Grid-interactive efficient buildings: Assessing the potential for energy flexibility alongside energy efficiency

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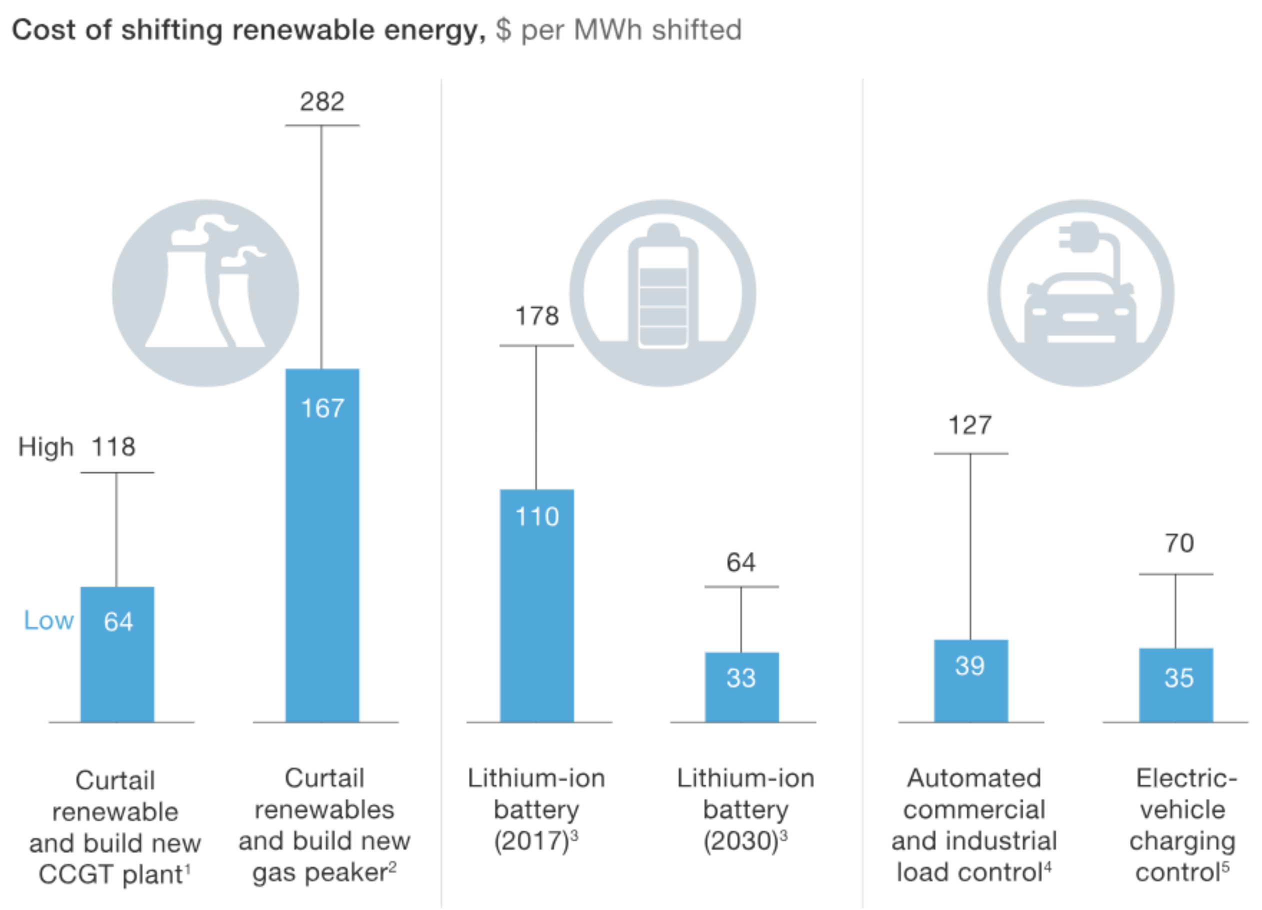
Motivating question

How much can grid-interactive efficient building technologies benefit U.S. electric grid operations?

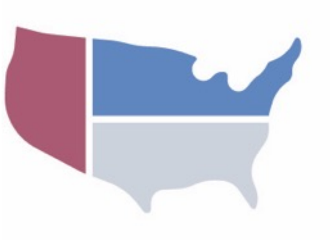
What is the available electric load “resource” from buildings?

- Buildings comprise 75% of U.S. electricity demand.
- Demand-side flexibility can support variable renewable electricity penetration cost-effectively.
- The magnitude of the potential grid resource from flexible building technologies has not yet been quantified.



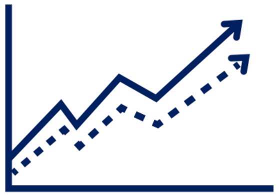
Comparison of the costs per MWh of shifting renewable energy from generation sources, and battery storage/distributed energy resources. Aggregated demand-side flexibility resources are found to be cost-effective and frequently cheaper than the generation alternative. Source: McKinsey.

A guide to interpreting our results

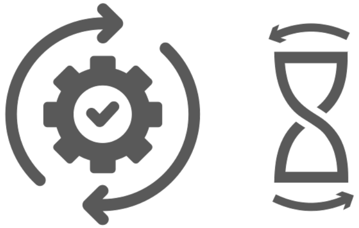


Geographical granularity: by 22 EIA Electricity Market Module (EMM) regions (no AK/HI).

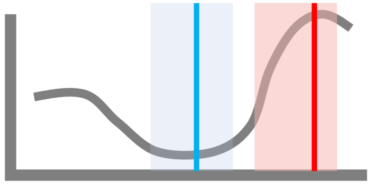
Electricity use segmentation: by building type (res./com.), end use, technology



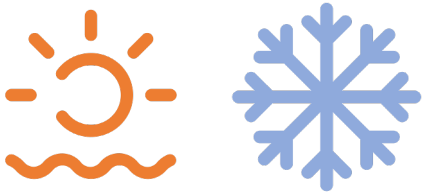
Time horizon: Annual and sub-annual results from 2015-2050; measure relative impacts persist over time.



Measure types: Energy efficiency (EE); demand flexibility (DF); packaged efficiency and flexibility (EE+DF).



Measure grid service: Reduce system annual electricity use and net peak period/hour use, increase net take period/hour use; net load shapes assume high renewable penetration.



Measure application: All hours/days with operational schedules that shift between summer and winter based on grid needs; operation at the edge of comfort bounds.

Measure adoption: Full overnight adoption, + realistic baseline market turnover, + achievable sales penetration.

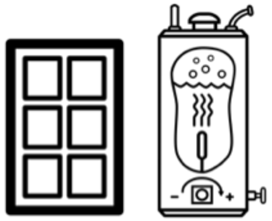
Approach

A bottoms-up stock-and-flow model of U.S. buildings, combined with hourly electric loads and simulated electricity use impacts of efficient and flexible technologies.

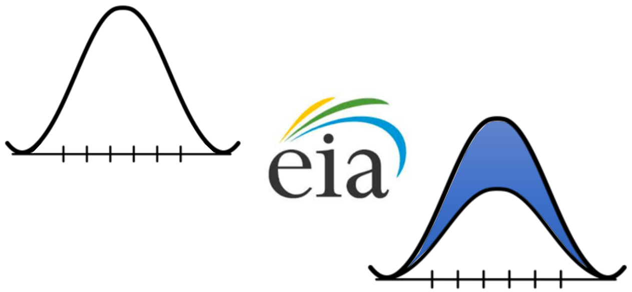
Approach to time-sensitive regional valuation of electricity use

1. Define measures in technology portfolios

   Energy efficiency (EE), demand flexibility* (DF), and combined EE+DF technology portfolios



2. Develop 8760 hourly fractions of baseline load by climate zone, building type, and end use



3. Identify seasonal peak period and low demand period by electricity market sub-region to inform flexible* measure operation

4. Simulate measures using ResStock (residential) and OpenStudio (commercial) and extract hourly savings fractions from the results

5. Translate measure impacts to Scout and use Scout to assess regional and national portfolio impacts, annually and sub-annually (2015–2050)

* "Flexibility" measures can reduce load during peak hours ("shed") or move electricity use out of the peak period ("shift").
Further details on demand flexibility can be found in the Building Technologies Office Grid-interactive Efficient Buildings Overview.

Residential measures were modeled using ResStock

ResStock, a framework for simulating a statistically representative sample of residential buildings in OpenStudio and EnergyPlus, was used to explore the effect of various measures on hourly residential building energy use.

Scenario	Measure Name	End Use(s)	Description
Energy Efficiency (EE)	Scout "Best Available" ECM portfolio	All major end uses	Current best available residential efficiency ECMs, definitions posted on Scout GitHub repository
	Programmable thermostat (PCT) setups and setbacks	HVAC	Apply thermostat setups and setbacks while maintaining temperature setpoint diversity
Demand Flexibility (DF)	PCT + pre-cooling and heating	HVAC	Decrease/increase temperature set points during peak period
	Grid-responsive water heater	Water Heating	Increase temperature setpoint at beginning of take period, decrease setpoint at beginning of peak period
	Grid-responsive washer/dryer, variable-speed pool pump	Appliances	Shift washer/dryer cycles and pool pump power to off-peak hours
	Low priority plug load adjustments	Electronics	Shift or switch off/unplug some low-priority electronics during peak hours (e.g., TVs, set top boxes, laptops/PCs)
EE + DF	PCT + pre-cool/heat + efficient envelope and HVAC equipment	HVAC, Lighting	Combine EE HVAC and envelope upgrades with DF HVAC controls
	Grid-responsive cycling/control + efficient equipment	Appliances, WH, Electronics	Combine DF WH, appliance, and electronics strategies with most efficient equipment
	All remaining EE ECMs	Refrigeration	Account for efficiency outside of other EE+DF measures

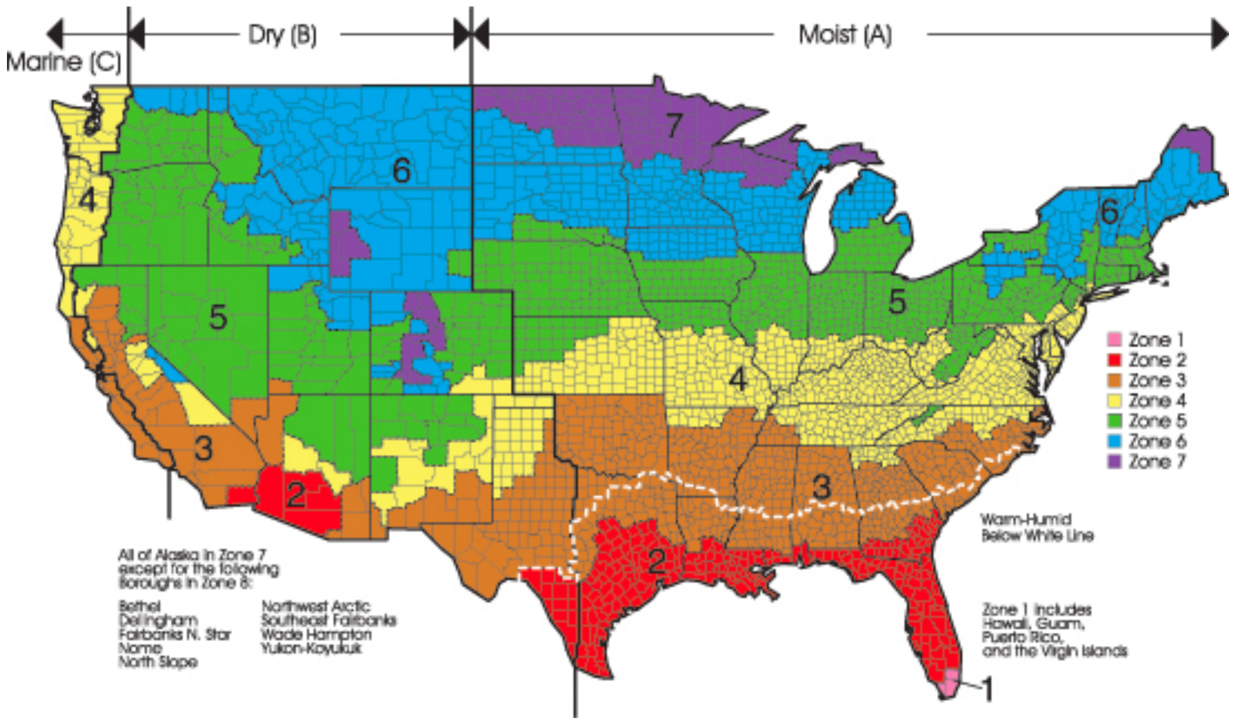
Commercial measures were modeled with prototype buildings

The Commercial Prototype Reference Models were used with OpenStudio and EnergyPlus to explore the effect of various measures on hourly commercial building energy use.

