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SUPPORTING INFORMATION FOR:

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Summary

This supporting information contains instructions on implementing the decision support algorithm presented in this article, two illustrative cases, and nine tables and eight figures.

Contents

Tables

Figures

Instructions

The decision support algorithm is described in the flow diagrams and lookup tables below. The flow diagrams consist of a series of questions, denoted by blue boxes. The black outlined boxes are possible answers and green outlines indicate the algorithm's recommendations. The user proceeds through the flow diagrams in numerical order from one to six, answering questions about the research question and the electricity load under study. Answers from the questions in flow diagram one, figure S1, are used in diagrams two and three, figures S2 and S3. Each question in figures S1 and S4-S6 is numbered, just to the left of the blue question box. Figure S5 is used with average emissions factors (AEF) and references the tables in the lookup table section. This figure may also require the use of EPA's Power Profiler tool (EPA 2012), which is a downloadable Excel file that can be accessed at the website listed in the references. Figure S6 is only used with marginal emissions factors (MEF). The emissions factor type (marginal or average) is determined in figure S1. It is important to read the notes in green outlined boxes because they present key results that are explained in the figure captions.

Algorithm Flow Diagrams

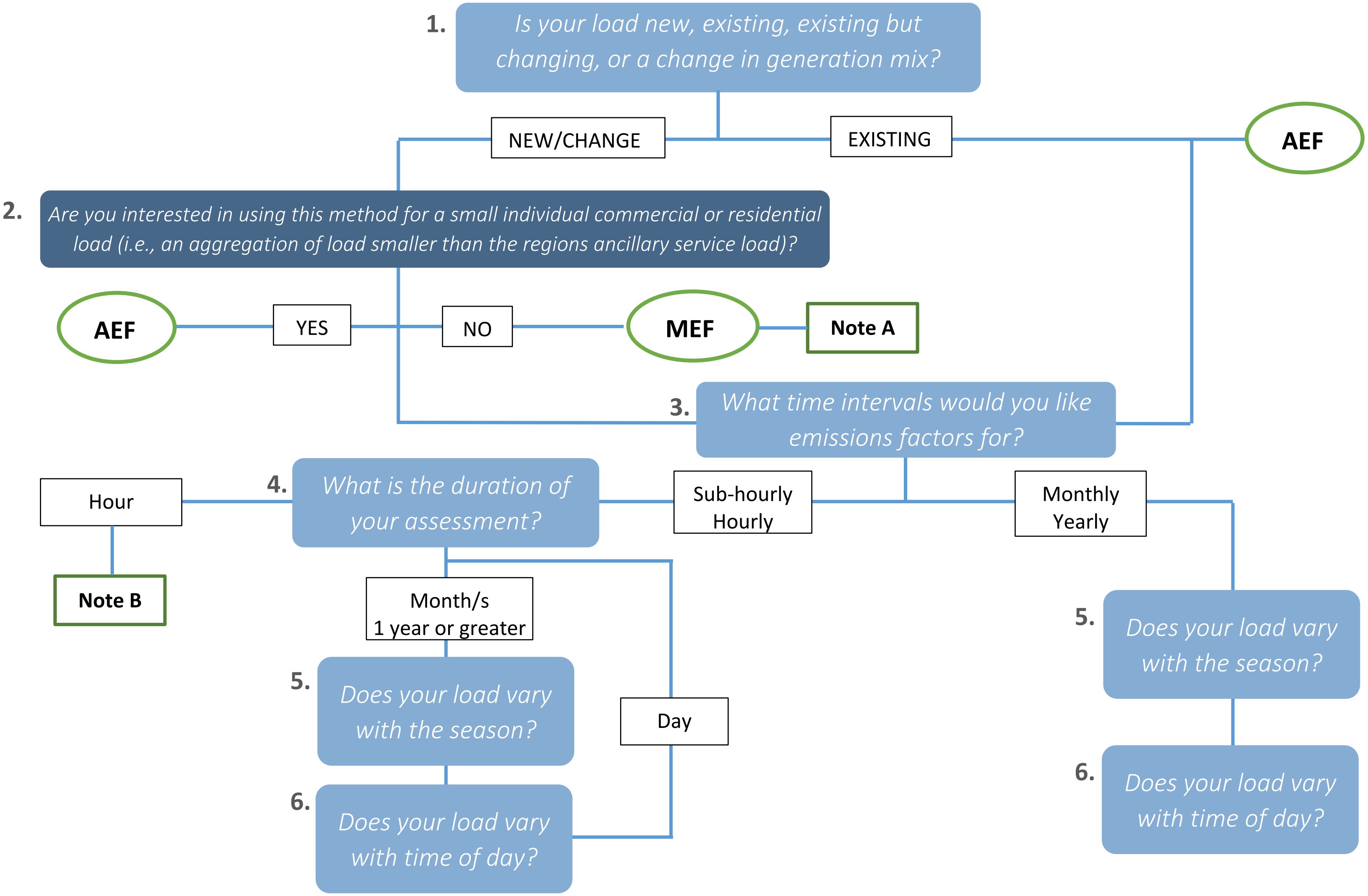

Figure S1 Flow diagram for load type and emissions variation with time (A: If trading is determined to be important then hourly temporal variation will be important and results from flow diagrams S2 & S3 can be ignored and the user should skip to figure S6 prior to proceeding back to figure S4, B: The user can move on to question 7, ref. S3 to determine the need for temporal variation).

