the circles and arrows is representative of annual consumption and trade of electricity (Fig. 1, *Upper*) and carbon (Fig. 1, *Lower*), respectively, and color is representative of consumption-based carbon intensity. The footprint of the US electricity system is dominated by its two largest regions, the Pennsylvania–New Jersey–Maryland Power Pool (PJM; 20% of electricity and 19% of emissions) and the Midcontinent Independent System Operator (MISO; 17% of electricity, but 21% of emissions). The Pacific Northwest is a large exporter of low-emissions-intensity hydroelectric power, while the Rocky Mountain region is a large exporter of carbon, as are some regions in the coal-heavy Midwest.

Exchanges between regions play an especially large role in the western interconnect, where net imports account for 29% of consumption for the 17 net importer regions, and net exports account for 37% of production for the 16 net exporter regions. Exchanges represent a smaller share of consumption and production in the eastern interconnect, while the Electric Reliability Council of Texas (ERCO) has few ties to the rest of the US electricity system. In the US system as a whole, carbon trade represents 5% of total carbon production.

Moving forward, annual accounting tools will not be enough to track decarbonization efforts in the US electricity system, because they will misstate carbon footprints for regions in which renewables and exchanges play a large role (19). The heterogeneity in the carbon footprint of electricity consumption and production, both in time and in space, is highlighted in Fig. 2, where we show the 10th, 50th, and 90th percentiles for hourly data on consumption- and production-based EFs for 20 regions. The overall US electric grid carbon intensity of 450 kg CO_2/MWh would accurately match the carbon embodied in electricity consumed only in PJM, ERCO, and the southeastern Southern Co. Services. For the others, the annual median carbon intensity can be lower than 100 kg/MWh or higher than 900 kg/MWh.

Hourly carbon intensity can fluctuate equally significantly around the median. In the MISO, consumption EFs swing by 15% around the median, from 480 to 660 kg/MWh. For the Idaho Power Company (IPCO), the carbon content of imports (625 kg/MWh) is much higher than that of local generation (71 kg/MWh), and the carbon emissions per unit of electricity consumed depends sensitively on time. While in the spring, this region generates almost enough low-emissions-intensity energy to meet its demand, in other months it relies heavily on imports from the neighboring PacifiCorp East (716 kg/MWh) and NorthWestern Energy (765 kg/MWh). The Salt River Project (SRP) exports a large fraction of its generation and simultaneously imports lower-emissions-intensity electricity: Its consumption-based EF is 22% lower than its production-based EF. Such trends cannot be captured without hourly exchange data.

In California, the Air Resources Board computes the electric system's carbon footprint from technology-specific EFs and the annual generation mix, including imports. Imports are incorporated by considering private contracts and market settlements (*SI Appendix*, refs. 4 and 5). In 2016, 14% of the electricity consumed was reported as imported from an unspecified source (and given a generic EF). In contrast, our more simple and transparent approach relies on publicly available physical observations (electricity balances between regions and measured emissions) to compute the corresponding embodied carbon flows, leaving no stranded electricity or emissions. Our results confirm that the largest carbon imports into the California Independent System Operator (CISO) originate from the SRP (654 kg/MWh) and Los Angeles (Los Angeles Department of Water and Power; 384 kg/MWh) regions. Considering imports to compute the median EF changes it by 20%, from 194 kg/MWh

