SI: Climate is projected to have severe impacts on the frequency and intensity of peak electricity demand across the United States

Maximilian Auffhammer, Patrick Baylis, and Catherine Hausman

November 7, 2016

This document contains supplementary information to Auffhammer, Baylis, and Hausman (2016). Section 1 shows additional figures. Figure S1 shows the geographic extent of our sample, with different zones shown in different colors. Coverage gaps are described in the main text. Figure S2 shows the projected change in the intensity of peak load under RCP4.5, for comparison with Figure 3 (RCP8.5) in the main text. Figures S3 and S4 display the average and peak temperature response functions for each individual zone, for comparison with Figure 1 in the main text. In general, peak responses (red) are larger than average load responses (blue). Moreover, a U-shape, with heating demands for low temperatures and cooling demands for high temperatures, can be seen in all zones. Finally, the appropriateness of imposing a linear response function for high temperatures (described in the text) can be seen in these zone-level figures. Section 2 examines the sensitivity of the results to recession effects. Section 3 describes the compilation of the energy consumption data sources, with zone-level maps for each data source shown in Figures S5-S8.
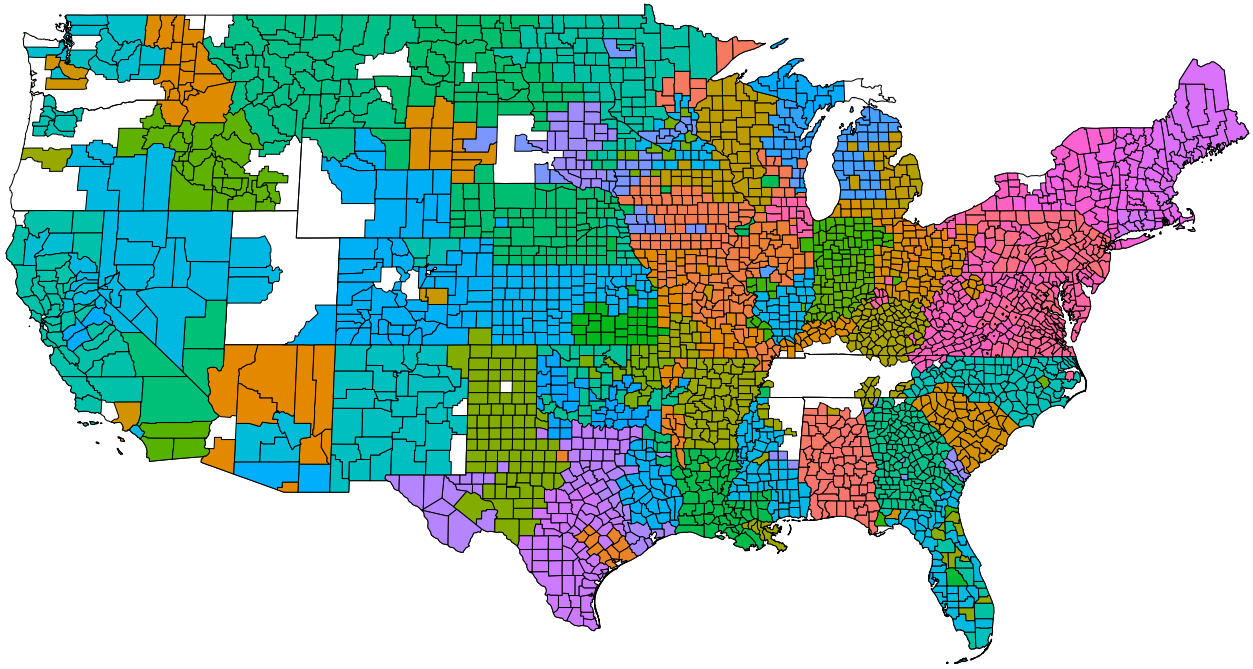
1 Supplemental figures

Figure S1: Map of sample

Notes: This map shows the geographic extent of our sample, with zones shown in different colors. Coverage gaps are described in the main text.
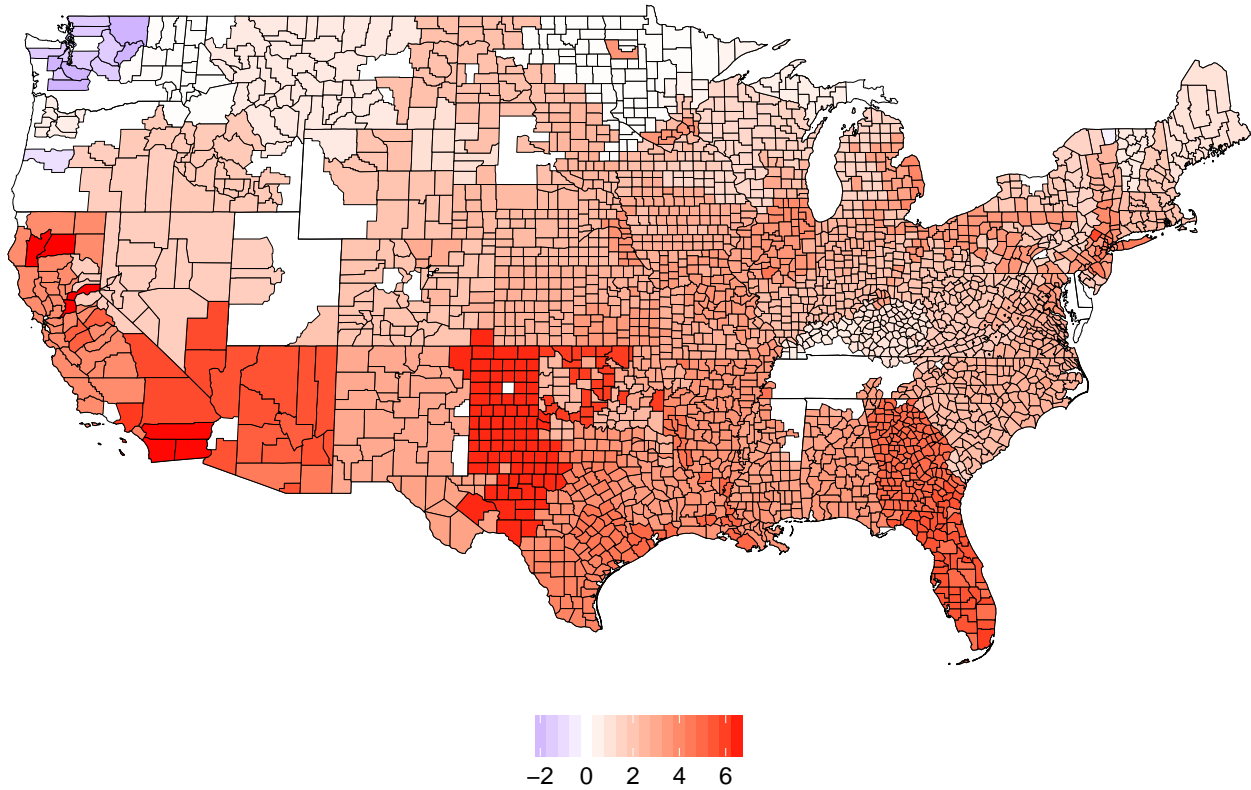
Figure S2: Projected change in intensity of peak load (RCP4.5)