Scenario	Measure Name	End Use(s)	Description
Energy Efficiency (EE)	Scout "Best Available" ECM portfolio	All major end uses	Current best available commercial ECMs, definitions posted on Scout GitHub repository
Demand Flexibility (DF)	Global temperature adjustment (GTA)	HVAC	Increase zone temperature set points for one or more peak hours
	GTA + pre-cooling		Decrease zone set points prior to peak period
	GTA + pre-cooling + storage		Charge ice storage overnight and discharge during peak period
	Continuous dimming	Lighting	Dim lighting, and shut off lighting in unoccupied spaces, for one or more peak hours
	Low priority device switching	Electronics	Switch off low-priority devices (e.g., unused PCs, equipment) for one or more peak hours
EE + DF	GTA + pre-cool/heat + efficient envelope and HVAC equip.; daylighting controls + dimming	HVAC, Lighting	Combine DF HVAC/lighting strategies with more efficient envelope/equipment, daylighting, and controls to maximize EE and DF
	Device switching + efficient electronics	Electronics	Combine DF electronics strategy with the most efficient electronic equipment
	All remaining EE ECMs	Refrigeration, WH	Account for efficiency outside of combined EE+DF measures above

Building-level measure operation addresses system-level needs

- Building-level measure operation is modeled in a representative city for 14 ASHRAE/IECC climate zones (excludes 1 and 8)
- Representative building types capture variations in loads and operational patterns
  - Residential: single family
  - Commercial: Large office, large hotel, medium office, retail, warehouse
- Measures adhere to acceptable service thresholds

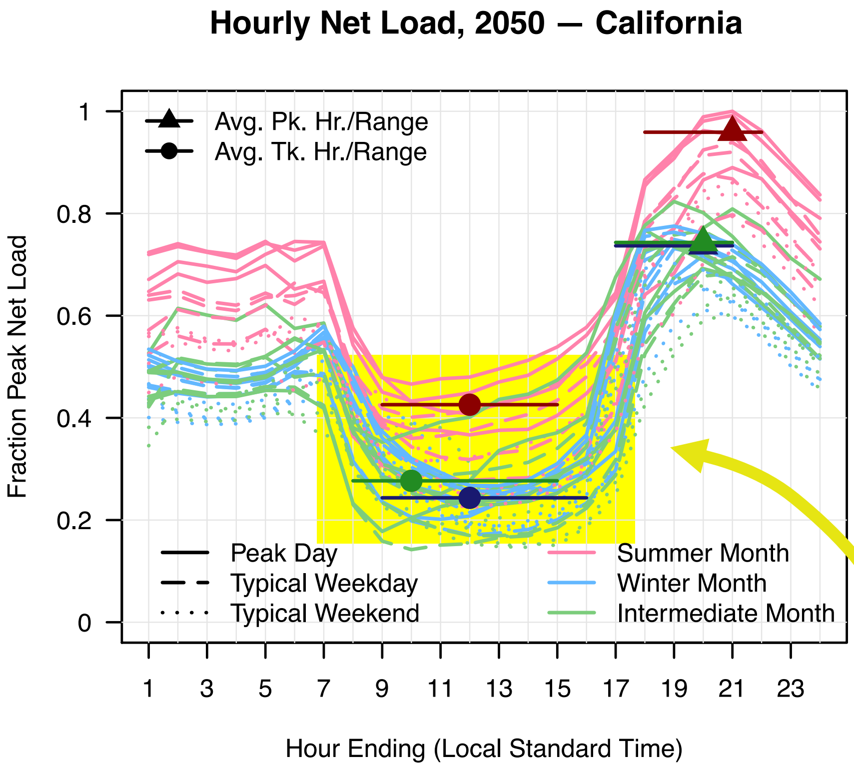


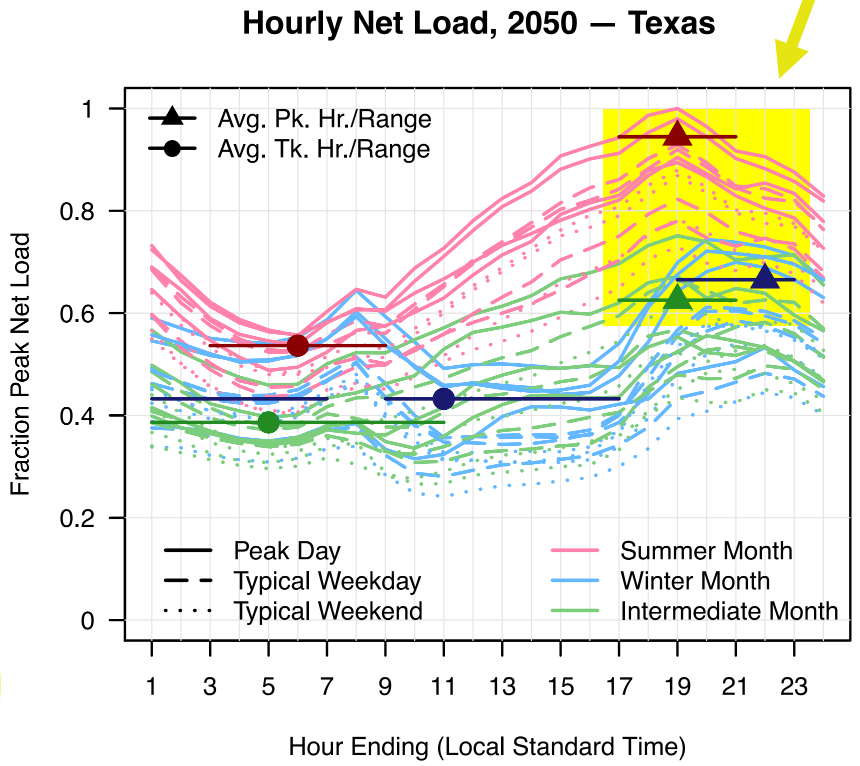
ASHRAE/IECC climate zones

Net load shapes vary by region, inform measure operation

- Regional net system load shapes for the year 2050 are used as a reference for measure development (year with the highest renewable penetration levels).
- Flexibility measures are designed to remove load during net peak periods and build load during low net demand periods (if possible), flattening the net load shape.

Period of net peak (high) demand



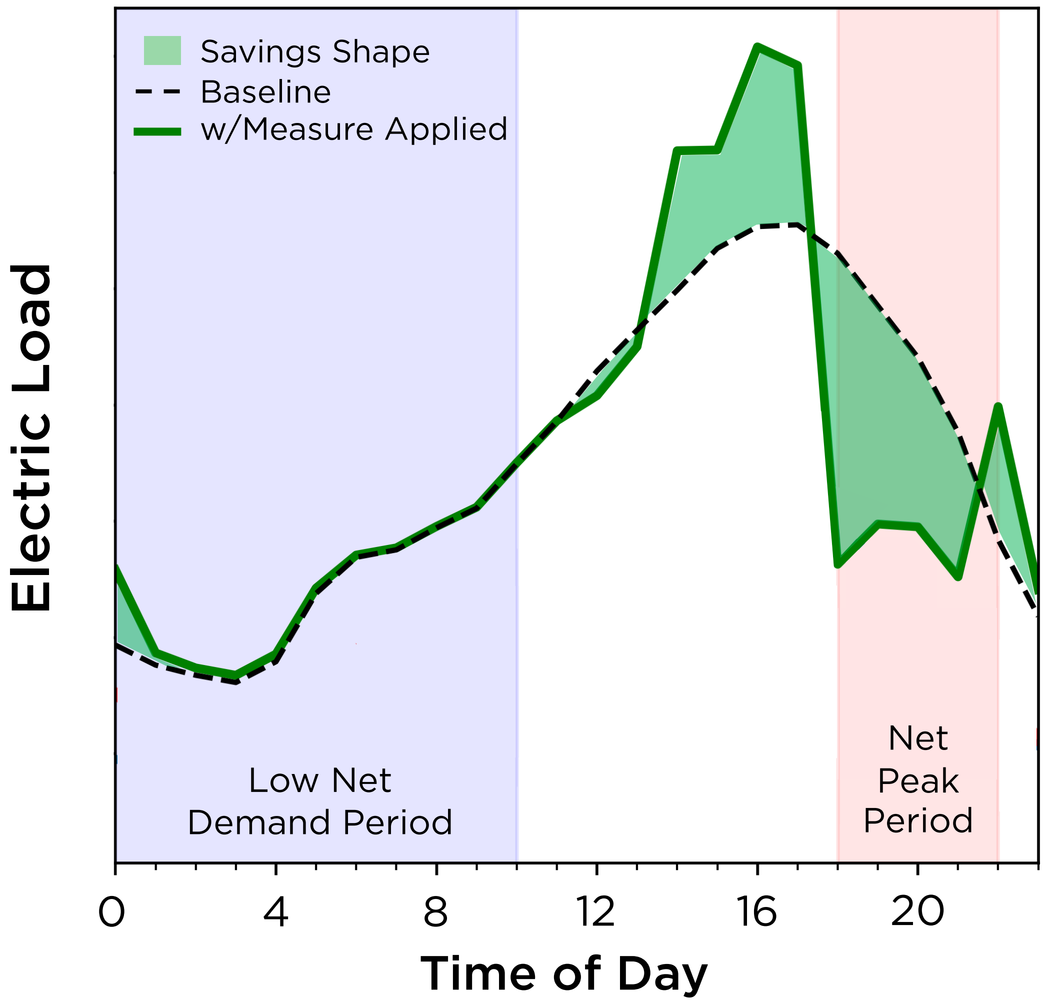


Period of low net demand

Data: EIA EMM, projection year 2050

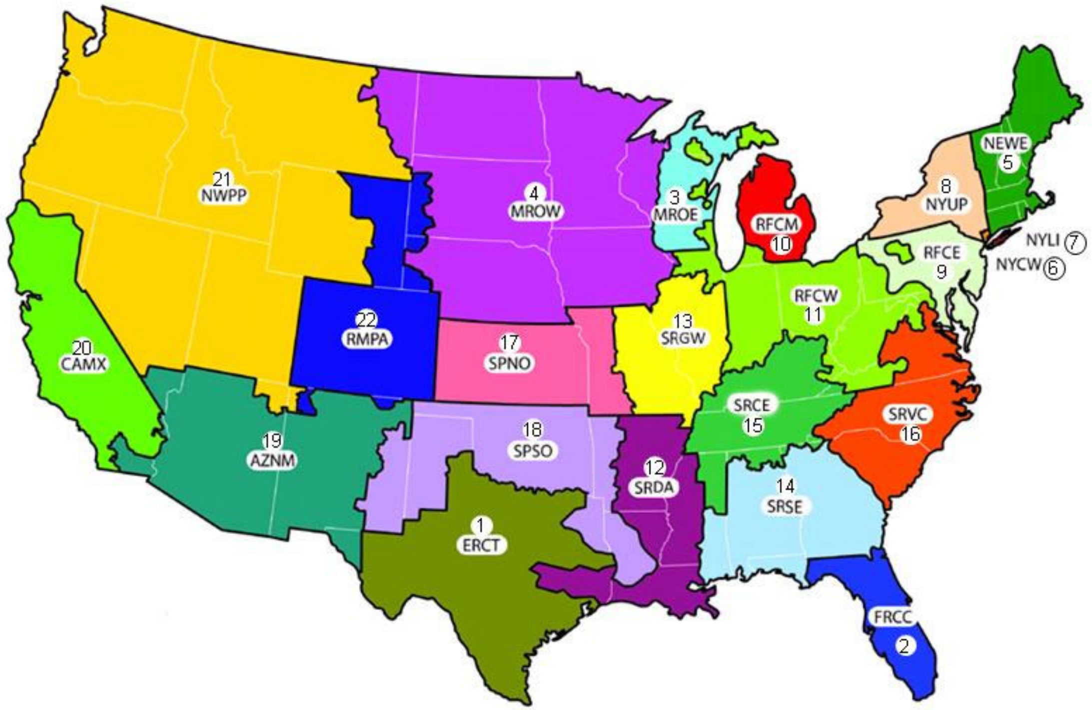
Simulation results yield hourly savings shapes for each measure

- Flexibility measure operation is defined based on measure configuration and EMM region
- Hourly savings fractions are the difference between the magnitude of baseline electric load and electric load with the measure applied
- Impacts on net peak and low demand period loads can be calculated as an average or maximum across all relevant hours and days within the given season