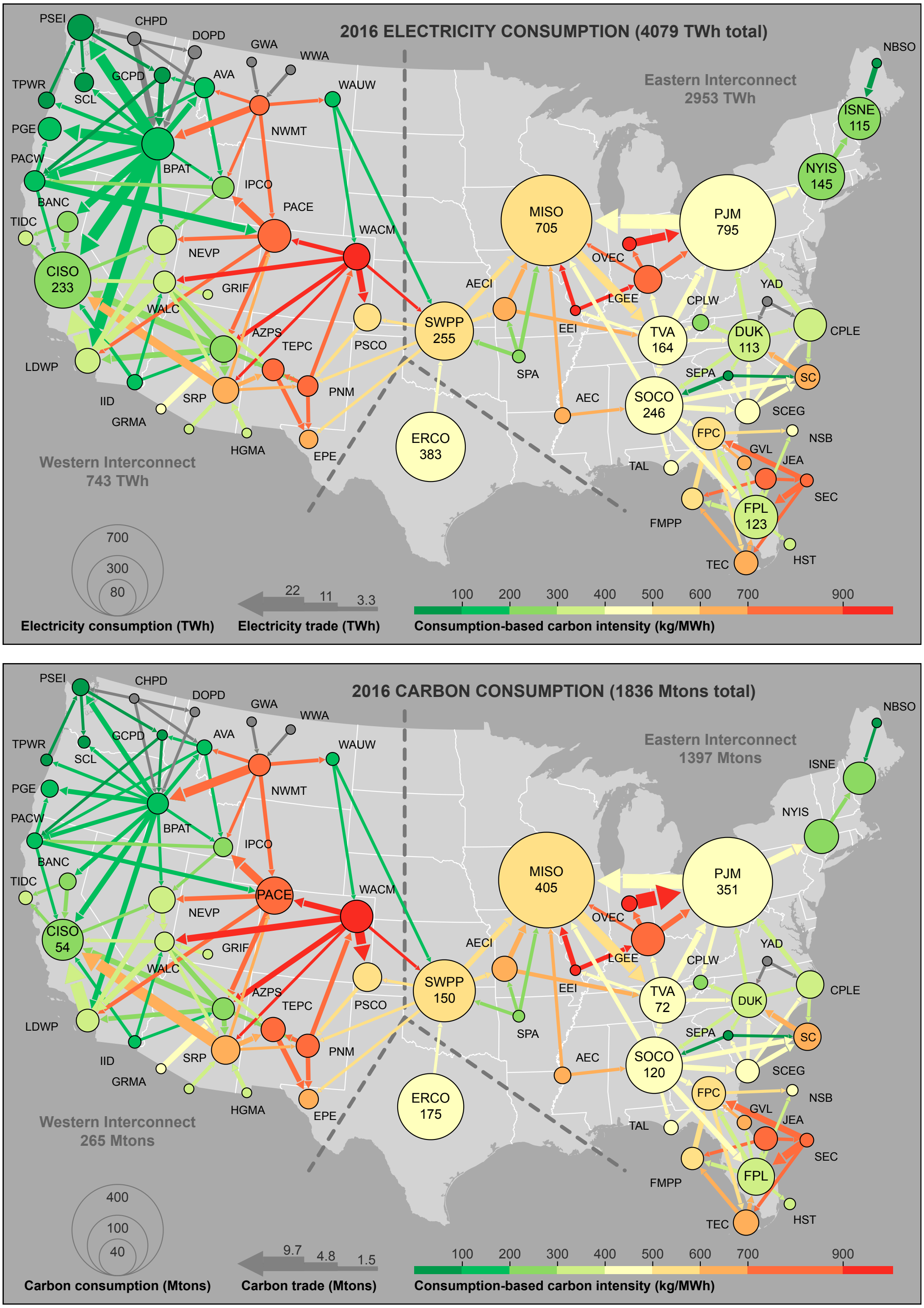

Fig. 1. Carbon footprint of the US electricity system. Electricity (*Upper*) and carbon (*Lower*) consumption and exchanges and consumption-based carbon intensity of grid electricity (*Upper* and *Lower*) for the 66 US BAs. The radius of the nodes and width of the arrows scale with consumption and trade, respectively. The color of the nodes and arrows scale with consumption-based carbon intensity. The gray nodes and arrows correspond to regions for which no emissions were reported. *SI Appendix*, Figs. S2 and S3 provide similar maps for SO_2 and NOx, respectively. *SI Appendix*, Table S1 provides a reference for abbreviations.