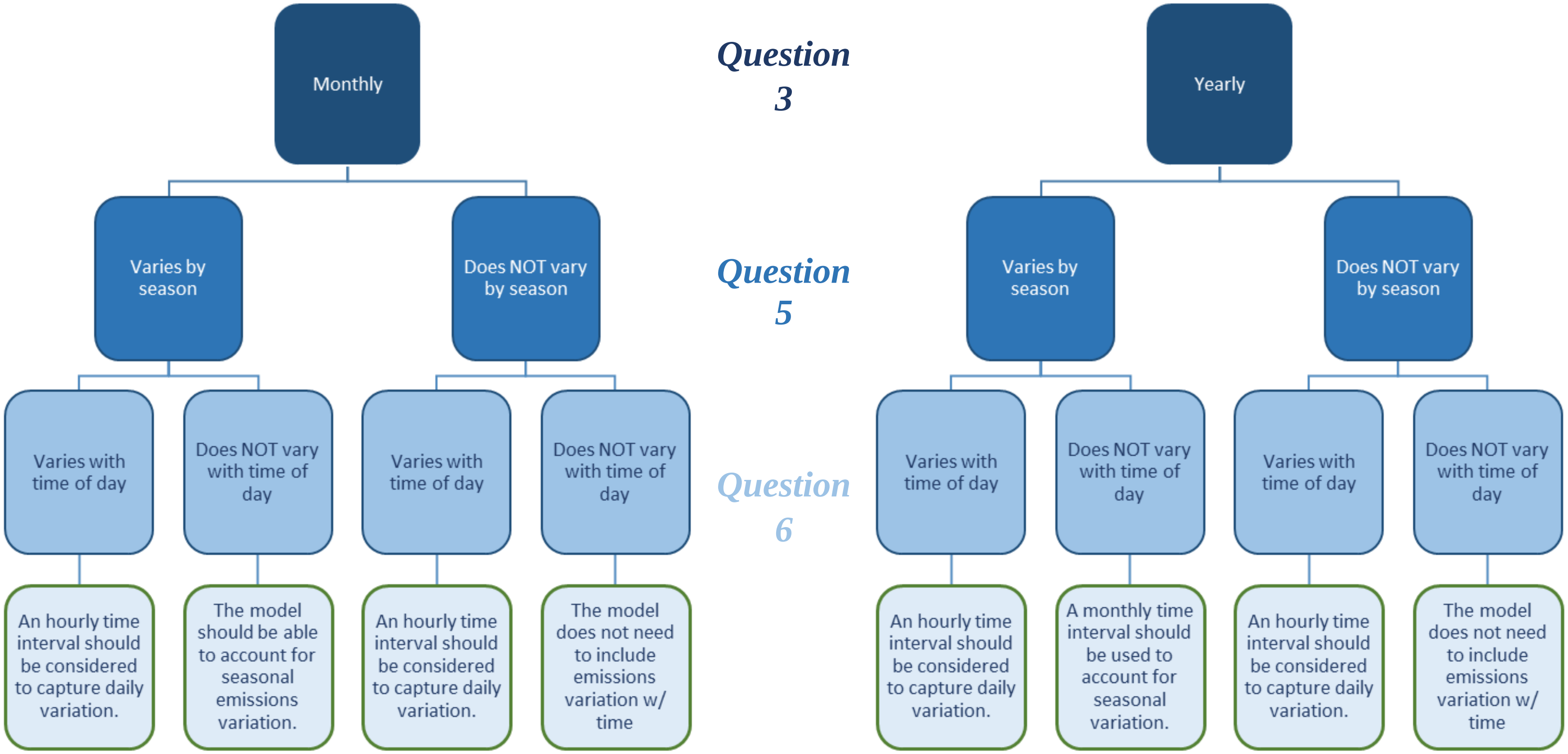

Figure S2 Decision support tree with monthly and daily time intervals for average emissions factor (AEF) loads and marginal emissions factor (MEF) loads where trading is not important.