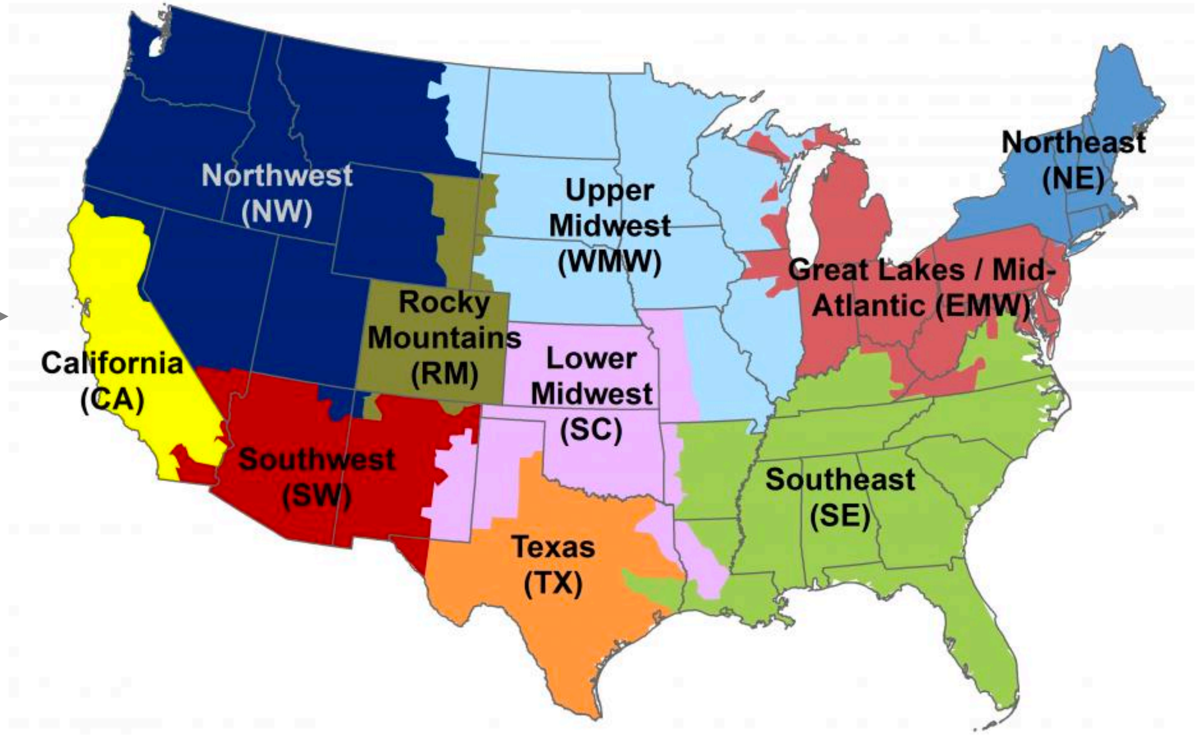


Measure results by EMM regions, aggregated to AVERT regions

- Measure building-level operation is assessed relative to system-level load shapes for the 22 EIA Electricity Market Module (EMM) regions
- EMM region results map to the 10 EPA AVERT regions for easier interpretation



U.S. EIA EMM regions



U.S. EPA AVERT regions

Current limitations

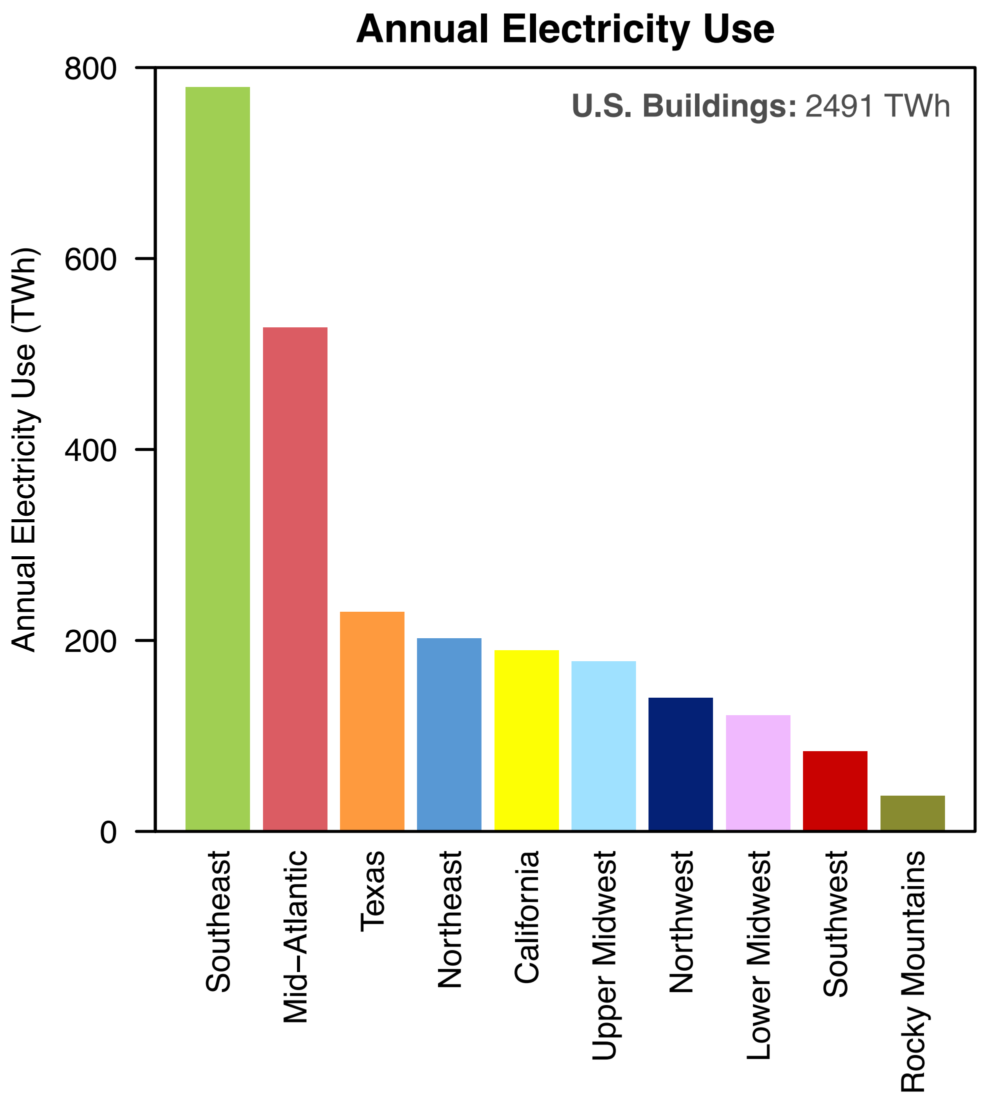
- **Primary focus is on technical potential results**
  - Results do not generally consider market conditions, consumer preferences, payback period, or price elasticity
- **Measures are based on the highest performance technologies currently available**
- **Does not include prospective technologies currently in development**
- **Measure operation is not based on real-time signals**
  - Flexible operation is defined based on preset net peak (high demand) and low demand periods set by EMM region

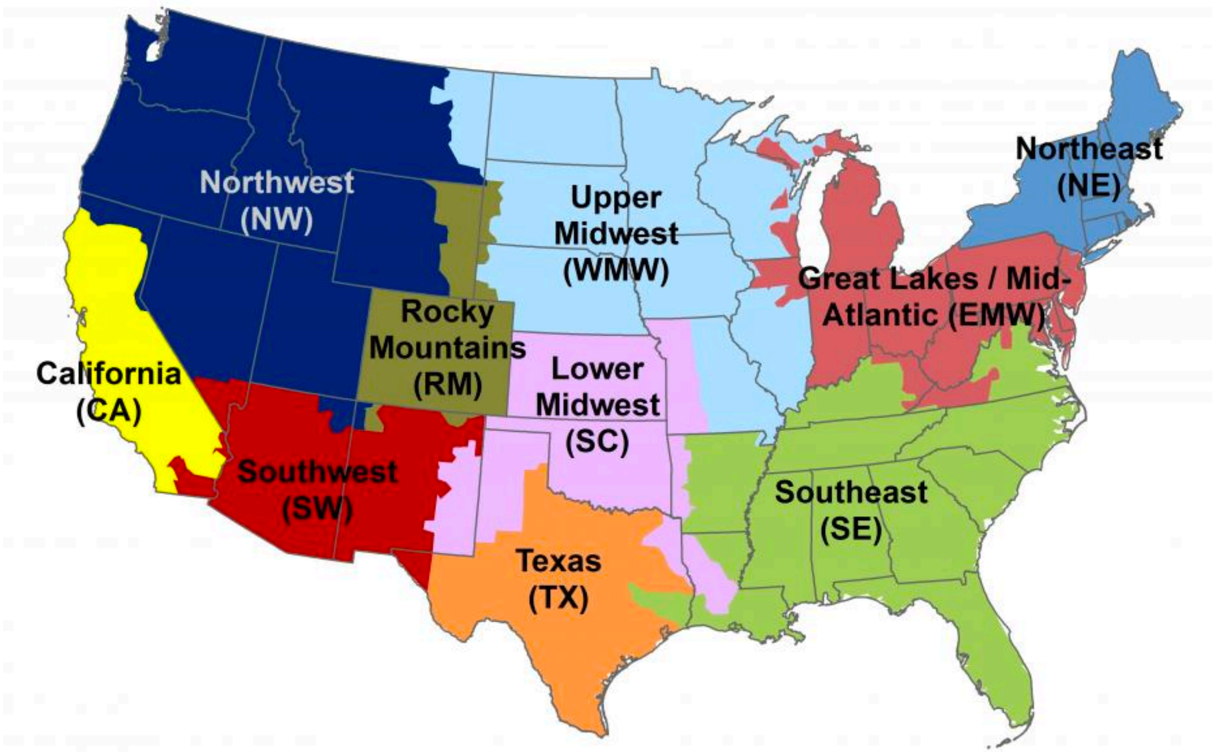
Context

In 2020, buildings comprise 75% of annual U.S. electricity demand.

Data: EIA AEO

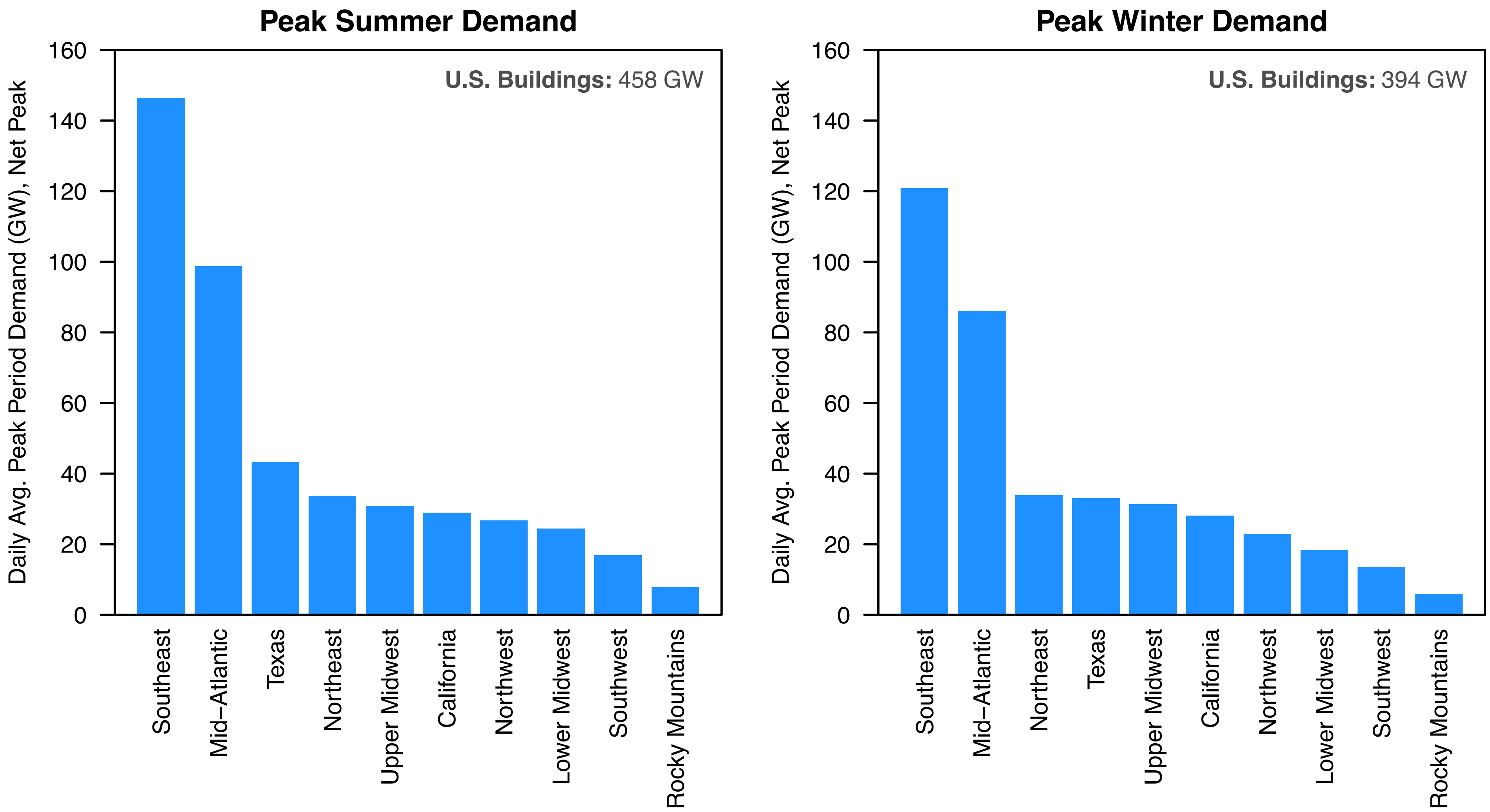
Baseline electricity use in 2020 varies widely by region of the U.S.