Notes: Map depicts the projected change in intensity of peak load under RCP4.5, for comparison with the RCP8.5 map provided in the main text (Figure 3). As in Figure 3, the largest increases are in the South and West.
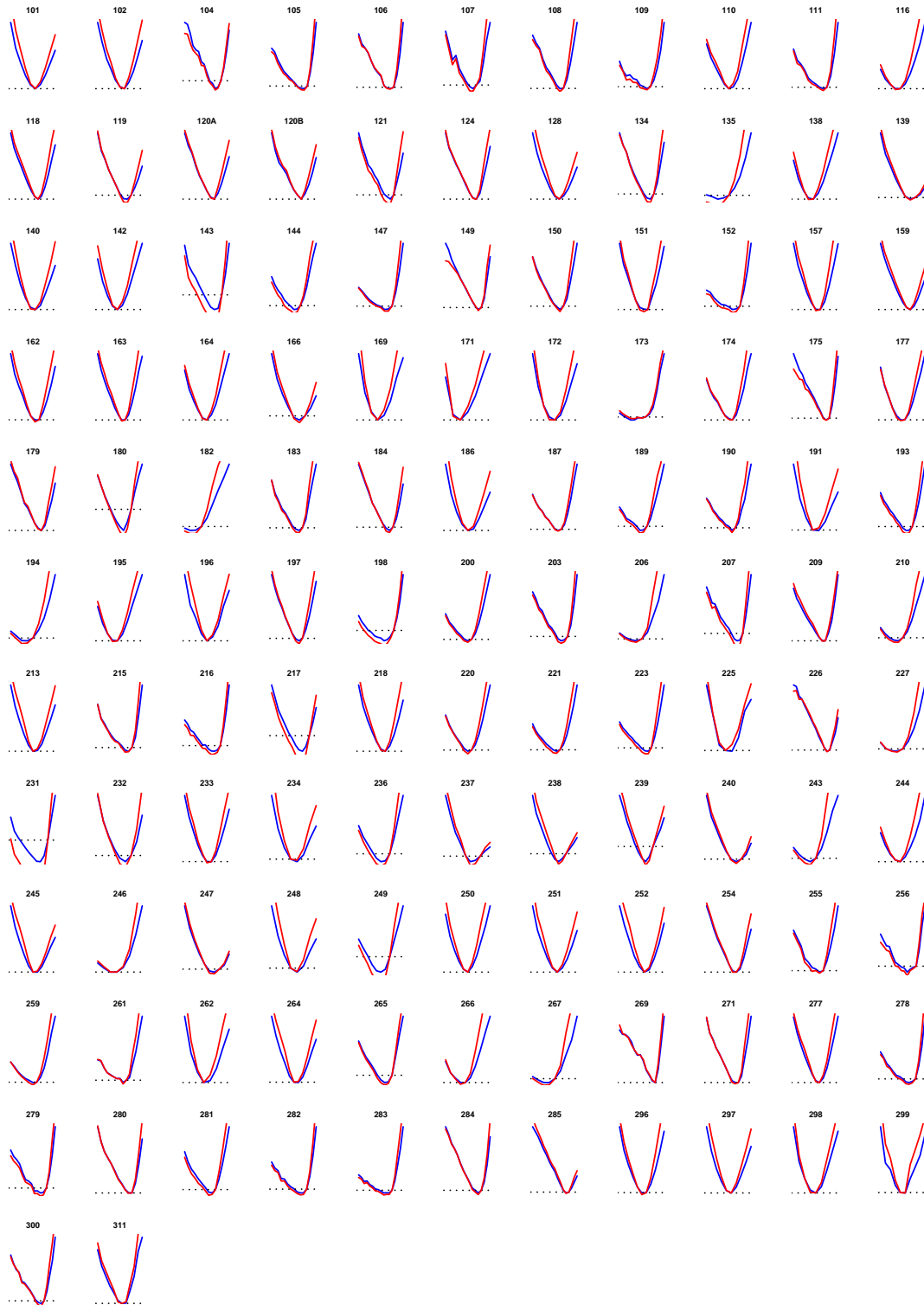
Figure S3: FERC zonal temperature responses

Notes: Estimated response functions for each load zone in the FERC data, for comparison with the aggregated results shown in Figure 1. As in Figure 1, the average (total hourly load / 24) and peak (max hourly load) electricity load response to temperature are shown in blue and red, respectively. Regressions control for precipitation, day of week fixed effects, month of year fixed effects, and a 6th-order Chebychev polynomial in time.