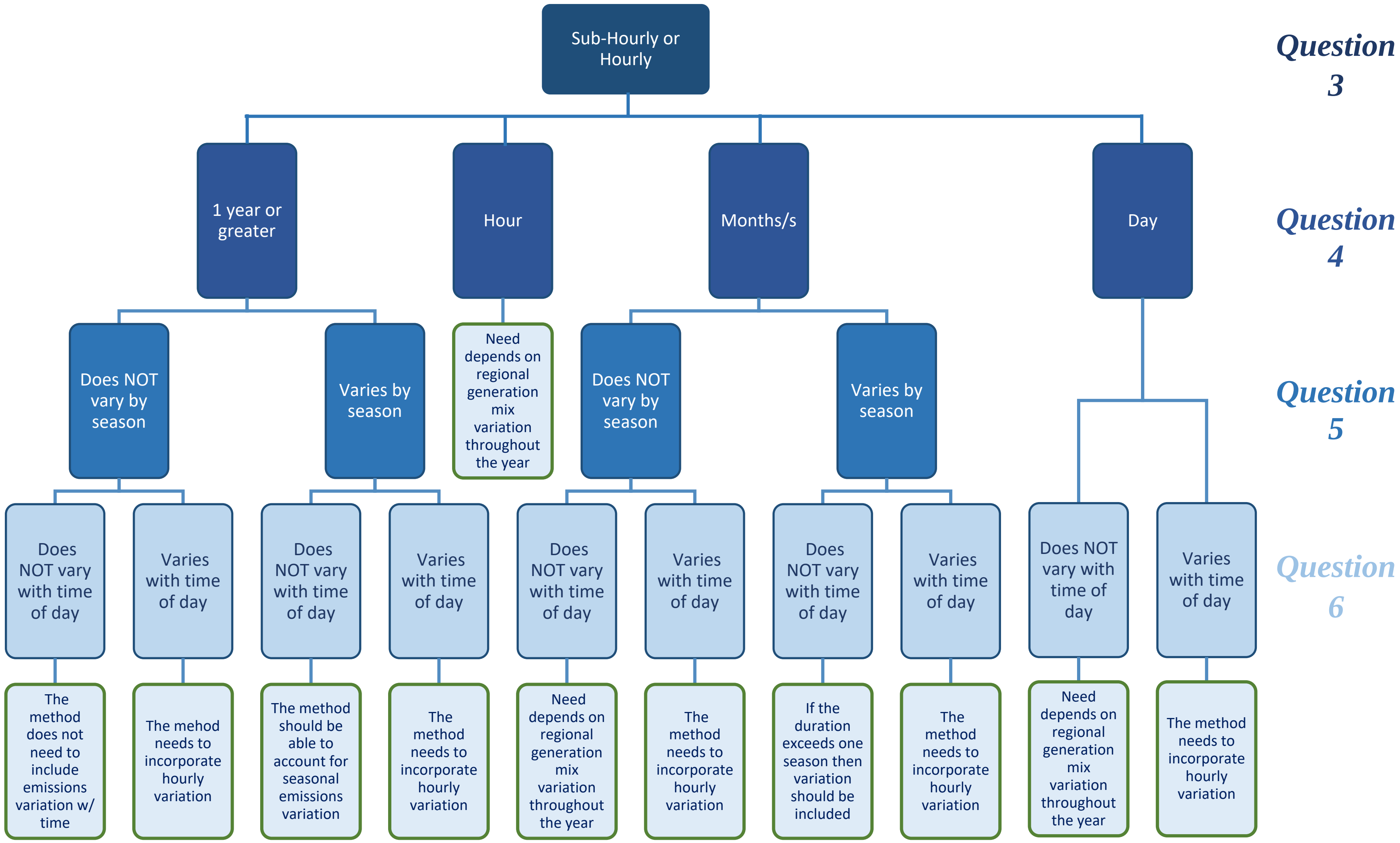

Figure S3 Decision support tree with hourly and sub-hourly time intervals for average emissions factor (AEF) loads and marginal emissions factor (MEF) loads where trading is not important.

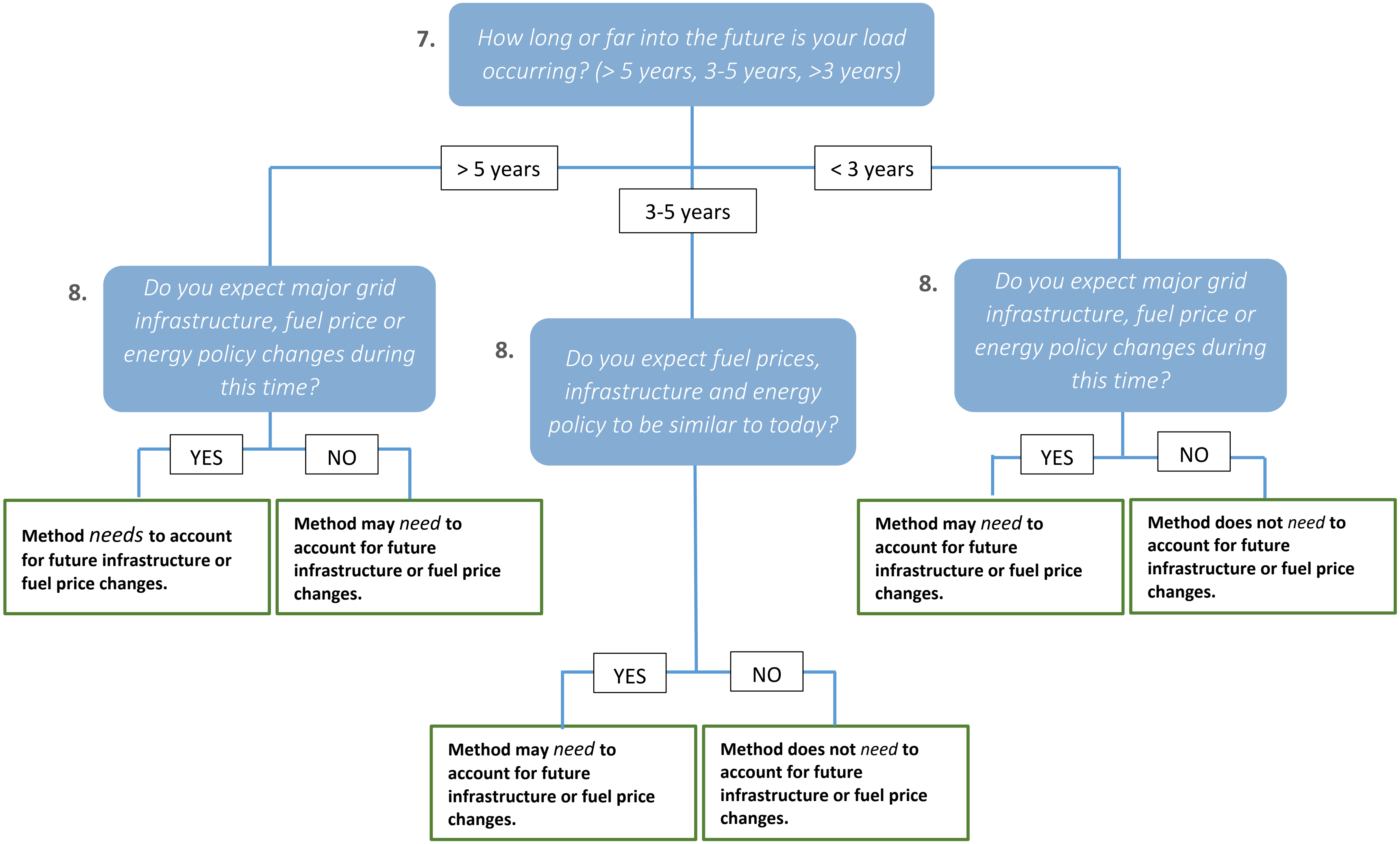

Figure S4 Flow diagrams for determining time scale for loads that are new or a change.