Data: EIA EMM, AEO; Scout

Peak loads in each region scale with regional total load



Data: EIA EMM, AEO; Scout

Finding 1

In 2020, buildings could reduce peak demand by
177 GW (24%*) in the summer and
128 GW (22%*) in the winter.

* Percent of U.S. total peak demand in the indicated season

Data: EIA EMM, Scout

Peak reduction potential relative to peak demand varies by region

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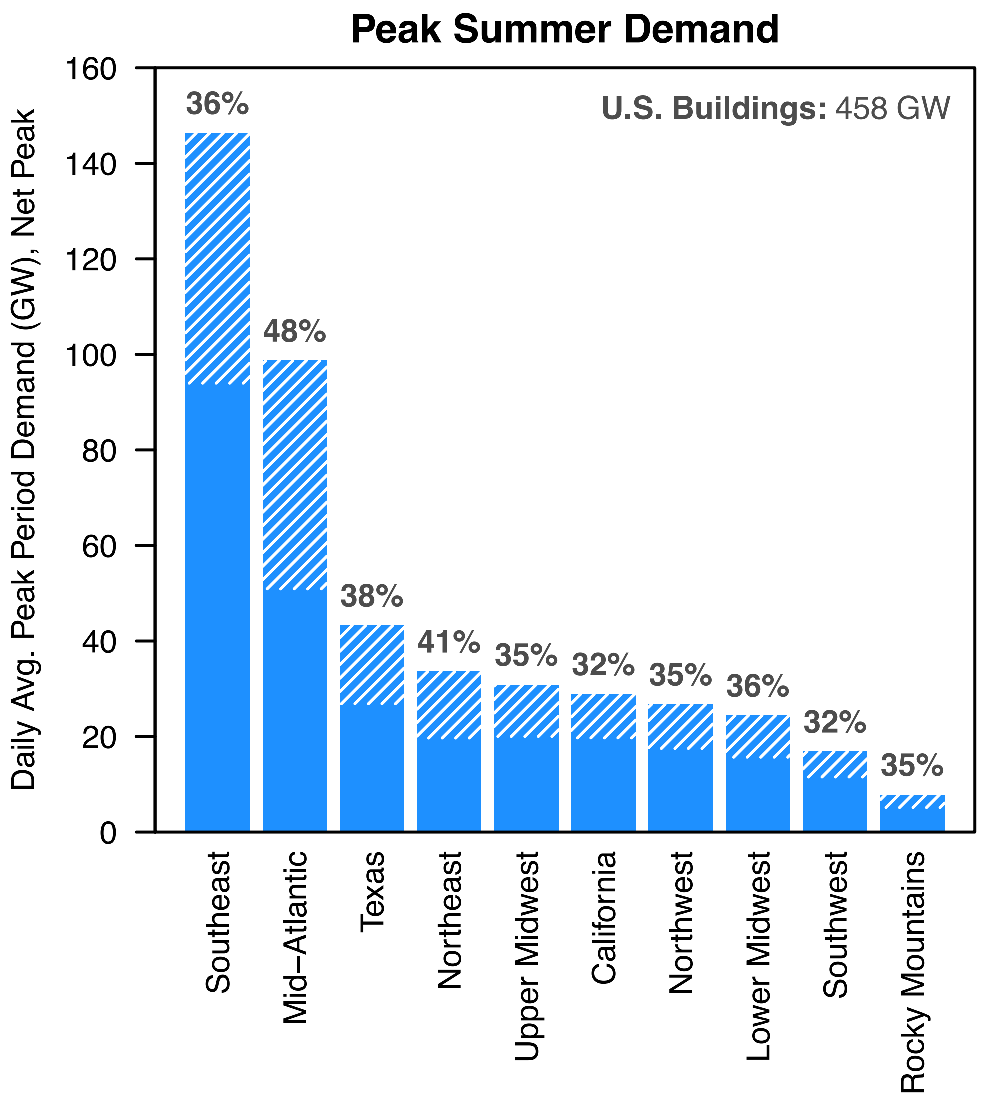

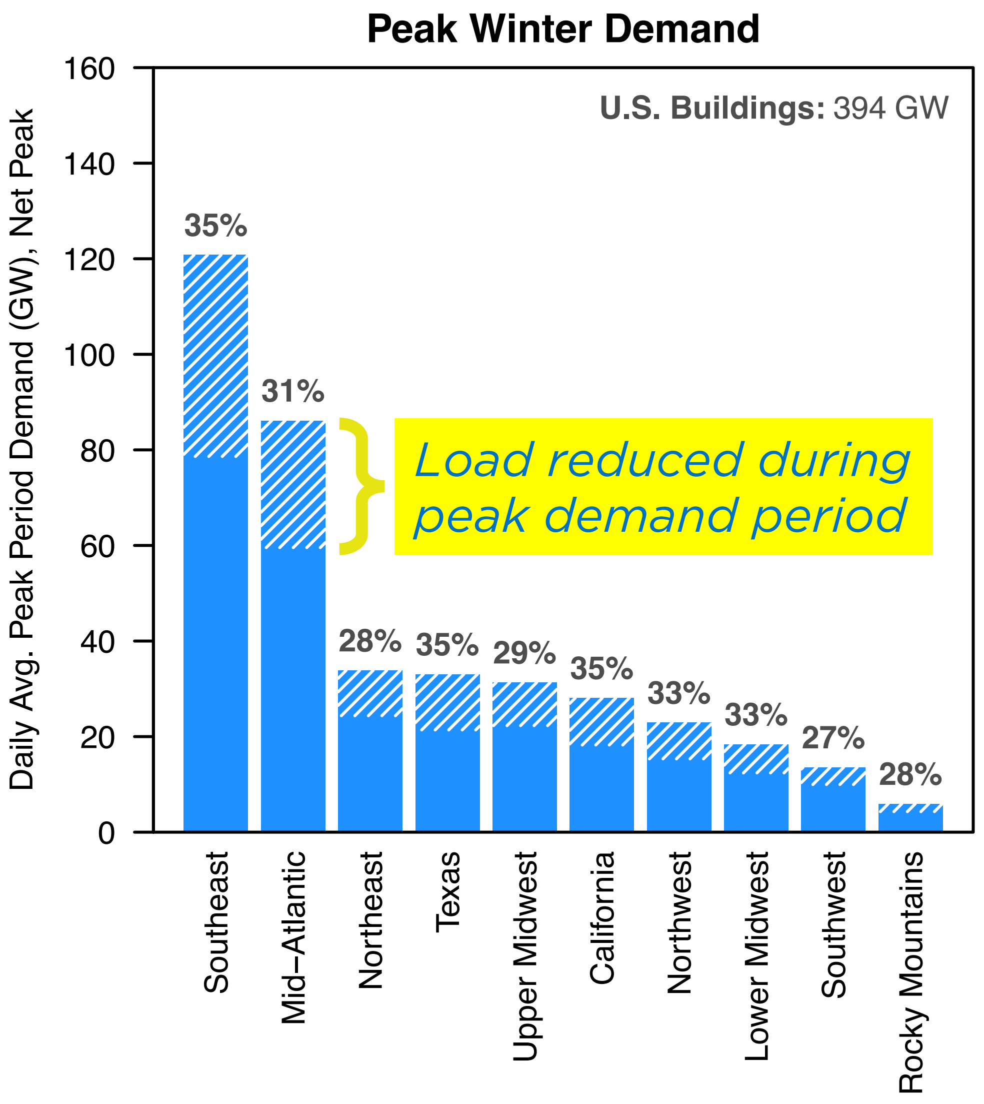

Data: EIA EMM, Scout

Finding 2

In 2020, buildings could move 15 GW (2%*) of summer and 14 GW (2%*) of winter peak demand to the hours when electricity demand is low.

* Percent of U.S. total peak demand in the indicated season

Data: EIA EMM, Scout

For the technologies considered, load building potential is limited

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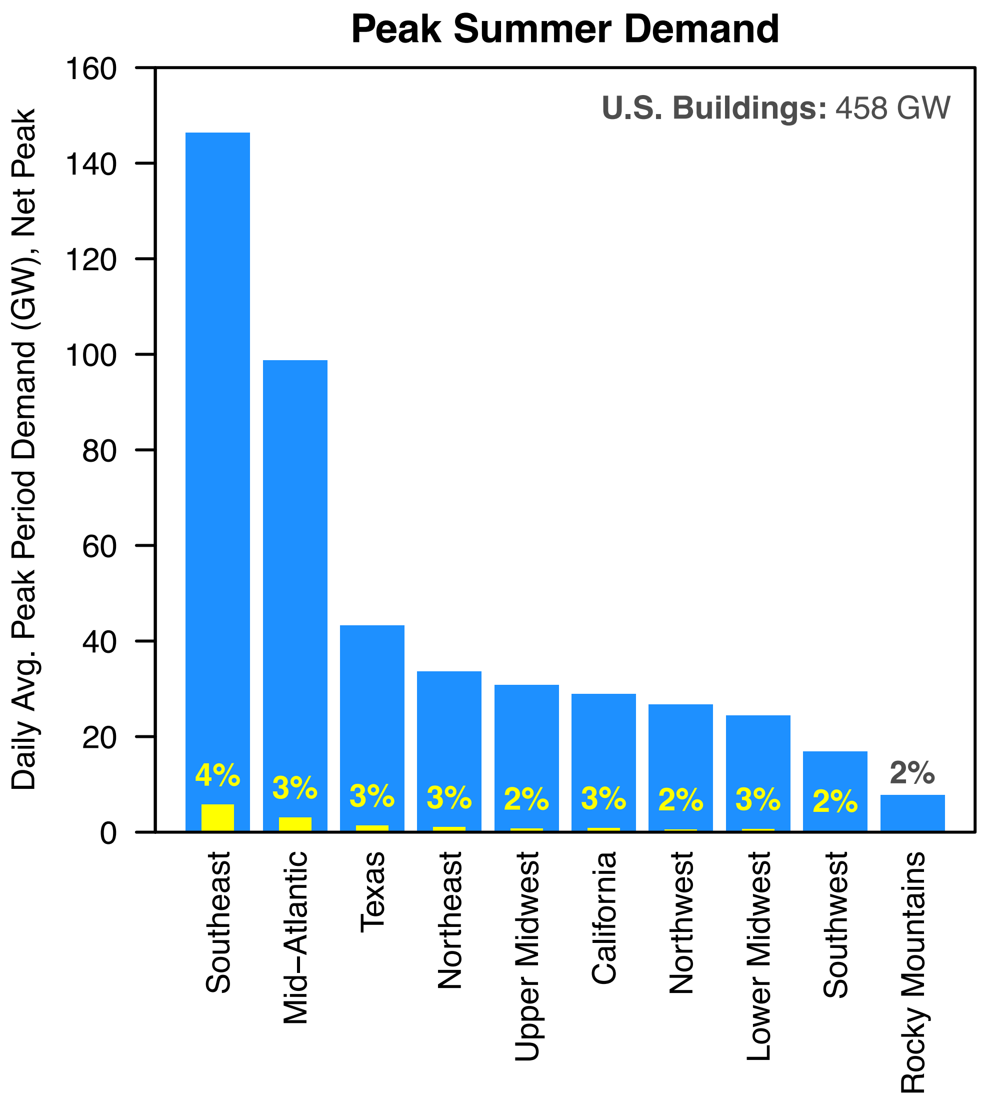