(a) ERCOT

(b) ISO-NE

(c) NYISO

(d) PJM

Figure S4: ISO zonal temperature responses

Notes: Estimated response functions for each load zone in the ISO data, for comparison with the aggregated results shown in Figure 1. Within each ISO, a separate figure is shown for each zone. As in Figure 1, the average (total hourly load / 24) and peak (max hourly load) electricity load response to temperature are shown in blue and red, respectively. Regressions control for precipitation, day of week fixed effects, month of year fixed effects, and a 6th-order Chebychev polynomial in time.
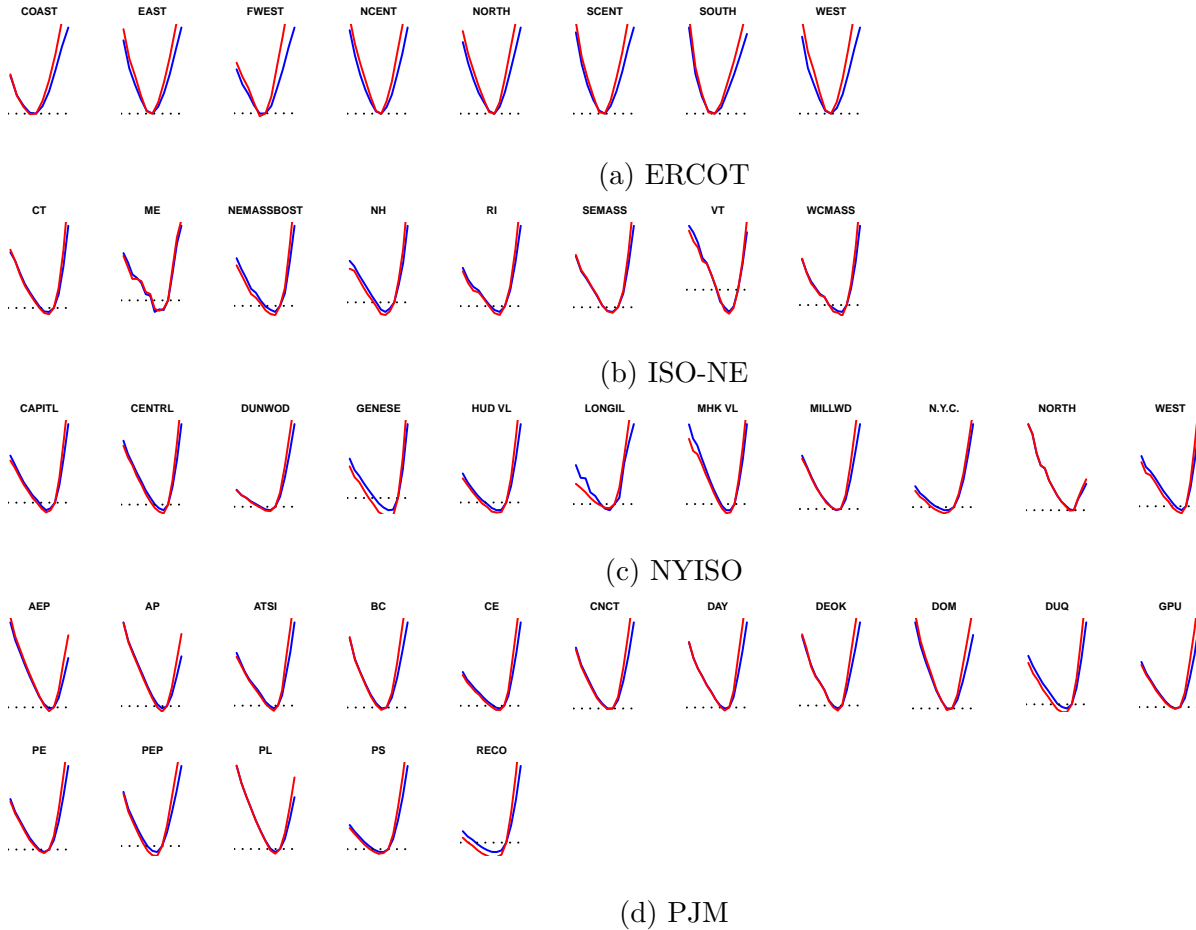
2 Sensitivity of results to recession effects

The following tables document the sensitivity of our predictions of future peak and average demand (Table 1 in main text) to response functions estimated from different time periods within the data. In order to properly compare these estimates, we drop the time polynomial and estimate our statistical models using data from 1) the entire sample, 2) only the recession (December 2007 to June 2009), and 3) not during the recession. Tables 1-3 (4-6) document predictions under RCP 4.5 (RCP 8.5).

2.1 RCP 4.5

RCP 4.5	%Δ Average Hourly Load	%Δ Peak Daily Load	%Δ 95th Percentile Daily Peak Load	%Δ Frequency Days w. Peak Load > current 95th Pctile.	%Δ Frequency Days w. Peak Load > current 99th Pctile.
FERC	2.8	3.5	6.9	168	409
ERCOT	3.7	4.3	6.5	178	571
ISONE	1.5	1.9	7.2	107	263
NYISO	3	3.3	8.6	124	332
PJM	2.3	3.1	8.1	131	331
Total	2.8	3.5	7.1	161	402

Table 1: Response of electricity demand to temperature estimated using all data

RCP 4.5	%Δ Average Hourly Load	%Δ Peak Daily Load	%Δ 95th Percentile Daily Peak Load	%Δ Frequency Days w. Peak Load > current 95th Pctile.	%Δ Frequency Days w. Peak Load > current 99th Pctile.
FERC	2.8	3.5	7.2	172	392
ERCOT	3.7	4.1	6.1	186	558
ISONE	1.6	1.9	6.8	96	270
NYISO	2.8	3.2	8.4	123	333
PJM	2.4	3.2	8.8	130	355
Total	2.8	3.5	7.3	165	392

Table 2: Response of electricity demand to temperature estimated using only recession time period

RCP 4.5	%Δ Average Hourly Load	%Δ Peak Daily Load	%Δ 95th Percentile Daily Peak Load	%Δ Frequency Days w. Peak Load > current 95th Pctile.	%Δ Frequency Days w. Peak Load > current 99th Pctile.
FERC	2.8	3.5	6.8	167	408
ERCOT	3.7	4.3	6.4	176	563
ISONE	1.6	1.9	7.2	104	260
NYISO	3	3.3	8.7	125	332
PJM	2.3	3.1	8.1	132	333
Total	2.8	3.5	7	161	401

Table 3: Response of electricity demand to temperature estimated using only non-recession time period