(production-based EF) to 233 kg/MWh (consumption-based EF). Our results also demonstrate the importance of time-of-year effects and that carbon accounting based on annual data alone is insufficient: The median hourly EF for imports into CISO was 216 kg/MWh between March and June but 394 kg/MWh between August and November. Accounting for

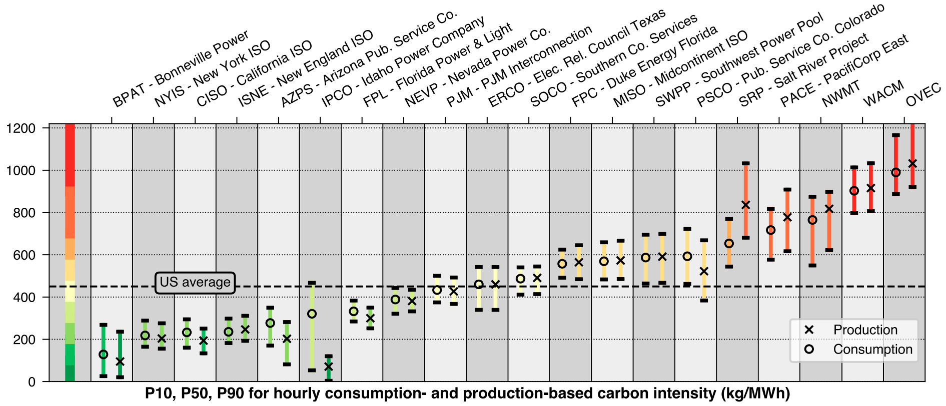

Fig. 2. The carbon footprint of electricity consumption. National- and annual-level carbon accounting does not capture the heterogeneity in space and time of EFs. The 10th, 50th, and 90th percentiles (P10, P50, and P90, respectively) of consumption- and production-based carbon intensity for selected BAs are shown.

these complex carbon flows will be critical for California to meet its ambitious decarbonization targets.

Exhaustive hourly time-series data for electricity and carbon produced, consumed, and traded as well as the corresponding hourly carbon EFs are provided in *SI Appendix*, Figs. S12–S77 for each of the regions in the United States and can be used to further interpret the trends observed in Figs. 1 and 2.

Balancing Area-Level and Hourly Level Carbon Accounting. Both the amount of electrical energy consumed and its carbon footprint vary significantly from region to region, by month and by hour. Understanding the dynamics of demand and supply for electricity will be key to help reduce emissions.

Median daily profiles for carbon consumption in the two largest eastern and western regions are shown in Fig. 3. In the western US grid, it is clear that capturing the impacts of electricity exchanges is critical to accurately portray pollutant flows and to design effective mitigation strategies. That is less true in the eastern US grid. For very large regions, such as PJM and MISO, further disaggregation of hourly electricity and emissions reporting (e.g., at the Power Control Area level) will enable more targeted policies. While base load represents a large portion of demand, electricity and, consequently, carbon consumption, is typically greatest in the late afternoon on hot summer days and in the early fall in PJM, MISO, and CISO. In the other seasons, demand profiles are much flatter throughout the day (although demand is very often lower at night). In the winter, base load is higher in PJM, MISO, and the Pacific Northwest's Bonneville Power Administration (BPAT). These daily profiles confirm that harsher temperatures drive emissions.

As can be seen in Eq. **1**, consumption-based carbon intensity is a function of the intensity of generation (largely driven by technology mix) and of imports. Generation mix varies significantly across the regions in the US electricity system, and so does the carbon intensity of electricity. Further daily and seasonal data on other regions are shown in *SI Appendix*, Figs. S4–S9, while *SI Appendix*, Fig. S1 presents monthly time series for 8 of the largest regions in the United States. Coal and gas dominate in the MISO and Southwestern Power Pool. High penetrations of hydropower and renewables are responsible for the low-emissions-intensity electricity consumed in the 2 major western regions, CISO and BPAT. Nuclear powers most of the low-emissions-intensity electricity consumed in the New York region (New York ISO). Even though they each represent a relatively small fraction of electricity consumed (3 to 4%) and emissions