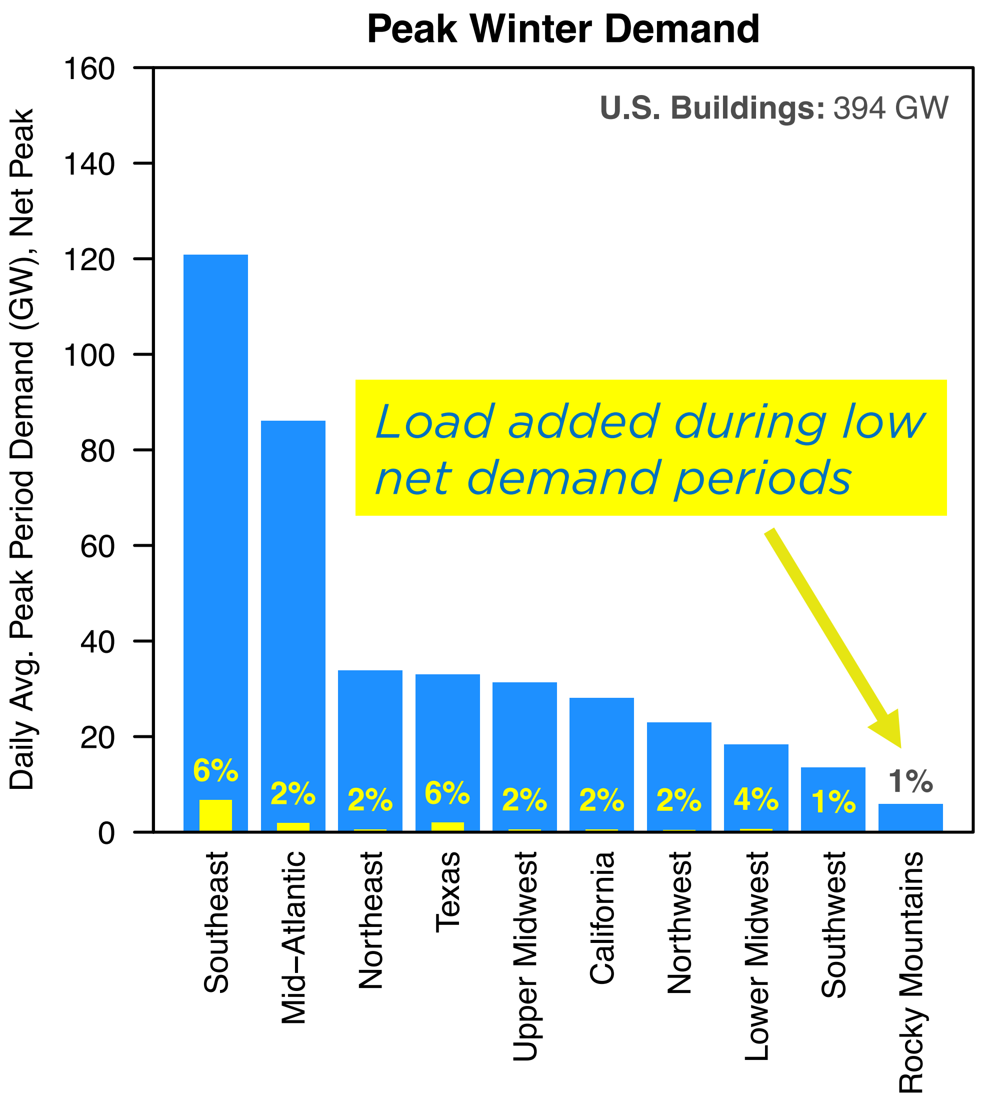

Data: EIA EMM, Scout

Finding 3

Efficiency and flexibility are complementary for peak demand reduction.

Efficiency and flexibility are complementary

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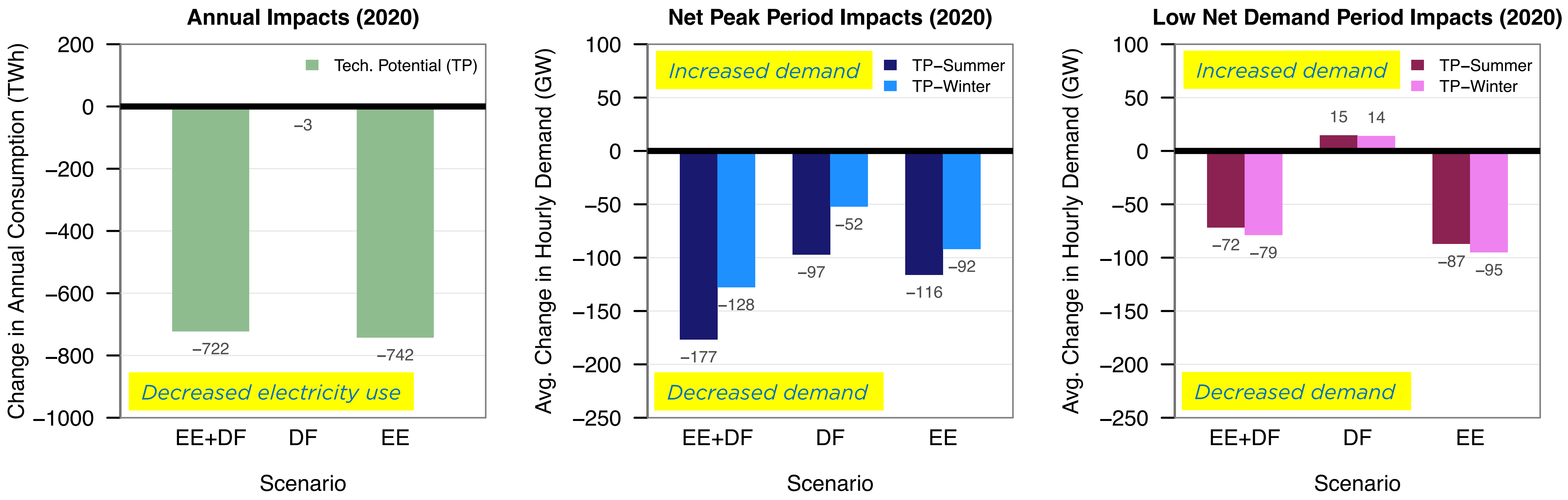

The annual impact of the EE+DF differs from the combined impact of EE and DF because EE reduces peak electricity demand, and thus reduces the potential effect of DF measures on peak and total electricity use

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

Finding 4

Cooling and heating in residential buildings yield the largest total electricity use and peak demand reductions. Commercial plug loads also offer large reduction potential.

Residential buildings drive changes in load across metrics

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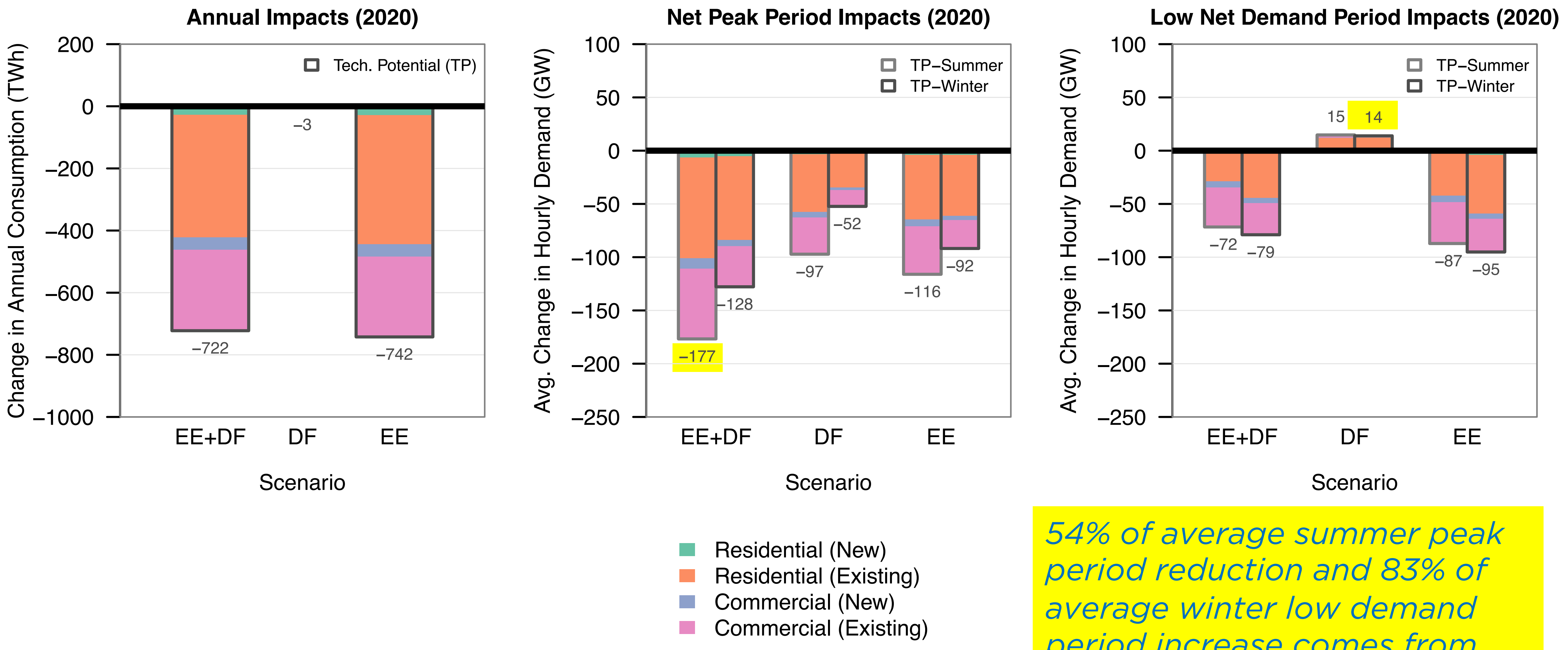

54% of average summer peak period reduction and 83% of average winter low demand period increase comes from residential buildings

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

Cooling drives peak reduction, water heating adds load

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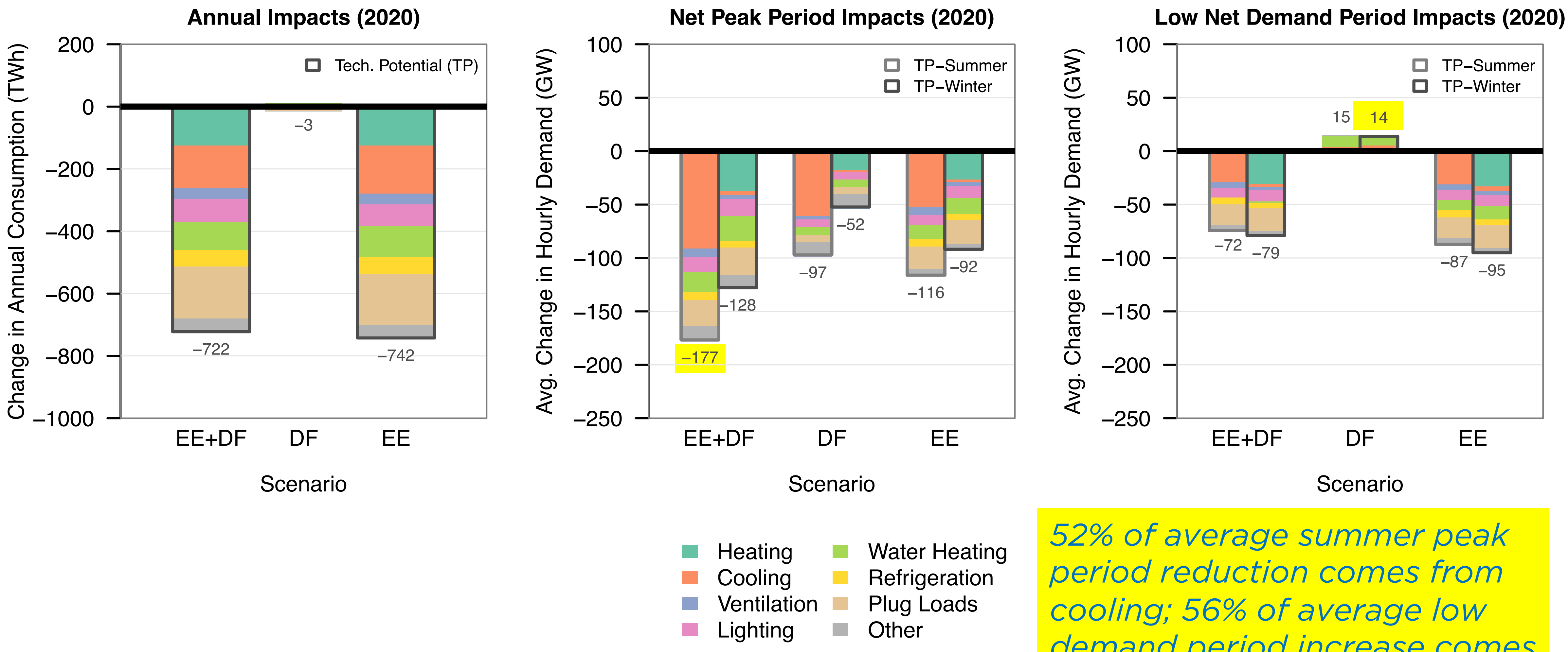


52% of average summer peak period reduction comes from cooling; 56% of average low demand period increase comes from water heating

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

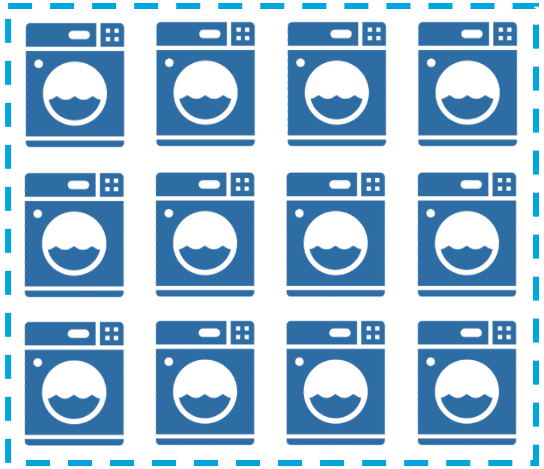
Finding 5

93% of long-run measure impact potential is captured by 2030 with replacement at end of life, or 59% with achievable sales penetration considered.