2.2   RCP 8.5

RCP 8.5	%Δ Average Hourly Load	%Δ Peak Daily Load	%Δ 95th Percentile Daily Peak Load	%Δ Frequency Days w. Peak Load > current 95th Pctile.	%Δ Frequency Days w. Peak Load > current 99th Pctile.
FERC	8	9.8	17.4	420	1,617
ERCOT	10.1	11.5	15.7	471	2,001
ISONE	4.9	5.8	17.7	282	1,029
NYISO	8.5	9.2	21.2	334	1,247
PJM	7	8.9	20.4	355	1,347
Total	7.9	9.6	17.8	409	1,578

Table 4: Response of electricity demand to temperature estimated using all data

RCP 8.5	%Δ Average Hourly Load	%Δ Peak Daily Load	%Δ 95th Percentile Daily Peak Load	%Δ Frequency Days w. Peak Load > current 95th Pctile.	%Δ Frequency Days w. Peak Load > current 99th Pctile.
FERC	8	9.7	18	411	1,515
ERCOT	9.9	10.8	14.8	452	1,997
ISONE	5.1	5.8	17.1	259	980
NYISO	8.2	9.1	20.6	330	1,214
PJM	7.3	9.3	22.5	351	1,375
Total	7.9	9.6	18.4	400	1,502

Table 5: Response of electricity demand to temperature estimated using only recession time period

RCP 8.5	%Δ Average Hourly Load	%Δ Peak Daily Load	%Δ 95th Percentile Daily Peak Load	%Δ Frequency Days w. Peak Load > current 95th Pctile.	%Δ Frequency Days w. Peak Load > current 99th Pctile.
FERC	7.9	9.7	17.2	422	1,631
ERCOT	10.1	11.6	15.7	471	1,986
ISONE	5	5.9	17.9	281	1,005
NYISO	8.5	9.3	21.4	335	1,244
PJM	7.1	9	20.5	356	1,349
Total	7.9	9.6	17.7	410	1,587

Table 6: Response of electricity demand to temperature estimated using only non-recession time period

3 Compilation of energy consumption data

The Federal Energy Regulatory Commisssion Form 714 (FERC-714) data provide the most geographically disaggregated view into hourly-level U.S. energy demand over the last decade currently available[1].

The FERC 714 dataset contains hourly reports of energy demand from 186 respondents. These respondents are either:

- An electric utility or group of utilities who operate a balancing authority

- An electric utility or group of utilities who operate a planning area with peak load >200 MW

Note that only utilities operating a planning area are required to file load data. In practice, respondents frequently represent both balancing authorities and planning areas.

To our knowledge, these data are the only source of information on hourly electricity usage that cover the entire United States and are sufficiently disaggregated to provide regional detail. For this reason, they are the best source of knowledge on electricity consumption in the United States.

However, because planning authorities typically do not conform to well-established geographies such as cities, counties, or states, linking these data to meteorological covariates is challenging.

For this project and for the benefit of future research in this area, we undertook the considerable task of linking each respondent to the geographic area served. Our general strategy is to link the FERC respondents with publicly available data on utilities from the Energy Information Administration Form 861 (EIA-861), which does indicate counties served by each utility. The primary challenge is in linking the respondents named in FERC-714 to utilities listed in EIA-861.

First, we limited the original set of 186 respondents by removing the following respondents:

- Respondents whose reporting was completely subsumed by any of the following major ISOs: Electricity Reliability Council of Texas (ERCOT), ISO New England (ISO-NE), PJM, and NYISO. We obtained sub-regional load data from each of the ISOs separately

- Respondents outside of the contiguous United States

- Respondents with <0 kWh total reported load

- Respondents whose entries were internal tests

- Respondents whose data duplicated other FERC-714 respondents

This left 123 respondents for which we required geographic service territory information.

More recent versions of FERC-714 provide a crosswalk from FERC-714 respondent identification numbers to EIA-861 utility identification numbers. For 81 of the respondents, the linked ID corresponded directly to a utility with service territory data in EIA-861. Figure S5 shows the counties covered by these 81 respondents.

---

[1]EIA-930 collects this information for the 67 balancing authorities, but the data date back only to 2015. This presentation has more information on EIA-930.
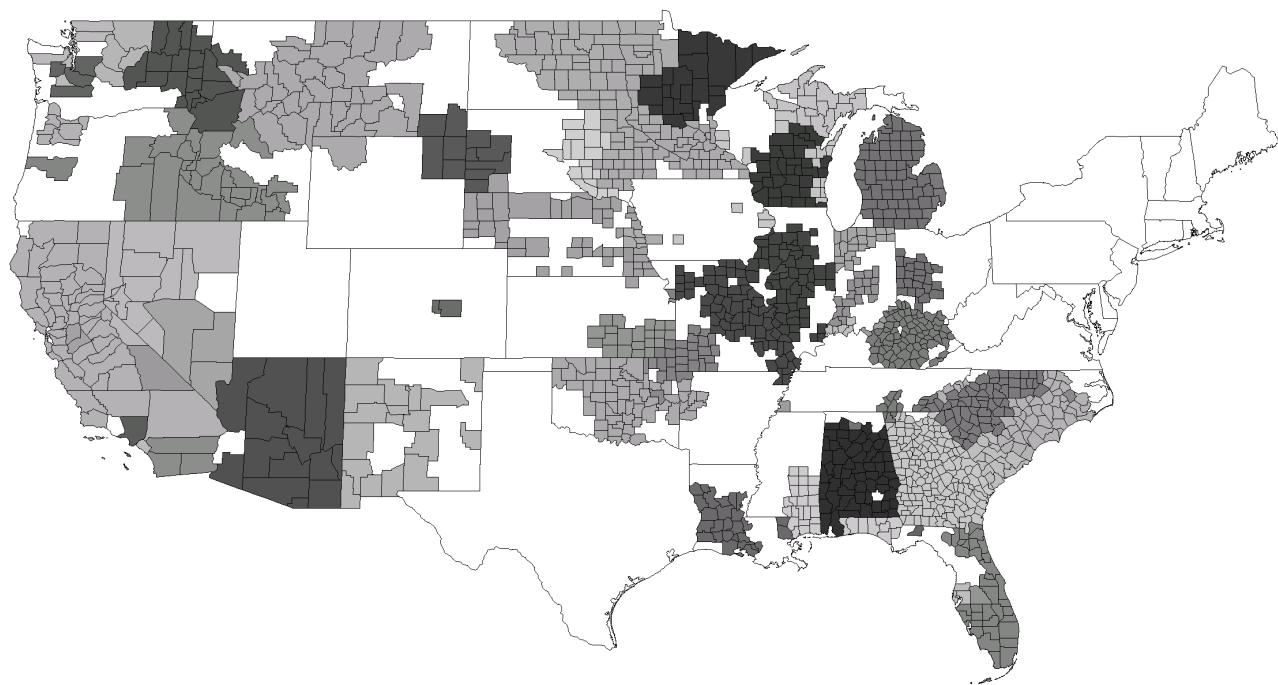
Figure S5: Directly matched territories