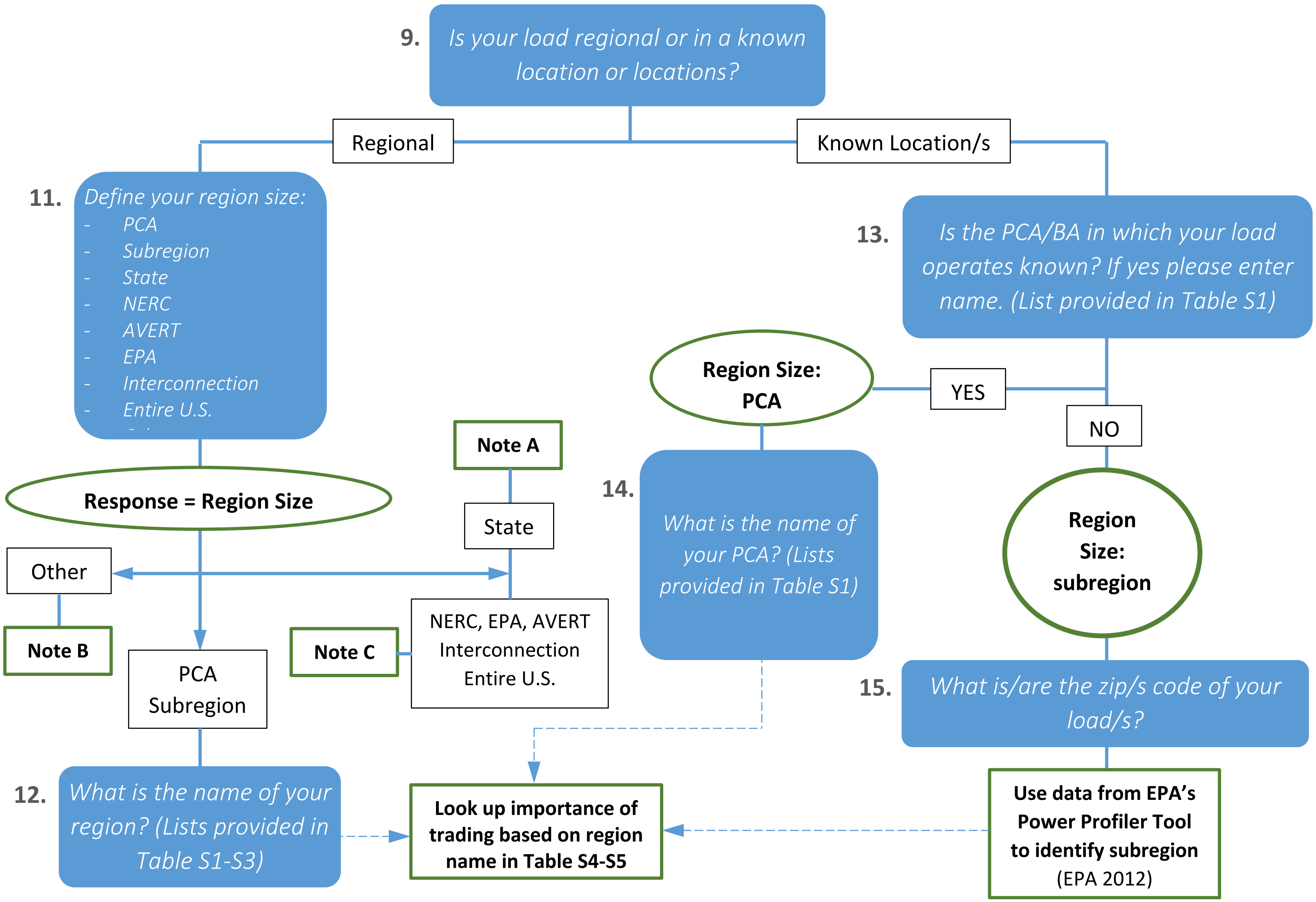

Figure S5 Flow diagram for determining region size and importance of trading for loads requiring average emissions factor (A: trading will be important in states other than Hawaii, Alaska and Texas, B: no trading recommendations can be made, C: inclusion of electricity trading is not a priority).