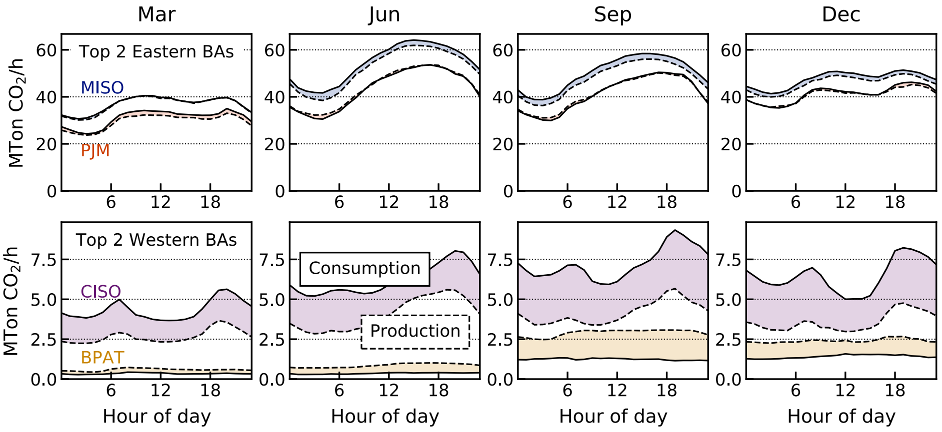

Fig. 3. Daily carbon profiles for the two largest balancing areas in both US interconnections: the midwestern MISO and northeastern PJM in the eastern interconnect, and California's CISO and Pacific Northwest's BPAT in the western interconnect. Daily profiles are computed as the median values for different months and hours of the day, using local time zones. The full lines represent consumed emissions, while the dashed lines represent produced emissions. The shaded area between the full and dashed lines corresponds to net carbon transfers. Trade is much more important in the West than in the East, as can also be seen in Fig. 4. *SI Appendix*, Figs. S4–S9 show similar daily profiles for selected regions in the US electricity system, as well as daily profiles for electricity and consumption-based carbon intensity. Dec, December; Jun, June; Mar, March; Sep, September.

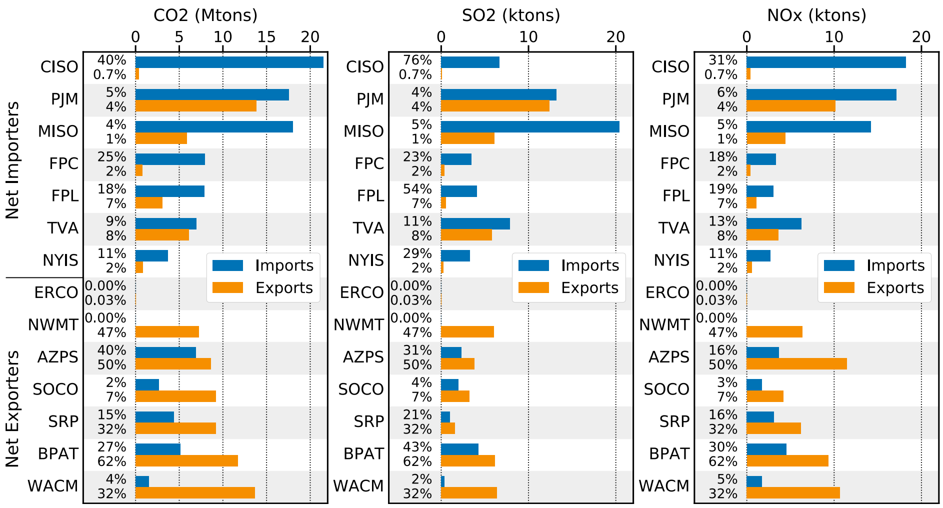

Fig. 4. Sharing responsibility for US electric-sector emissions. Top net importers and exporters of pollutants are shown. Relative imports and exports are expressed as a fraction of the total embodied pollution for a region—i.e., if we call imports, exports, production, and consumption as I, E, P, and C, the percentages in the graph represent $\frac{I}{I+P}$ for imports and $\frac{E}{I+P}$. We note that pollutant flows are balanced: For each region, $I+P=E+C$, and for the regions that almost only import $\frac{I}{I+P}\approx\frac{I}{C}$, while for regions that almost only export $\frac{E}{I+P}\approx\frac{E}{P}$. In the West, trade is particularly important. *SI Appendix*, Fig. S10 provides further insight into the pollutant trading patterns there in the form of Sankey diagrams. *SI Appendix*, Table S1 provides a reference for abbreviations.