The remaining 42 respondents did not have an EIA utility ID that corresponded directly to a service territory. Of these, 29 respondents did have IDs that indicated they served as balancing authorities. Using file1 in EIA-861, we linked these balancing authorities to their constituent utility identification numbers, and obtained the total service territory for each balancing authority. The following map shows the counties covered by these 29 respondents. Because planning authorities (not balancing authorities) were required to report, it is likely that there is some error in the service territory covered. However, manual checks on the service territory of the 29 respondents mapped in this way suggested that the service territories we obtain in this manner correspond closely to their actual territories. Figure S6 is the map for these areas.

Note the overlap between Figures S5 and S6. This is reflective of the reality that many counties are served by more than one balancing authority.
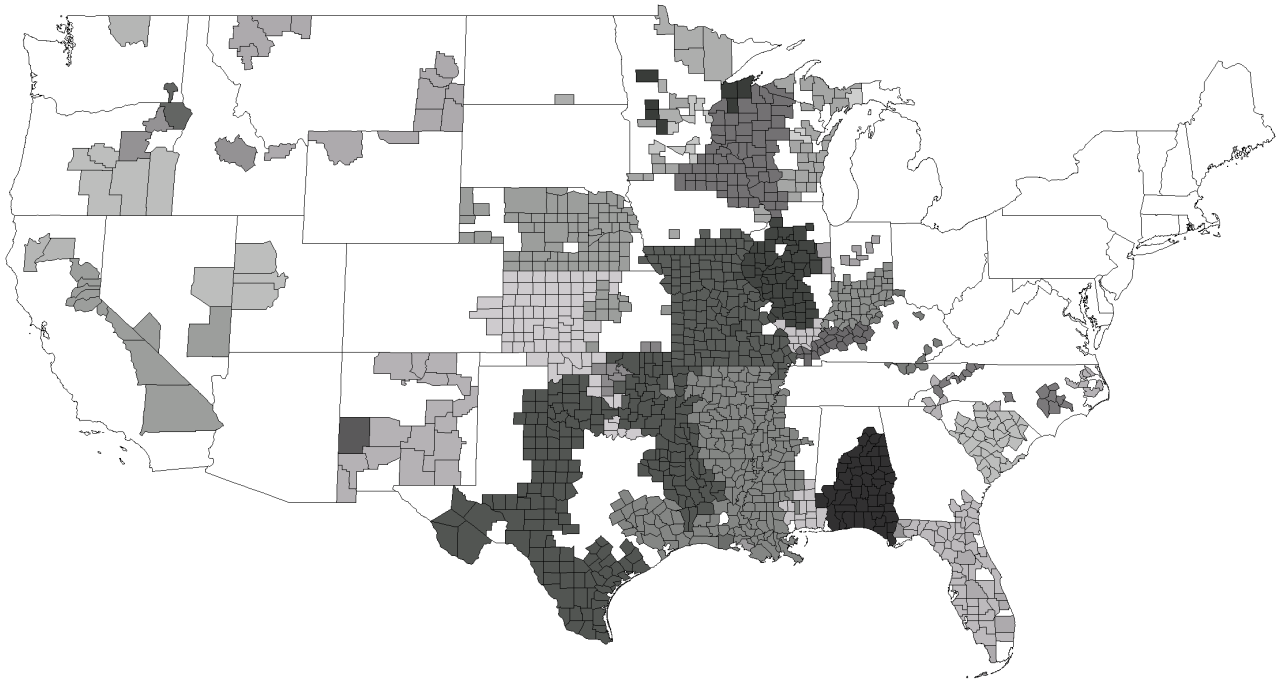
Figure S6: Territories matched to a balancing authority

For the 13 respondents whose service territories we were unable to obtain using their EIA-861 ID directly or as a balancing authorities we loaded the listed utilities from FERC-714 for each respondent and string-matched them to utilities in EIA-861[2]. This produced an extensive set of string-matches and allowed us to obtain service territories for the remaining respondents, mapped below in Figure S7.
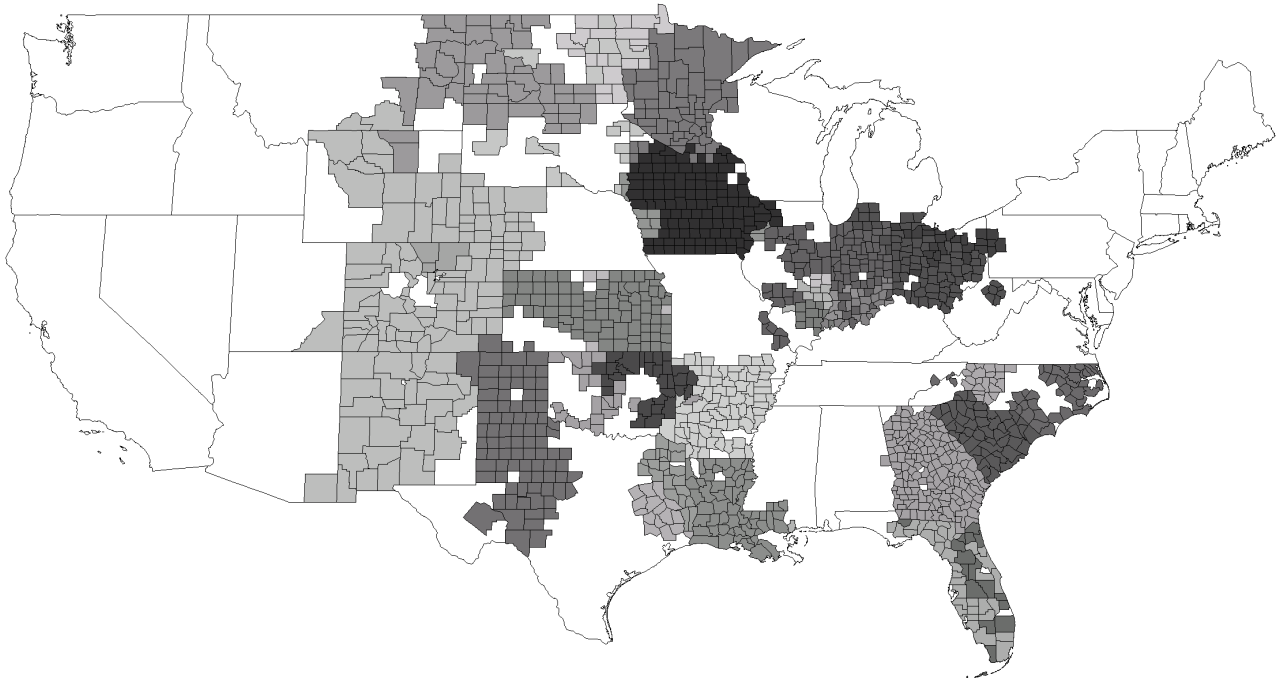
Figure S7: Territories matched manually