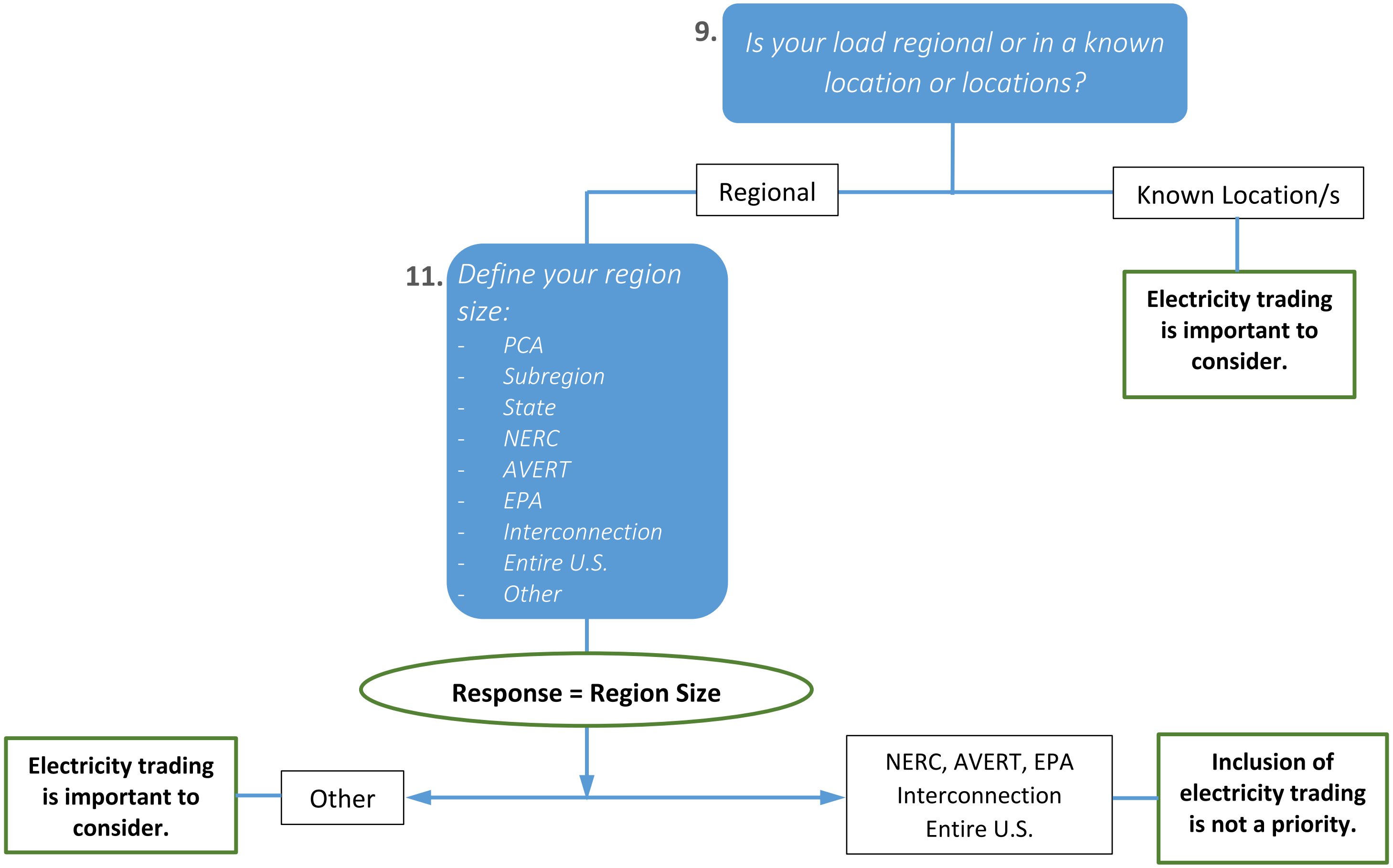

Figure S6 Flow diagram for determining region size and importance of trading for loads that require marginal emissions factors. If trading is not important return to figure S1-S3 to determine the importance of temporal variation. If trading is important then temporal variation is also important to consider.

Algorithm Lookup Tables

Table S1 Power Control Area (PCA) Lookup Table (EPA 2014).

PCA ID	PCA name	PCA ID	PCA name
-20	Plum Point Energy Associates	13143	Muscatine Power and Water
-19	NaturEner Power Watch	13337	Nebraska Public Power District
-18	Balancing Authority of Northern California	13407	Nevada Power Company
-17	CECD - Batesville	13434	New England ISO
-2	Hawaii Misc	13485	New Smyrna Beach Utilities Commission of
-1	Alaska Misc	13501	New York ISO
1	New Brunswick Power Corporation	13718	North Little Rock AR City of
186	Alliant - East	13756	Northern Indiana Public Service Company
189	PowerSouth Energy Cooperative	13781	Northern States Power
193	Alliant - West	14015	Ohio Valley Electric Corporation
599	Anchorage Municipality of	14063	Oklahoma Gas and Electric Company
803	Arizona Public Service Company	14127	Omaha Public Power District
924	Associated Electric Cooperative Inc	14232	Otter Tail Power Company
1692	Big Rivers Electric Corporation	14354	PacifiCorp
1738	Bonneville Power Administration	14412	Gila River Power
2775	California ISO	14624	PUD No. 2 of Grant County
2777	Louisiana Generating	14725	PJM Interconnection
3046	Duke Energy Progress	15248	Portland General Electric Company
3265	Cleco Corporation	15466	Public Service Company of Colorado
3413	PUD No. 1 of Chelan County	15473	Public Service Company of New Mexico
3522	Chugach Electric Assn Inc	15500	Puget Sound Energy
3542	Duke Energy Corporation	16572	Salt River Project
4045	Columbia MO City of	16868	Seattle City Light
4254	Consumers Energy Company	17166	Sierra Pacific Power Company
4716	Dairyland Power Cooperative	17539	South Carolina Electric & Gas Company
5109	DTE Electric Company	17543	South Carolina Public Service Authority
5326	PUD No. 1 of Douglas County	17568	South Mississippi Electric Power Assn
5416	Duke Energy Carolinas	17632	Southern Illinois Power Cooperative
5580	East Kentucky Power Cooperative	17633	Southern Indiana Gas & Electric Company
5701	El Paso Electric Company	17698	AEP - PSO/SWEPCO
5723	ERCOT ISO	17716	Southwestern Power Administration
5860	Empire District Electric Company	17718	Southwestern Public Service Company
6452	Florida Power & Light Company	17828	Springfield IL - CWLP City of
6455	Duke Energy Florida	18195	Southern Company Services
6567	Florida Municipal Power Pool	18315	Sunflower Electric Power Corporation
6909	Gainesville Regional Utilities	18429	Tacoma Power
7353	Golden Valley Elec Assn Inc	18445	Tallahassee City of

7490	Grand River Dam Authority	18454	Tampa Electric Company
7570	Great River Energy	18642	Tennessee Valley Authority
8287	Hawaii Electric Light Co Inc	19281	Turlock Irrigation District
9096	Lafayette Utilities System	19547	Hawaiian Electric Co Inc
9191	Idaho Power Company	19578	Upper Peninsula Power Company
9208	Ameren Services Company	19610	WAPA - Desert Southwest Region
9216	Imperial Irrigation District	20169	Avista Corporation
9231	Independence MO City of	20447	Western Farmers Electric Cooperative
9267	Hoosier Energy REC	20847	Wisconsin Energy Corporation
9273	Indianapolis Power & Light Company	20860	Wisconsin Public Service Corporation
9617	JEA	21554	Seminole Electric Cooperative
9996	Kansas City Board of Public Utilities	22500	Westar Energy
10000	Kansas City Power & Light Company	24211	Tucson Electric Power
11018	Lincoln Electric System	25470	WAPA - Upper Great Plains East
11208	Los Angeles Department of Water and Power	25471	WAPA - Upper Great Plains West
11249	LG&E and KU Services Company	26253	Louisiana Energy & Power Authority
11479	Madison Gas and Electric Company	28503	WAPA - Rocky Mountain Region
12341	MidAmerican Energy Company	32790	New Harquahala Generating Company
12427	Michigan Electric Coordinated Systems	40580	Southern Minnesota Municipal Power Agcy
12506	Entergy	54796	Union Power Partners
12647	Minnesota Power	54805	Arlington Valley
12699	Kansas City Power & Light Co-GMO	56090	Griffith Energy
12825	NorthWestern Corporation	56093	Alcoa Power - Yadkin Division