(0.75 to 1.8%), 20% of the US population lived in these 3 regions in 2016.

Emissions Embodied in Electricity Exchanges. Pollution traded in Fig. 4 corresponds to the emissions embodied in electricity exchanges for the US electric grid's top net importers and exporters. In the same figure, relative pollution traded is expressed as a fraction of the total embodied pollution for a region (consumption plus exports or, equivalently, production plus imports). While CO_2 emissions cause global climate damages, emissions of SO_2 and NOx cause local health damages.

For regional climate policies, accurately measuring and tracking the carbon emissions embodied in electricity exchanges will be key to achieving the desired impact. Imported electricity may run counter to climate goals. Of the 265 Mt of CO_2 that were emitted to the atmosphere when generating electricity in 2016 in the western grid, the interconnection where trade is the most relevant, 17% were emitted to satisfy electrical consumption in a different region. In the CISO, for example, 2016 imports represented 28% of consumption, but 40% of the carbon emissions related to California electricity consumption were produced in a different region. Carbon exports represent 30 to 60% of total embodied carbon for a group of large western regions in Washington state, the Rocky Mountains, and Arizona (BPAT, NorthWestern Corporation, Western Area Power Administration–Rocky Mountain Region [WACM], Arizona Public Service Company [AZPS], and SRP). Some of the same regions act as trade routes for electricity and embodied pollution, simultaneously importing and exporting large amounts of carbon (AZPS, SRP, and BPAT). The Tennessee Valley is another region which experiences such transshipments of electricity and carbon. For a few trade links, electricity (and carbon) can flow both ways during the year, or even during the day. Reverse flows represent from 5 to 40% of total trade for the 6 largest of these bidirectional trade routes (*SI Appendix*, Fig. S11). In contrast, net carbon imports represented less than 3% of consumption in the 2 largest eastern regions (PJM and MISO), and the Texas electricity grid is almost completely independent.

Citizens in regions exporting electricity from higher-intensity-generating sources bear a disproportionate local air pollution burden. For some of the extreme cases in Fig. 4, like the CISO or Idaho's IPCO on the importer side or the Rocky Mountain WACM and the Southwestern Power Administration on the exporter side, almost all of the local pollution caused by electricity generation is not colocated with the electricity consumption that caused it. This is particularly troublesome for the exporters: While the generated electricity physically leaves those regions through the electricity grid, these local pollutants don't. Our computation of consumption-based pollutant intensity of electricity can provide an indication as to how embodied pollution propagates through the electric grid. Fig. 4 also highlights that levels of pollution for SO_2 and NOx (and CO_2) are not always correlated and that each of these pollutants needs to be tracked individually. Higher levels of SO_2 are typically indicative of higher shares of coal generation, and higher shares of NOx are typically indicative of higher shares of gas generation. In the CISO, SO_2 imports represent 76% of SO_2 consumed, while this number is only 31% for NOx.

Discussion

In this work, we build and analyze a dataset for pollutant production, consumption, and trade between the 66 continental US regions, from which localized hourly emissions footprints can be built. If the damages from pollution are priced, be it through a price- or a quantity-based approach (20), electricity generators and consumers will internalize the environmental costs of electricity and adapt their behavior. For instance, large electricity consumers could respond to variations in electric-grid carbon intensity by shifting their operations schedules to better match the environmental quality of the grid through carbon-aware or pollution-aware scheduling. Similarly, developers of renewable energy projects could target renewable resources that are available where and when grid electricity is currently carbon-intensive. Such economic signals will have the most impact, however, when emissions data are reported at the appropriate scales in time and space—namely, hourly and at the BA level.

This work has strong implications for both private and public actors at the local, regional, and federal levels, even without a price on emissions. Coarse national- and annual-level carbon accounting will not capture the heterogeneity of hourly production- and consumption-based EFs and may misstate emissions and emissions reductions. Understanding emissions flows and their drivers will be key to ensuring that climate-change policies address the bigger picture and to avoid resource shuffling. Similarly, local environmental and health policies that ignore how the responsibility for pollutants flows from producers to consumers through the electric grid and that do not result from the cooperation of all of the parties involved will have little effect in networks where trade volumes represent a large share of consumption and production. In contrast, regions with fewer connections to the rest of the US electric grid and less electricity trade, such as in Texas, have more direct control over their consumed emissions.