---

[2]Prior versions of FERC-714 did not include the FERC-EIA ID crosswalk. As a result, early versions of the project used this string-matching technique for all respondents. This has been deprecated in favor of the more precise procedure described herein.

Table 7 lists all of the respondents in the FERC-714 dataset, if (and why not) they are used in our data, and how they were mapped to a geographic area.

| Respondent ID	Respondent Name	In data?	Match type
101	PowerSouth Energy Cooperative	TRUE	Balancing authority
102	Alabama Power Company	TRUE	Direct match
103	Alcoa Power Generating Inc. - Yadkin	FALSE	NA
104	Allete	TRUE	Direct match
105	Alliant Energy-East	TRUE	Direct match
106	Alliant Energy-West	TRUE	Manual
107	Ameren	TRUE	Direct match
108	Ameren Corporation Control Area	TRUE	Direct match
109	Ameren CILCO	TRUE	Direct match
110	American Electric Power Company, Inc.	TRUE	Balancing authority
111	American Municipal Power-Ohio, Inc.	TRUE	Manual
112	Anchorage Municipal Light & Power	FALSE	NA
113	KCP&L Greater Missouri Operations Company	FALSE	NA
114	Aquila Networks	FALSE	NA
115	Arizona Electric Power Cooperative, Inc.	FALSE	NA
116	Arizona Public Service Company	TRUE	Direct match
118	Associated Electric Cooperative, Inc.	TRUE	Balancing authority
119	Avista Corporation	TRUE	Direct match
120	Big Rivers Electric Corporation	TRUE	Balancing authority
121	Black Hills Corporation	TRUE	Direct match
122	Bonneville Power Administration, USDOE	FALSE	NA
123	Boston Edison Company	FALSE	NA
124	Buckeye Power, Inc.	TRUE	Manual
125	California Independent System Operator	FALSE	NA
126	Cambridge Electric Light Company	FALSE	NA
128	Central Electric Power Cooperative, Inc.	TRUE	Manual
133	Chugach Electric Association, Inc.	FALSE	NA
134	Duke Energy Corp.	TRUE	Manual
135	City of Burbank	TRUE	Direct match
136	City of Homestead	FALSE	NA
137	City of Independence, MO	FALSE	NA
138	City of Lafayette Utilities System	TRUE	Direct match
139	City of Tacoma, Dept. of Public Utilities	TRUE	Direct match
140	City of Tallahassee	TRUE	Direct match
141	City Utilities of Springfield, MO	FALSE	NA
142	Cleco Corporation	TRUE	Direct match
143	Colorado Springs Utilities	TRUE	Direct match
144	Columbia Water & Light	TRUE	Direct match
145	Commonwealth Electric Company	FALSE	NA
146	Consolidated Edison Co. of NY Inc.	FALSE	NA
147	Consumers Energy Company	TRUE	Direct match
148	Corn Belt Power Cooperative	FALSE	NA
149	Dairyland Power Cooperative	TRUE	Balancing authority
150	Dayton Power & Light Company, The	TRUE	Direct match
151	Decatur Utilities	TRUE	Direct match
152	Detroit Edison Company	TRUE	Direct match
153	Duke Energy Control Area Services, LLC	FALSE	NA
154	Duke Energy Control Area Services, LLC	FALSE	NA
155	Duke Energy Control Area Services, LLC	FALSE	NA
156	City of North Little Rock	FALSE	NA
157	Duke Energy Carolinas, LLC	TRUE	Direct match
159	East Kentucky Power Cooperative	TRUE	Direct match
160	El Paso Electric Company	FALSE	NA
161	Electric Energy, Inc.	FALSE	NA
162	Electric Power Board of Chattanooga	TRUE	Direct match
163	Empire District Electric Company	TRUE	Direct match
164	Entergy Corporation/Services	TRUE	Balancing authority
165	ERCOT	FALSE	NA
166	Eugene Water & Electric Board	TRUE	Direct match
167	FirstEnergy Corporation	FALSE	NA
169	Florida Municipal Power Agency	TRUE	Manual
170	Florida Municipal Power Pool	FALSE	NA