Table S2 eGRID Subregion Lookup Table (EPA 2014).

eGRID subregion name	eGRID subregion acronym	eGRID subregion name	eGRID subregion acronym
ASCC Alaska Grid	AKGD	NPCC Long Island	NYLI
ASCC Miscellaneous	AKMS	NPCC Upstate NY	NYUP
WECC Southwest	AZNM	RFC East	RFCE
WECC California	CAMX	RFC Michigan	RFCM
ERCOT All	ERCT	RFC West	RFCW
FRCC All	FRCC	WECC Rockies	RMPA
HICC Miscellaneous	HIMS	SPP North	SPNO
HICC Oahu	HIOA	SPP South	SPSO
MRO East	MROE	SERC Mississippi Valley	SRMV
MRO West	MROW	SERC Midwest	SRMW
NPCC New England	NEWE	SERC South	SRSO
WECC Northwest	NWPP	SERC Tennessee Valley	SRTV
NPCC NYC/Westchester	NYCW	SERC Virginia/Carolina	SRVC

Table S3 NERC region Lookup Table (EPA 2014).

NERC region name	NERC region acronym
Alaska Systems Coordinating Council	ASCC
Florida Reliability Coordinating Council	WECC
Hawaiian Islands Coordinating Council	TRE
Midwest Reliability Organization	FRCC
Northeast Power Coordinating Council	HICC
Reliability First Corporation	MRO
SERC Reliability Corporation	NPCC
Southwest Power Pool	RFC
Texas Regional Entity	SPP
Western Electricity Coordinating Council	SERC

Table S4 Trading and emissions effects for eGRID subregions.

Subregion	*RIT*	Subregion	*RIT*
AKGD	0.0%	NYLI	0.0%
AKMS	0.0%	NYUP	0.0%
AZNM	1.3%	RFCE	0.0%
CAMX	4.4%	RFCM	1.5%
ERCT	0.0%	RFCW	0.2%
FRCC	0.0%	RMPA	4.8%
HIMS	0.0%	SPNO	0.5%
HIOA	0.0%	SPSO	0.1%
MROE	0.5%	SRMV	2.0%
MROW	0.1%	SRMW	0.6%
NEWE	0.4%	SRSO	0.1%
NWPP	2.5%	SRTV	0.1%
NYCW	0.0%	SRVC	0.2%

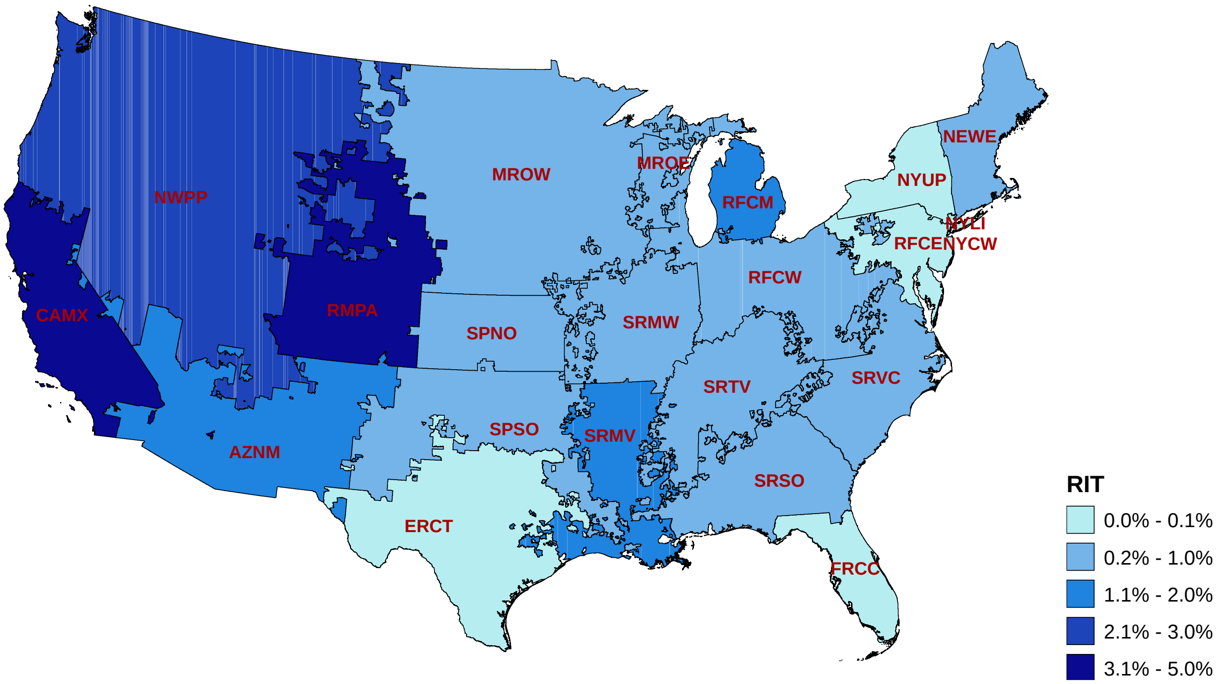

Figure S7 The relative importance of trading (RIT) for each subregion.

Table S5 Trading and emissions effects for PCA/BAs.