Three adoption scenarios considered

Technical Potential

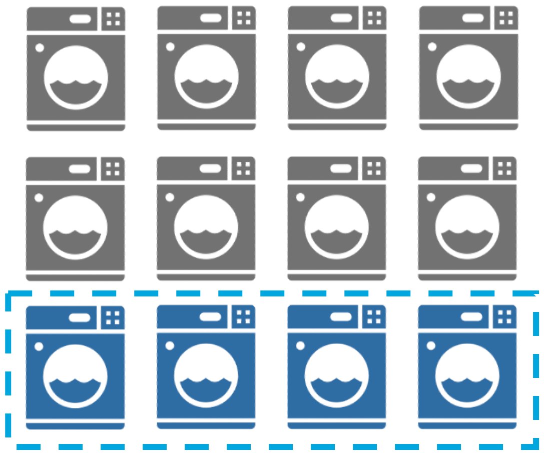
All units are replaced overnight with the efficient/flexible alternative



total stock

Max Adoption Potential

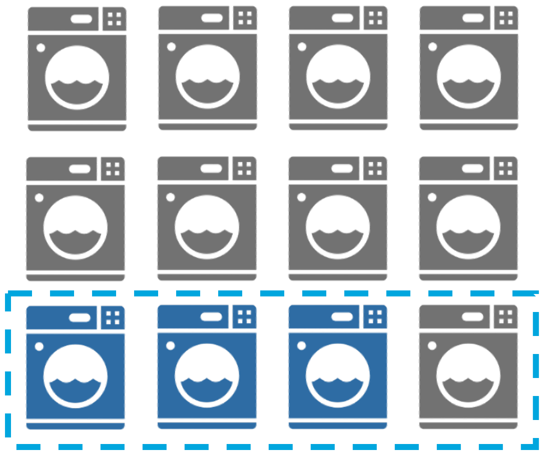
All units are replaced at end of life with the efficient/flexible alternative



stock at end of life each year

Adjusted Adoption Potential

An increasing share of units are replaced at end of life with the efficient/flexible alternative, rising to 85% of sales by 2035



stock at end of life each year

 Stock unit

 Replaced stock unit

Technical potential impacts across measure scenarios

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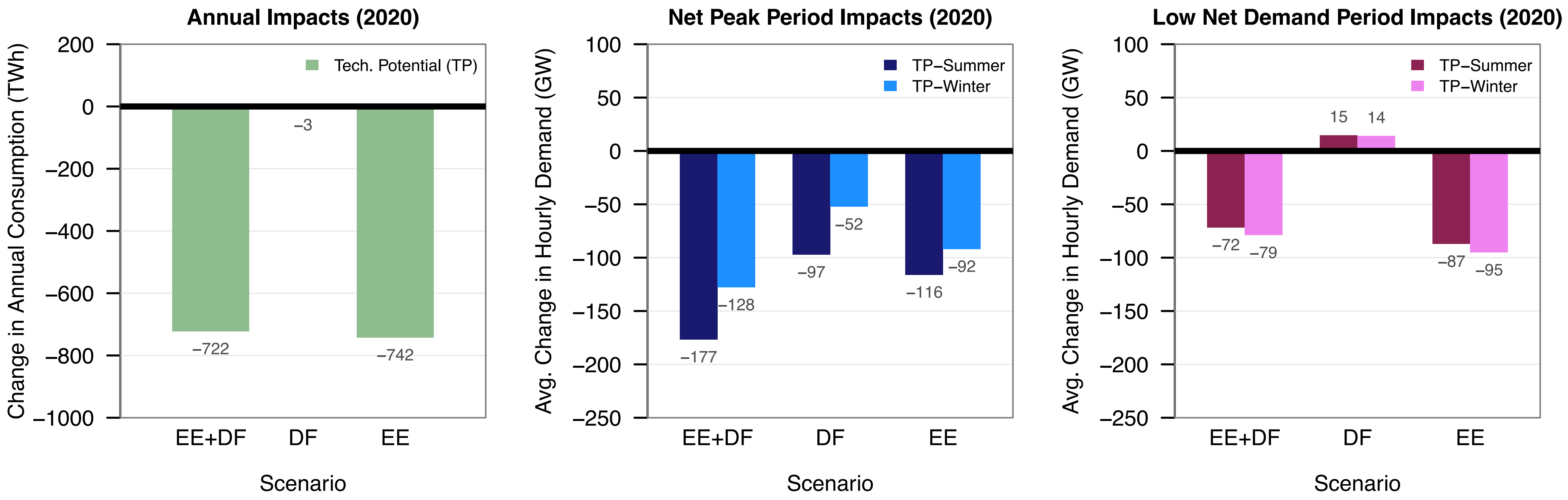

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

Accounting for adoption reduces potential impacts in 2020

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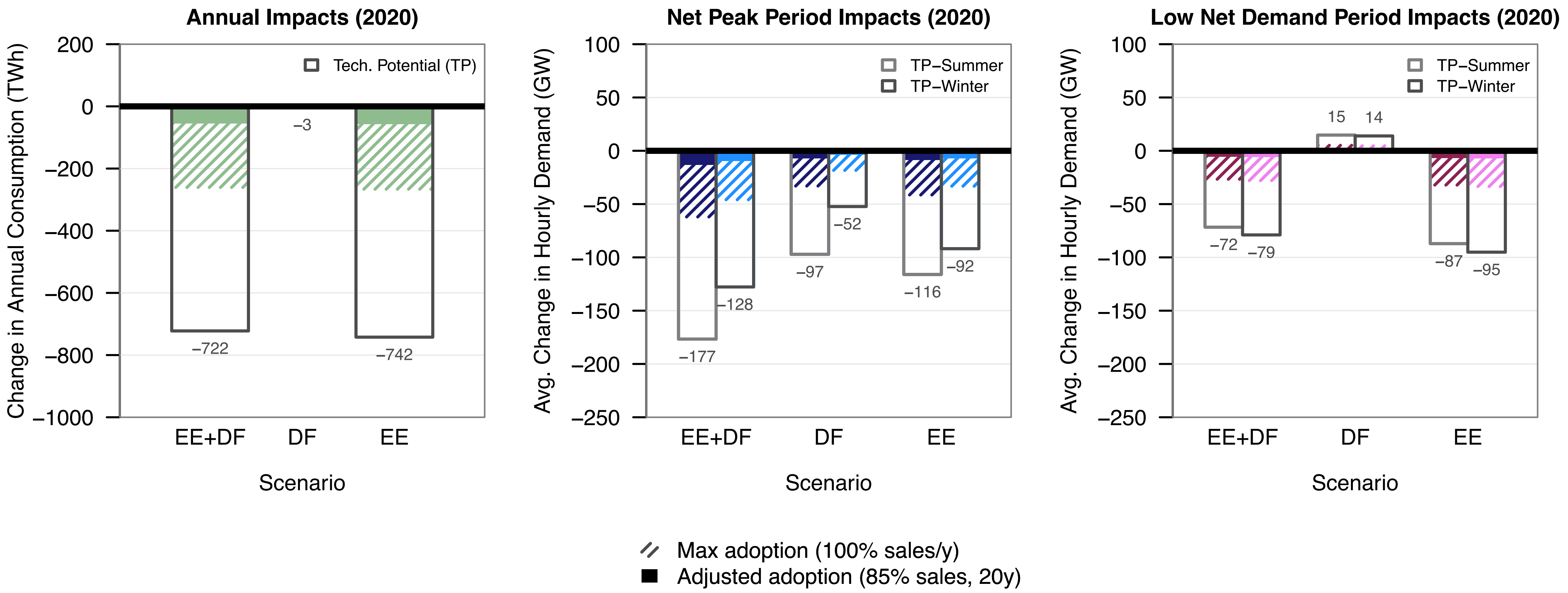

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

In the max adoption scenario, most potential is captured by 2030

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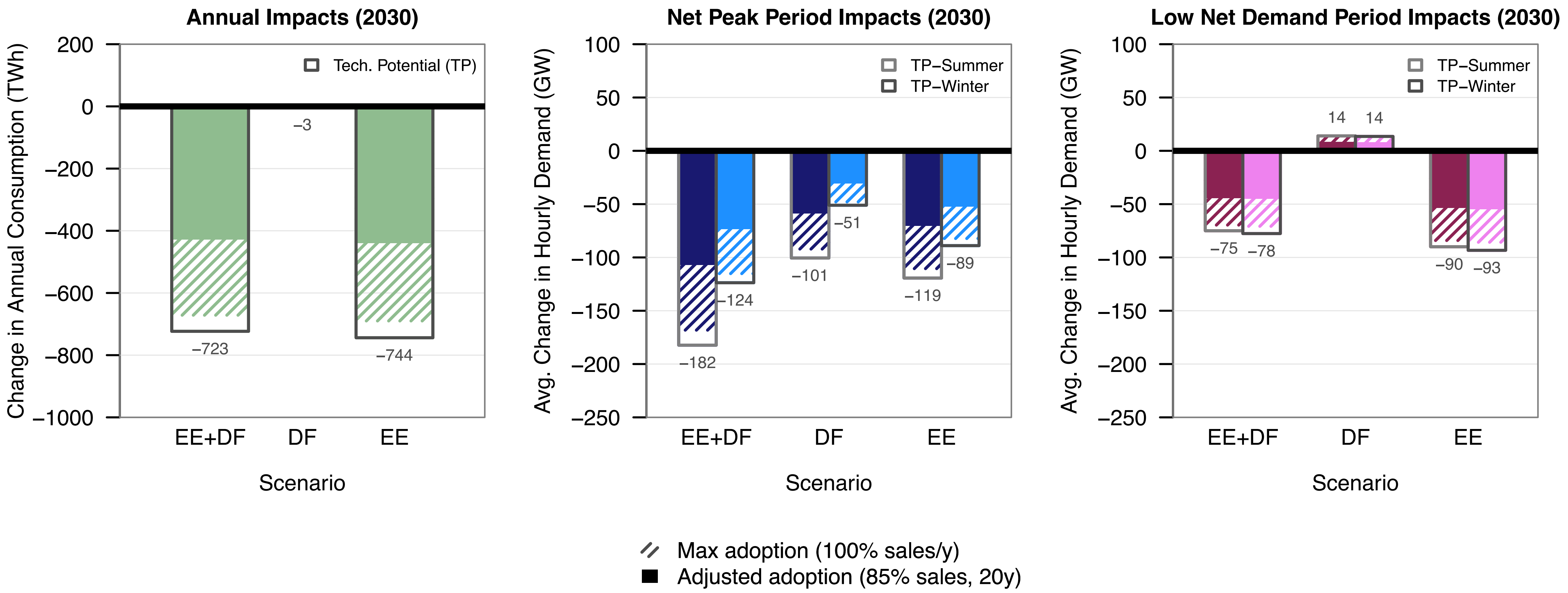