Table 7: FERC respondents

171	Florida Power & Light Company	TRUE	Direct match
172	Gainesville Regional Utilities	TRUE	Direct match
173	Golden Spread Electric Cooperative, Inc.	TRUE	Manual
174	Grand River Dam Authority	TRUE	Direct match
175	Great River Energy	TRUE	Manual
176	Green Mountain Power Corporation	FALSE	NA
177	Greenville Utilities Commission	TRUE	Direct match
178	Hawaiian Electric Company, Inc	FALSE	NA
179	Hoosier Energy REC, Inc.	TRUE	Balancing authority
180	Idaho Power Company	TRUE	Direct match
182	Imperial Irrigation District	TRUE	Direct match
183	Indiana Municipal Power Agency	TRUE	Manual
184	Indianapolis Power & Light Company	TRUE	Direct match
185	ISO New England Inc.	FALSE	NA
186	JEA	TRUE	Direct match
187	Kansas City Board of Public Utilities & Wyandotte County	TRUE	Direct match
188	Kansas City Power & Light Company	FALSE	NA
189	Kansas Gas & Electric a Westar Energy company	TRUE	Direct match
190	Westar Energy	TRUE	Manual
191	Lakeland Electric	TRUE	Direct match
193	Lincoln Electric System	TRUE	Direct match
194	Los Angeles Department of Water and Power	TRUE	Direct match
195	Louisiana Energy & Power Authority	TRUE	Balancing authority
196	Louisiana Generating	TRUE	Manual
197	Louisville Gas & Electric and Kentucky Utilities	TRUE	Direct match
198	Madison Gas & Electric Company	TRUE	Direct match
199	Massachusetts Municipal Wholesale	FALSE	NA
200	Memphis Light, Gas and Water	TRUE	Direct match
201	Metropolitan Water District of Southern California	FALSE	NA
202	Michigan Electric Power Coordinated Center	FALSE	NA
203	MidAmerican Energy Company	TRUE	Manual
204	Mid-Continent Area Power Pool	FALSE	NA
206	Modesto Irrigation District	TRUE	Direct match
207	Montana-Dakota Utilities Company	TRUE	Manual
208	Muscatine Power & Water	FALSE	NA
209	Nebraska Public Power District	TRUE	Direct match
210	Nevada Power Company	TRUE	Direct match
211	New York Independent System Operator, Inc.	FALSE	NA
212	New York State Electric & Gas Corporation	FALSE	NA
213	Northeast Texas Electric Cooperative	TRUE	Manual
214	Northeast Utilities Service Company	FALSE	NA
215	Northern Indiana Public Service Company	TRUE	Direct match
216	Northern States Power Company	TRUE	Direct match
217	NorthWestern Energy	TRUE	Direct match
218	Oglethorpe Power Company	TRUE	Manual
219	Ohio Valley Electric Corporation & Indiana-Kentucky Electric Corp.	FALSE	NA
220	Oklahoma Gas & Electric Company	TRUE	Direct match
221	Oklahoma Municipal Power Authority	TRUE	Manual
222	Old Dominion Elec. Coop., Inc.-Dom VA Pwr Planning	FALSE	NA
223	Omaha Public Power District	TRUE	Direct match
224	Orange & Rockland Utils., Inc.	FALSE	NA
225	Orlando Utilities Commission	TRUE	Direct match
226	Otter Tail Power Company	TRUE	Direct match
227	Pacific Gas and Electric Company	TRUE	Direct match
228	PacifiCorp - East	FALSE	NA
229	PacifiCorp - West	FALSE	NA
230	PJM Interconnection LLC	FALSE	NA
231	Platte River Power Authority	TRUE	Manual
232	Portland General Electric Company	TRUE	Direct match
233	Progress Energy	TRUE	Direct match
234	Progress Energy	TRUE	Manual
235	Public Service Company of Colorado	FALSE	NA
236	Public Service Company of New Mexico	TRUE	Direct match
237	PUD No. 1 of Chelan County	TRUE	Direct match
238	PUD No. 1 of Douglas County	TRUE	Direct match
239	PUD No. 2 of Grant County	TRUE	Direct match
240	Puget Sound Energy, Inc.	TRUE	Direct match
241	Rochester Gas and Electric Corporation	FALSE	NA
242	Reedy Creek Improvement District	FALSE	NA
243	Sacramento Municipal Utility District	TRUE	Direct match
244	Salt River Project	TRUE	Direct match
245	Sam Rayburn G&T Electric Coop.	TRUE	Manual
246	San Diego Gas & Electric Company	TRUE	Direct match
247	Seattle City Light	TRUE	Direct match
248	Seminole Electric Cooperative, Inc.	TRUE	Balancing authority
249	Sierra Pacific Resources	TRUE	Direct match
250	South Carolina Electric & Gas	TRUE	Direct match