EIA Code	*RIT*	EIA Code	*RIT*
9208	0.0%	14624	0.4%
599	0.3%	15500	18.2%
803	0.5%	16572	0.4%
924	0.0%	16868	64.1%
20169	31.1%	21554	7.5%
1692	1.3%	17166	12.6%
1738	0.0%	17539	0.9%
3522	1.0%	17543	11.0%
3265	0.1%	17568	0.0%
4045	10.2%	18195	0.0%
4716	0.0%	17632	3.0%
5416	0.2%	17633	0.8%
6455	1.9%	40580	68.0%
3046	0.1%	17716	0.5%
5580	3.7%	17718	0.1%
5701	3.0%	17828	2.9%
5860	2.2%	18315	5.8%
12506	0.4%	18429	75.6%
5723	0.0%	18445	1.1%
6452	1.3%	18454	0.0%

6909	7.6%	18642	0.5%
7490	0.8%	24211	6.6%
19547	0.0%	19281	5.8%
9267	0.0%	19578	35.6%
9191	18.3%	19610	0.0%
9216	67.4%	28503	0.5%
9231	0.8%	25471	54.9%
9273	0.3%	20447	10.3%
9617	4.0%	20847	1.4%
9996	3.3%	20860	2.2%
10000	0.9%	-20	Trading data not available for this region.
9096	10.6%	-19	Trading data not available for this region.
11249	0.2%	-18	Trading data not available for this region.
11018	16.8%	-17	Trading data not available for this region.
11208	12.7%	-2	Trading data not available for this region.
26253	17.7%	-1	Trading data not available for this region.
11479	3.4%	1	Trading data not available for this region.
12427	1.9%	186	Trading data not available for this region.
12647	4.1%	193	Trading data not available for this region.
13143	1.6%	2775	Trading data not available for this region.
13337	0.0%	2777	Trading data not available for this region.
13407	1.9%	3542	Trading data not available for this region.
13434	0.1%	4254	Trading data not available for this region.
13501	0.7%	5109	Trading data not available for this region.
13718	146.3%	6567	Trading data not available for this region.
13756	2.2%	7353	Trading data not available for this region.
13781	6.4%	7570	Trading data not available for this region.
12825	2.2%	8287	Trading data not available for this region.
14015	0.0%	12341	Trading data not available for this region.
14063	0.1%	12699	Trading data not available for this region.
14127	0.1%	13485	Trading data not available for this region.
14232	0.0%	14412	Trading data not available for this region.
14354	1.3%	17698	Trading data not available for this region.
14725	0.1%	22500	Trading data not available for this region.
15248	17.7%	25470	Trading data not available for this region.
189	3.1%	32790	Trading data not available for this region.
15466	2.4%	54796	Trading data not available for this region.
15473	1.5%	54805	Trading data not available for this region.
3413	0.0%	56090	Trading data not available for this region.
5326	0.0%	56093	Trading data not available for this region.

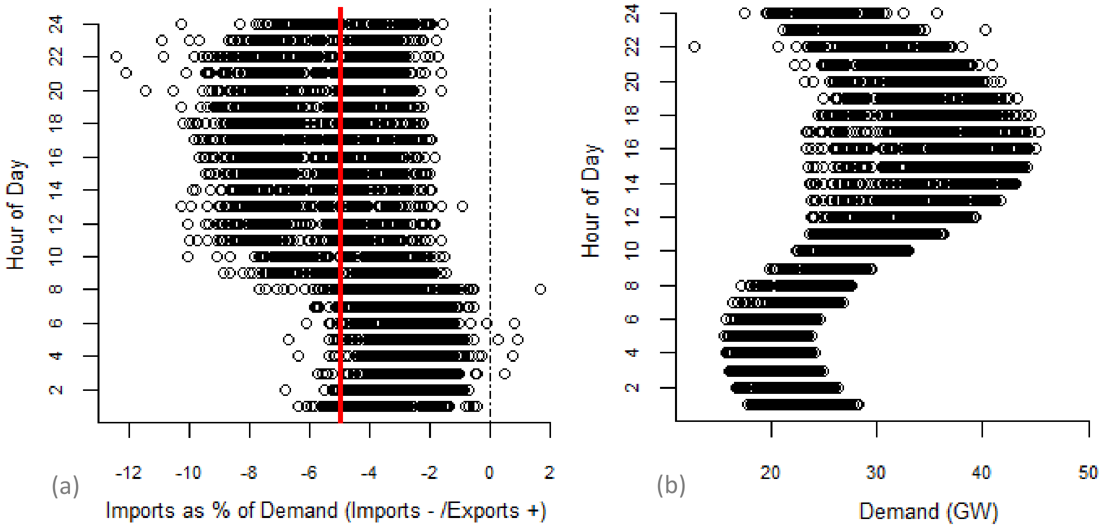

Figure S8 (a) Hourly electricity imports and exports for Florida from July 2015 to December 2015 by hour of the day with the red line delineating the six-month net electricity traded (b) hourly electricity demand in Florida for the same time period (U.S. Energy Information Administration 2017).

Algorithm Inputs for Case Studies

Table S6 Question responses for household appliances: air conditioner case to Table S9 Question responses for aluminum material production case contain the inputs into the Excel tool. None of these cases employed the weighting function of the tool. The results of the EV and aluminum smelter runs are discussed in the illustrative cases section of the paper, and the air conditioner and PV cases are discussed below.

Table S6 Question responses for household appliances: air conditioner case.

Question Number	Answer	Question Number	Answer
1. Type of load (new, existing, change)	Existing	9. Regional granularity	Known Location
2. Scale of load	*Blank*	10. Multiple locations	One
3. Time interval	Monthly	11. Number of locations	*Blank*
4. Duration	*Blank*	12. Zip code	06010
5. Seasonal variation	Yes	13. Knowledge of PCA	Yes, 13434
6. Daily variation	Yes	14. Region size	*Blank*
7. Length of load	*Blank*	15. Name	*Blank*
8. Expected system changes	*Blank*		

Table S7 Question responses for electric vehicle fleet case.