While US power plants reliably report hourly data for CO_2 on a quarterly basis, accurate hourly measurements of SO_2 and NOx emissions remain unreliable in some regions (*SI Appendix*). This study demonstrates that it is now possible to track electricity and pollutants in real time and that doing so will provide valuable benefits for policymakers and investors alike.

Materials and Methods

Different publicly available sources for emissions and electricity data are used in this work. The US Environmental Protection Agency (EPA) tracks emissions for 3 major pollutants through its Continuous Emissions Monitoring Systems: CO_2, SO_2, and NOx (*SI Appendix*, ref. 1). The US Energy Information Administration Electric System Operating Data website has reported hourly consumption, production, and interregional exchanges at the BA level since 2015 (*SI Appendix*, ref. 2). Finally, plant, BA, and national statistics at the annual level from the EPA's Emissions and Generation Integrated Resource database (*SI Appendix*, ref. 3) are used to adjust emissions levels when dealing with missing data and for validation. The full procedure that is used to clean data from these sources and the underlying assumptions are detailed in *SI Appendix*. This analysis does not account for life-cycle emissions associated with building power plants or extracting fuels.

Consumption-based emissions inventories are computed at hourly, monthly, and annual resolution for CO_2, and annual resolution for SO_2 and NOx. To estimate the pollution emitted on behalf of electricity consumption at a certain node, we assumed that emissions are embodied in traded electricity and that we can write the following balance equation for a given pollutant (CO_2, SO_2, or NOx):

$$x_i d_i = f_i + \sum_j x_j u_{ij} - \sum_k x_i v_{ki}, \qquad [1]$$

where for node i, d_i is electricity consumed, x_i is the intensity of electricity consumed, f_i is pollutant production, u_{ij} is electricity imported from j to i, and v_{ki} is electricity exported from i to k. This represents the balance equation for a fully coupled MRIO model, accounting for transshipments of electricity and embodied pollution. All quantities (and, in particular, trade) are positive. We rearrange this to:

$$x_i \left(d_i + \sum_k v_{ki} \right) - \sum_j x_j u_{ij} = f_i. \qquad [2]$$

We can also write a balance equation for electricity (assuming there are no transmission losses):

$$p + U = d + V, \qquad [3]$$

where U, V are total import and export vectors and p is electricity produced. We can substitute this to obtain:

$$x_i \left(p_i + U_i \right) - \sum_j x_j u_{ij} = f_i. \qquad [4]$$

This equation can be rewritten in the form $Mx = f$, with $M = diag\,(P + U) - u$. To access the intensity of consumption, we solve a linear system at each time step, of size the number of nodes.

To illustrate and guide intuition, we consider a simple example with 2 electric grid regions, A and B. We call x_i, y_i the consumption and production carbon intensities at node i; D_i, P_i the consumption and production of electricity at node i; and $T_{A,B}$ a 1-way transfer of electricity from node A to node B. We write the following balance equations for carbon:

$$\begin{cases} x_A D_A = y_A P_A - x_A T_{A,B}, \\ x_B D_B = y_B P_B + x_A T_{A,B}. \end{cases} \qquad [5]$$

By writing that energy is conserved at node A, we obtain:

$$\begin{cases} x_A = y_A, \\ x_B = y_B \frac{P_B}{D_B} + x_A \frac{T_{A,B}}{D_B}. \end{cases} \qquad [6]$$

For the exporter-only node, production and consumption intensity are the same. For the importer-only node B, on the other hand, the consumption intensity is the weighted average of its production intensity and of node A's consumption intensity. Weights correspond to the fractional sourcing of node B's electricity consumption from its own production and from node A. In a network with a more complex topology, the framework still applies, but consumption-based intensities may be less intuitive, in particular for nodes that simultaneously import and export electricity, since all nodes in the network are coupled by Eq. **1**.

We have released both the code and data from this work on GitHub (21).

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