251	South Carolina Public Service Authority	TRUE	Direct match
252	South Mississippi Electric Power Association	TRUE	Balancing authority
253	Southern Company	FALSE	NA
254	Southern Illinois Power Coop	TRUE	Balancing authority
255	Southern Indiana Gas & Electric Company	TRUE	Direct match
256	Southern Minnesota Municipal Power Agency	TRUE	Balancing authority
257	Southwest Power Pool	FALSE	NA
258	Southwestern Power Administration	FALSE	NA
259	Southwestern Public Service Company	TRUE	Manual
260	Square Butte Electric Coop	FALSE	NA
261	Sunflower Electric Power Corporation	TRUE	Balancing authority
262	Tampa Electric Company	TRUE	Direct match
263	Tennessee Valley Authority	FALSE	NA
264	Tex-La Electric Cooperative of Texas, Inc.	TRUE	Manual
265	Tri-State G & T Assn., Inc.	TRUE	Manual
266	Tucson Electric Power Company	TRUE	Direct match
267	Turlock Irrigation District	TRUE	Direct match
268	United Illuminating Company	FALSE	NA
269	Upper Peninsula Power Company	TRUE	Direct match
271	Wabash Valley Power Association, Inc.	TRUE	Manual
272	Western Area Power Admin - Upper Missouri-East (Upper Great Plains Region operat	FALSE	NA
273	Western Area Power Administration - Colorado-Missouri Control Area (Rocky Mtn Re	FALSE	NA
274	Western Area Power Administration - Lower Colorado control area (Desert Southwe	FALSE	NA
275	Western Area Power Administration - Upper Missouri West (Upper Great Plains Regi	FALSE	NA
277	Western Farmers Electric Cooperative	TRUE	Balancing authority
278	Wisconsin Electric Power Company	TRUE	Direct match
279	Wisconsin Public Service Corporation	TRUE	Direct match
280	Wolverine Power Supply Coop., Inc.	TRUE	Direct match
281	City of Springfield	TRUE	Direct match
282	Wisconsin Public Power Inc.	TRUE	Direct match
283	Minnesota Municipal Power Agency	TRUE	Manual
284	Missouri River Energy Services	TRUE	Manual
285	Minnkota Power Cooperative, Inc.	TRUE	Manual
286	Gen-Sys Energy	FALSE	NA
287	Basin Electric Power Cooperative	FALSE	NA
288	Batesville Balancing Authority	FALSE	NA
289	City of Conway	FALSE	NA
290	City of Ruston	FALSE	NA
291	Union Power Partners	FALSE	NA
292	City of West Memphis	FALSE	NA
293	New Harquahala Generating Station	FALSE	NA
294	City of Benton	FALSE	NA
295	Old Dominion Elec. Coop., Inc.-Delmarva P&L Planning	FALSE	NA
296	Georgia Power Company	TRUE	Direct match
297	Mississippi Power Company	TRUE	Direct match
298	Gulf Power Company	TRUE	Direct match
299	Southern Power Company	TRUE	Direct match
300	NorthWestern Energy	TRUE	Direct match
301	PJM Interconnection Eastern Hub	FALSE	NA
302	PJM Interconnection Western Hub	FALSE	NA
303	PJM Interconnection Illinois Hub	FALSE	NA
304	PJM Interconnection North Illinois Hub	FALSE	NA
305	PJM Interconnection Dominion Hub	FALSE	NA
306	PJM Interconnection AEP-Dayton Hub	FALSE	NA
307	PacifiCorp - Part II Sch 2	FALSE	NA
308	City of St. Cloud	FALSE	NA
309	Michigan Electric Powr Coor. Center - Detroit	FALSE	NA
310	Southern California Edison Company	FALSE	NA
311	Arkansas Electric Cooperative Corporation	TRUE	Manual
312	Glacier Wind Balancing Authority	FALSE	NA
313	Plum Point Energy Associates -SERC REGION	FALSE	NA
315	Griffith Energy	FALSE	NA
319	Test Company E	FALSE	NA
320	City of Osceola - SERC	FALSE	NA
321	MISO	FALSE	NA
322	Constellation Energy Control and Dispatch - for Brazos	FALSE	NA
323	Constellation Energy Control and Dispatch, LLC	FALSE	NA
324	NaturEner Wind Watch, LLC	FALSE	NA
325	New Smyrna Beach Utilities Commission	FALSE	NA
326	City of Lake Worth	FALSE	NA
327	City of Vero Beach	FALSE	NA
99991	{Test Company A}	FALSE	NA
99992	{Test Company B}	FALSE	NA
99994	{Test Company D-edited}	FALSE	NA

In total, the FERC 714 data resulted in 123 load zones corresponding to 2,377 counties. As stated above, we additionally obtained sub-regional load data from ERCOT, ISO-NE, PJM, and NYISO. Because these ISOs report to FERC as single entities, we instead use the disaggregated load data available on their website. This resulted in 43 load zones corresponding to 869 counties, mapped in Figure S8.
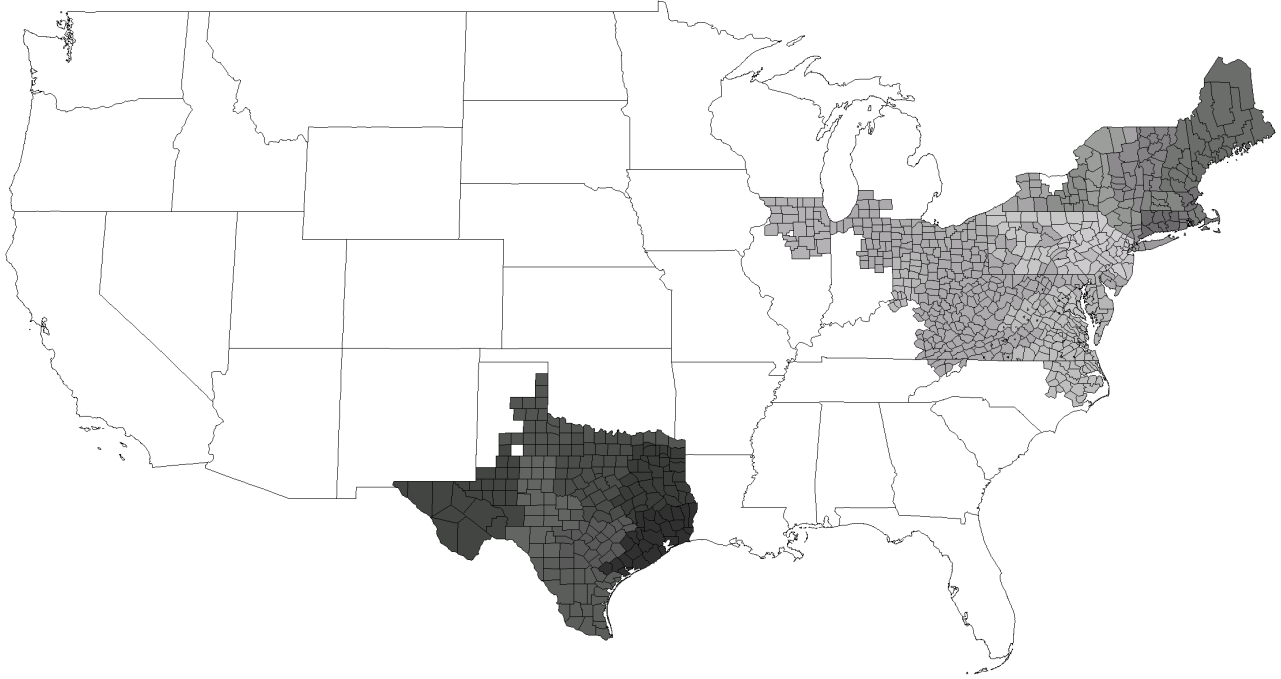

Figure S8: ISO territories

Finally, we compiled the geographies obtained from FERC and from the ISOs into a single dataset. This resulted in 166 load zones covering 2,888 counties. The final coverage map for this dataset is Figure S1.