Question Number	Answer	Question Number	Answer
1. Type of load (new, existing, change)	New	9. Regional granularity	Regional
2. Scale of load	No	10. Multiple locations	*Blank*
3. Time interval	Hourly	11. Number of locations	*Blank*
4. Duration	1 year or greater	12. Zip code	*Blank*
5. Seasonal variation	No	13. Knowledge of PCA	*Blank*
6. Daily variation	Yes	14. Region size	State

7. Length of load	3-5 years	15. Name	CA
8. Expected system changes	Yes		

Table S8 Question responses for grid-connected solar case.

Question Number	Answer	Question Number	Answer
1. Type of load (new, existing, change)	New	9. Regional granularity	Know Location/s
2. Scale of load	No	10. Multiple locations	One
3. Time interval	Hourly	11. Number of locations	*Blank*
4. Duration	1 year or greater	12. Zip code	89109
5. Seasonal variation	Yes	13. Knowledge of PCA	Yes, 13407
6. Daily variation	Yes	14. Region size	*Blank*
7. Length of load	3-5 years	15. Name	*Blank*
8. Expected system changes	Yes		

Table S9 Question responses for aluminum material production case.

Question Number	Answer	Question Number	Answer
1. Type of load (new, existing, change)	Existing	9. Regional granularity	Known location/s
2. Scale of load	*Blank*	10. Multiple locations	Multiple
3. Time interval	Yearly	11. Number of locations	2
4. Duration	*Blank*	12. Zip code	42348, 29445
5. Seasonal variation	No	13. Knowledge of PCA	Yes: 1692, 17543
6. Daily variation	No	14. Region size	*Blank*
7. Length of load	*Blank*	15. Name	*Blank*
8. Expected system changes	*Blank*		

Illustrative case discussion

Household appliances: Air Conditioners

A homeowner in Bristol, CT is interested in calculating their air conditioner's monthly emissions from electricity consumption. The algorithm's recommendations are presented in table 2. Although the homeowner would like monthly emissions values, because the load has diurnal variation (in addition to the obvious seasonal variation) an hourly time interval was recommended. The homeowner knows the PCA for their household, so the algorithm recommended a PCA as the appropriate region size to use.

For emissions factor type, there was no variation between past methods presented here or the algorithm's recommendations. Two studies analyzing the life-cycle emissions of residential cooling systems (Shah, Debella, and Ries 2008; Grignon-Massé, Rivière, and Adnot 2011) and a study on optimal refrigerator replacement time (Kim, Keoleian, and Horie 2006) all used annual average emissions factors (refrigerators and air conditioners are mechanically and functionally equivalent). Kim et al. (2006) estimated emissions using Franklin Associates emissions factors. Shah et al. (2011) used state annual electricity mixes, and Grignon-Massé et al. (2011) used the European average emissions value for electricity from Ecodesign. Despite finding that 93% of the energy consumption occurred in the use-phase of the air conditioner's life (i.e., almost all the energy consumption was derived from electricity) and the air conditioner having strong seasonal and diurnal fluctuations in electricity demand, annual averages were employed (Grignon-Massé, Rivière, and Adnot 2011).

The three studies above align with the algorithm's recommendation on emissions factor type but not on *inclusion of temporal variation*. When assessing products whose most significant energy impact is the use-phase electricity consumption and whose consumption has strong diurnal variation, it should be a priority to include temporal variation in emissions modeling. As seen in figure 4, emission factors can vary significantly with time of day. Although the literature methods discussed above make comparable assumptions, including temporal variation would likely result in more appropriate emissions estimates. However, this presents trade-offs in model types, since most models that include temporal variation are either more complex or use larger regions than a PCA.

Grid-connected solar

A hotel owner in Las Vegas, NV is interested in installing grid-connected solar panels on the hotel's roof and wants to estimate resulting reductions in CO_2 emissions for the next five years. The algorithm's recommendations are presented in table 2. The load was a 'change in generation mix,' resulting in the recommendation to use a *marginal emissions factor*. The owner also expects fuel prices, electricity infrastructure, or energy policy to change during the time frame of the analysis, resulting in a recommendation that the method selected *may need to account for these changes*. The recommended method type is prospective dispatch methods (i.e., Power System Optimization Methods) that can incorporate future changes, hourly variation, and marginal emissions factors.

Emissions factor type and the need to account for future infrastructure changes are important differences among the methods used in previous literature and the algorithm's recommendations. Spiegel et al. (2005) used state-level yearly average emissions factors from eGRID to determine the emissions offsets of 214 simulated PV systems. They used state boundaries since they were assessing PV across a wide geography, a region choice that they justified since most states are part of only one NERC region (Spiegel, Leadbetter, and Chamú 2005). eGRID contains historical emissions factors so their analysis is not applicable to a future time frame, which was the desire of the case study. Additionally, their grid simplifications (e.g., average emissions factors and yearly values) do not align with the algorithm's recommendations and differ from Denholm et al. (2009).

Denholm et al. (2009) employed PROSYM to estimate the potential for solar PV to reduce fossil fuel use in the Western United States. They assessed PV penetrations of up to 10% and looked at scenarios more than five years into the future (Denholm, Margolis, and Milford 2009), requiring a method that *can account for infrastructure, fuel price, and policy changes*. PROSYM is a production cost model, which is able to incorporate infrastructure changes, *electricity trading, temporal variation* and *marginal* emissions (ibid.). The algorithm's recommendations align closely with Denholm et al.'s (2009) methods.

The two studies discussed above varied significantly in scale and were concerned with wider geographic areas than the hotel PV case, which led to some of the method variations, but the need to account for temporal variation holds for both of these studies due to the strong diurnal and seasonal patterns of solar insolation. If these two methods were employed over the same time frame and geographic area they would most likely estimate different quantities of emissions due to their differing method assumptions. Without a benchmark of best practices in modeling the offset emissions it would be difficult to determine which study's results were more applicable for this case.

References

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