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

By 2050, most impacts are captured in the adjusted adoption scenario

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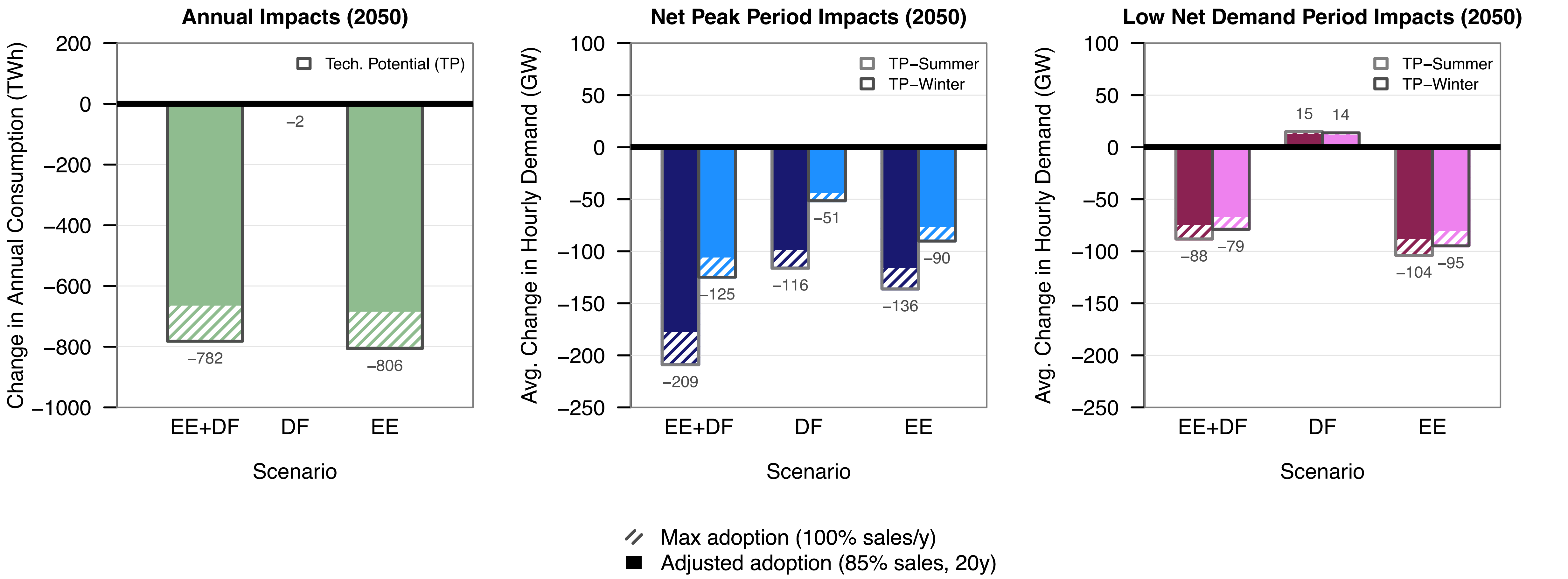

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)

Conclusion

An initial step in quantifying the building-grid resource

A quantitative framework was established for time-sensitive, region-specific valuation of building efficiency and flexibility measures across the U.S.

- Adapts the Scout impact analysis software to enable sub-annual assessment of U.S. building electricity use under baseline conditions and given efficiency/flexibility measure adoption
- Leverages ResStock (residential) and DOE Prototype Models (commercial) to develop hourly baseline and measure electric load shapes across 14 climate zones

Initial results show a large potential peak reduction resource from buildings, interactions between efficiency and flexibility, and regional differences

- In 2020, up to 177 GW U.S. net peak hour load (24% peak) could be removed by efficiency and flexibility measures, with 722 TWh annual electricity savings (19% total)
- Opportunities to increase load off-peak via flexibility measures (up to 15 GW increase) are reduced by the addition of efficiency measures (up to 79 GW decrease)
- The EE+DF scenario yields the largest potential peak period reduction, with a substantial reduction in total annual electricity use—177 GW and 722 TWh, respectively, compared to 97 GW and 3 TWh (DF) or 116 GW and 742 TWh (EE)

Residential and commercial cooling, residential heating, and commercial plug loads show large potential for impacts on electricity demand

- Cooling yields more than half of maximum peak reduction potential (EE+DF)
- Plug load efficiency and controls (EE, EE+DF) yield the second largest peak reductions and comparable total annual electricity use reductions to cooling

Thank you

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Scout: scout.energy.gov

ResStock: www.nrel.gov/buildings/resstock.html

Commercial Prototypes:
https://www.energycodes.gov/development/commercial/prototype_models

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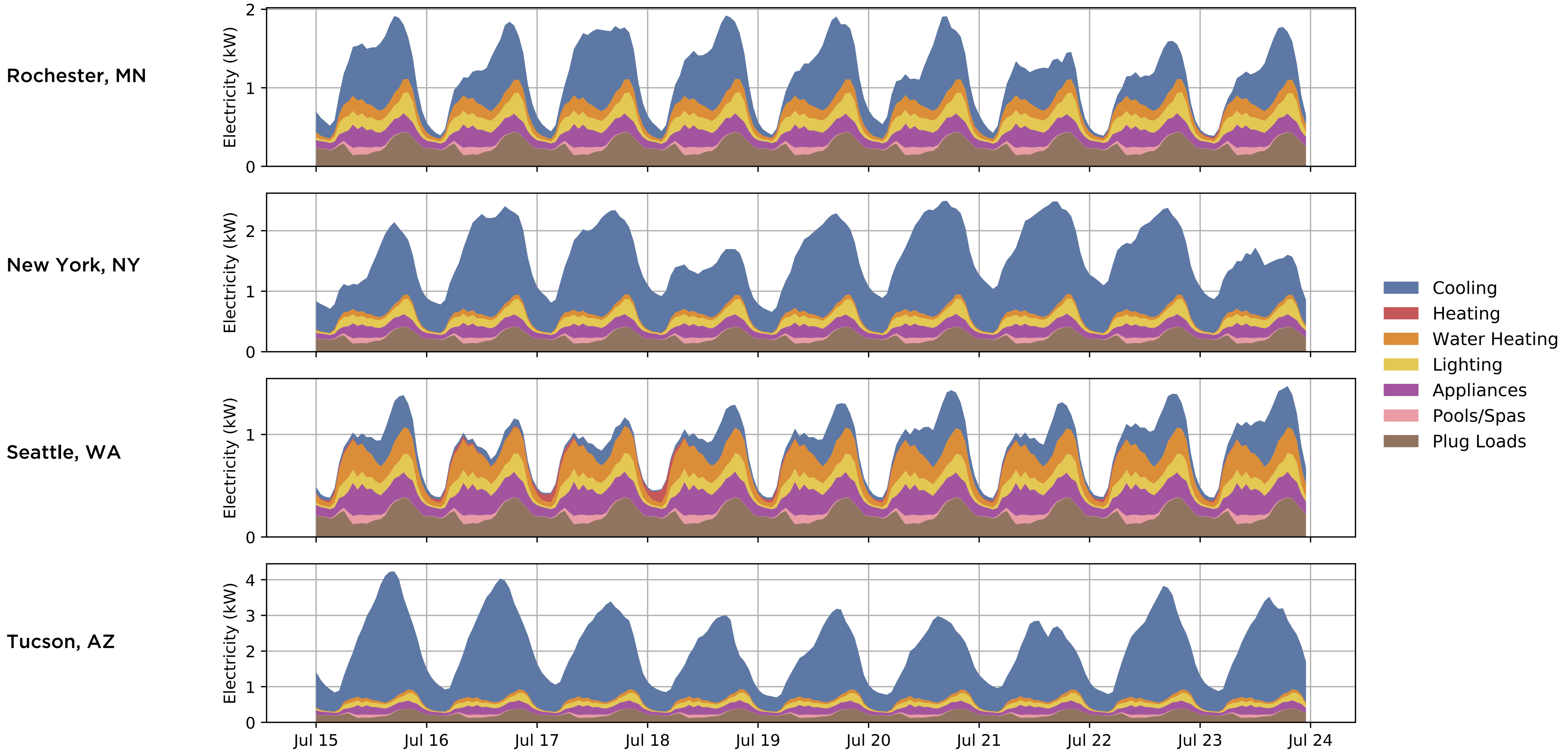
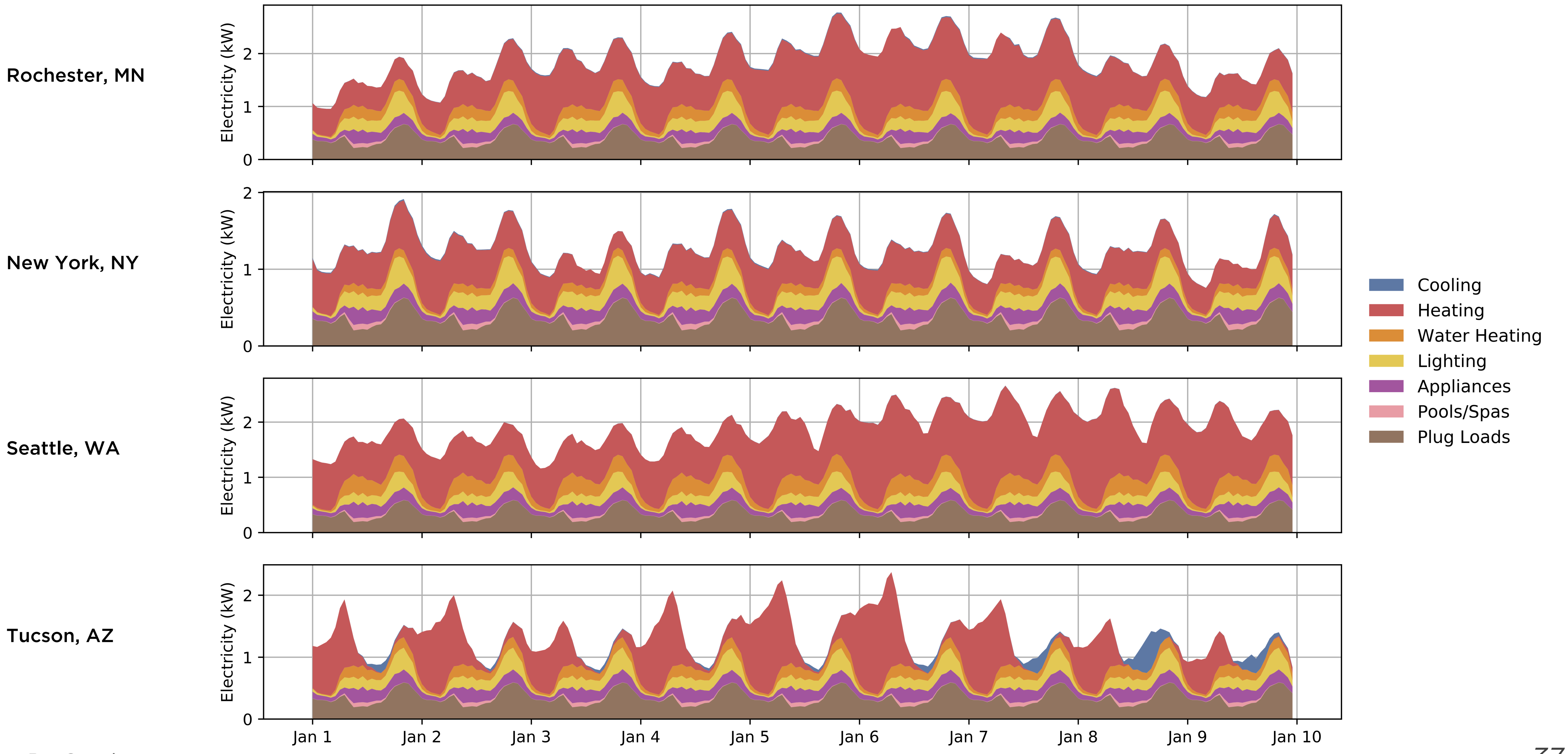
Additional methodology details

Example baseline residential load shapes (summer)



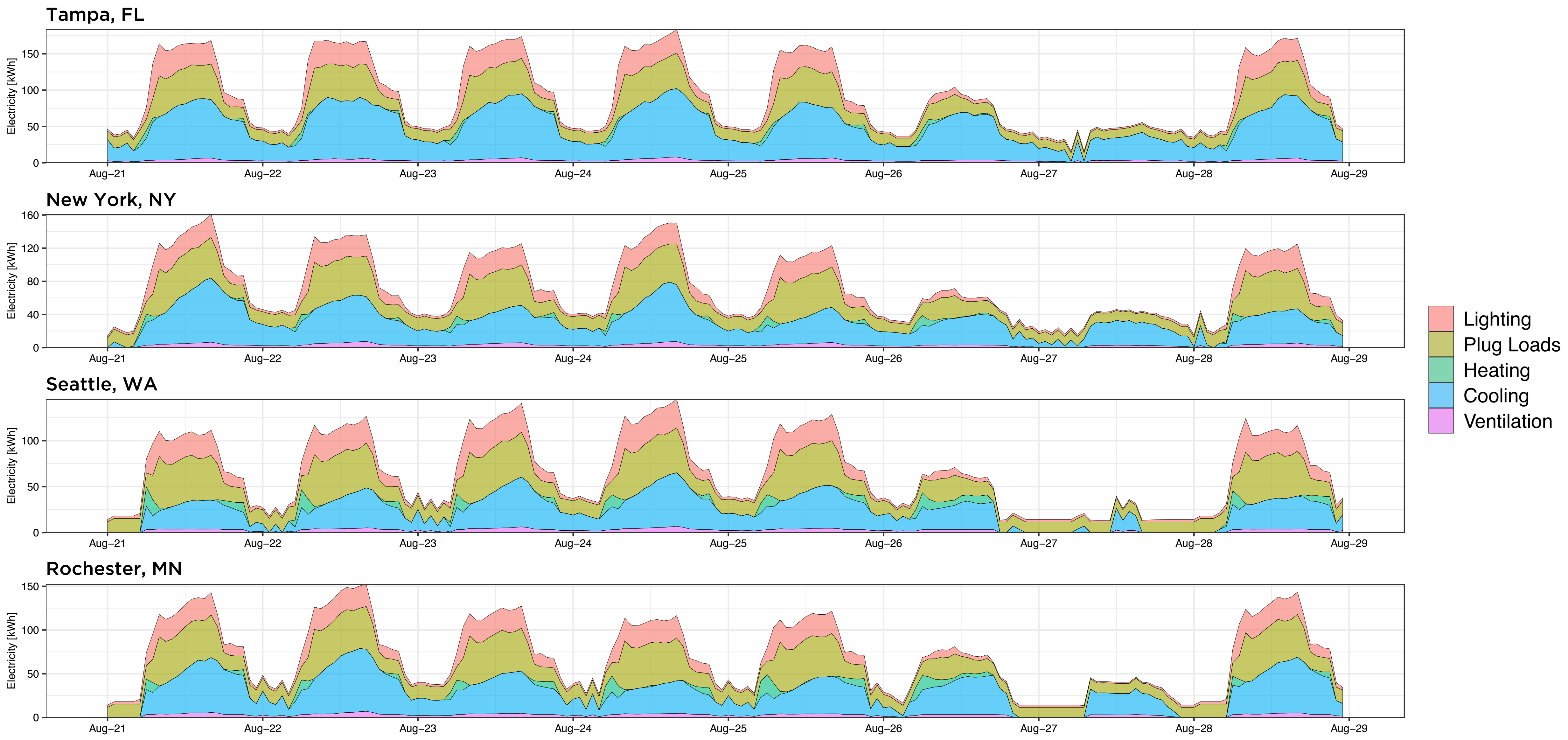
Data: ResStock

Example baseline residential load shapes (winter)



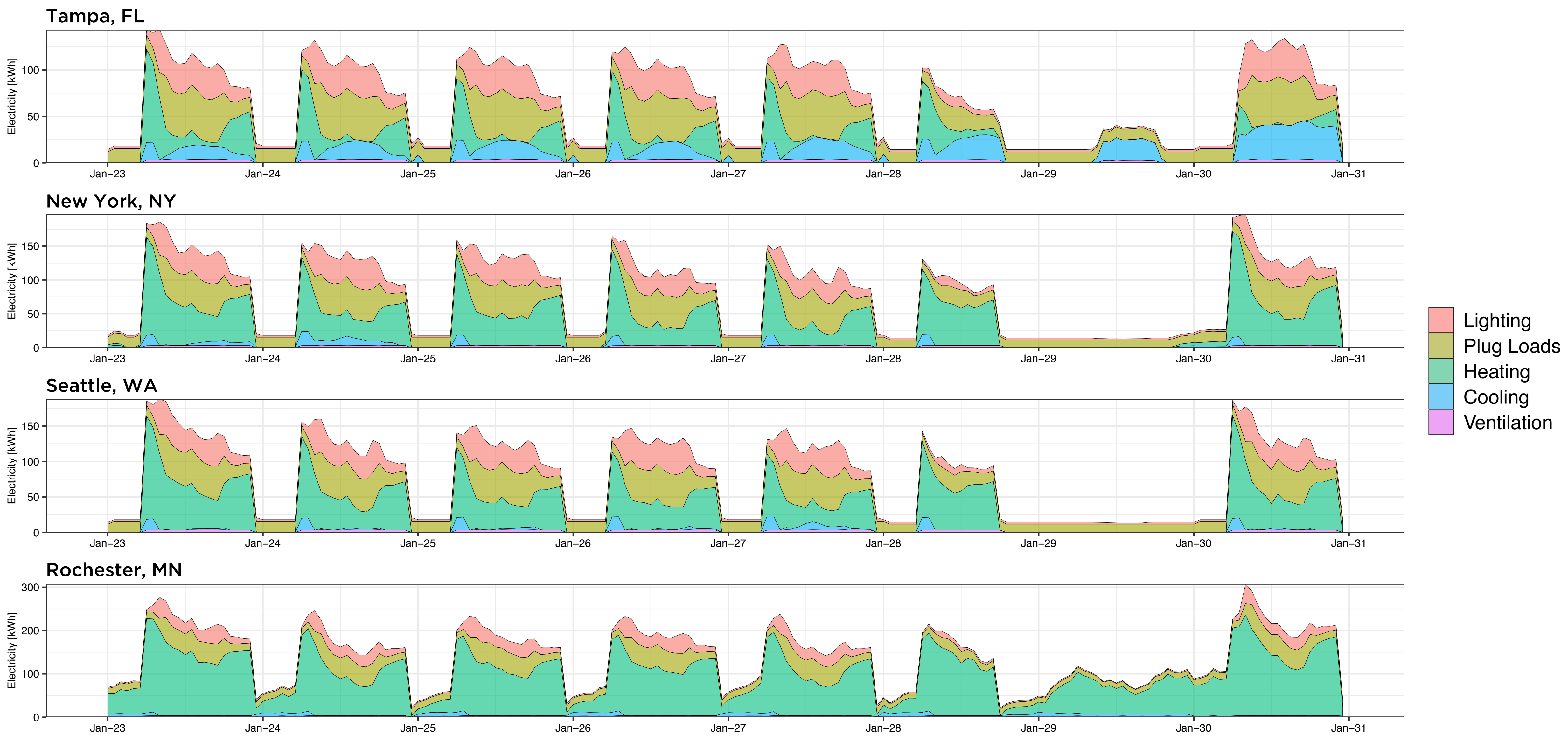
Data: ResStock

Example baseline commercial loads (summer, medium office)



Data: EnergyPlus/OpenStudio Commercial Prototype simulations

Example commercial baseline loads (winter, medium office)



Data: EnergyPlus/OpenStudio Commercial Prototype simulations

Residential measure scenario load impacts

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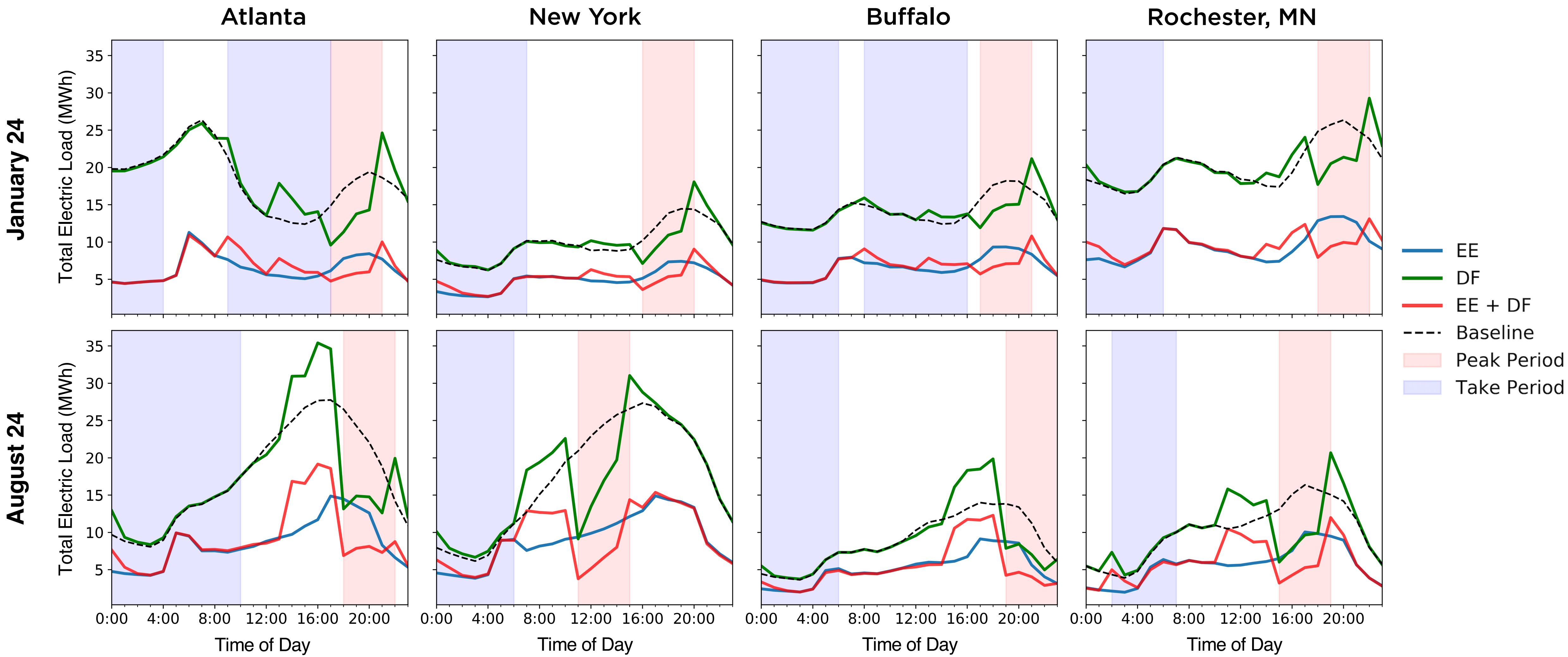

Data: ResStock, GEB Measures

Residential EE and DF measures: key assumptions

EE Measure	*Approach*
Central AC	*Upgrade to SEER 18 AC from any lower SEER.*
ASHP	*Upgrade to SEER 22/HSPF 10 from any lower ASHP, or (in some cases) electric furnaces.*
Thermostat controls	*Applied 10 hour daytime set-back of 8°F in winter and set-up of 7°F in summer, and 8 hour nighttime set-back of 8°F in winter and 4°F in summer.* *Daytime set-back only weekdays for 43% of homes.*
Refrigerator	*Upgrade to EF 22.2.*
Walls	*Upgrade to R-13 cavity with R-20 external XPS.*
Roofs	*Upgrade unfinished attic insulation to R-49.*
Air sealing	*Upgrade to 1 ACH_{50} with mechanical ventilation.*
Windows	*Upgrade to: U-0.17, 0.49 SHGC in AIA CZ1; U-0.17, 0.42 SHGC in AIA CZ2; U-0.17, 0.27 SHGC in AIA CZ3; U-0.17, 0.25 SHGC in AIA CZ4–5.*
Floors	*Upgrade wall and ceiling insulation.*
HPWH	*Upgrade to high EF, 80-gal HPWH.*
Clothes washer	*Upgrade to IMEF 2.92, usage level maintained.*
Clothes dryer	*Upgrade to CEF 3.65, usage level maintained.*
Dishwasher	*Upgrade to 199 rated annual kWh, usage maintained.*
Pool pump	*Upgrade to (0.75 hp) 1688 rated annual kWh.*
Electronics	*Decrease total annual energy use by 50%.*

DF Measure	*Approach*
Water heater	*Pre-heat to 140°F during take period (second take period, if applicable), then return to 125°F setpoint.*
Thermostat	*Pre-cool/pre-heat by 3°F starting 4 hours before the peak, then set-back/set-up of 4°F relative to original setpoint during peak period. Thermostat DR setpoints take precedence over EE thermostat setpoints.*
Clothes washer, Clothes dryer, Dishwasher	*Baseline schedules are generated as normal (randomly based on distributions). Then event clusters during peak are shifted after peak if possible, if not then before peak if possible, if not then left as-is.* *No change in total energy use.*
Pool pump	*All energy use during peak period is removed and added uniformly to energy use during the (first) take period.* *No change in total energy use.*
Electronics	*Of peak period electronics energy usage:* • *11% is shifted to the 2 hour period following the peak, representing discharging batteries during peak.* • *4% is removed, representing zero standby power consumption (i.e., advanced power strip controls).* *Total energy use decreases.*

Commercial measure scenario load impacts (medium office)

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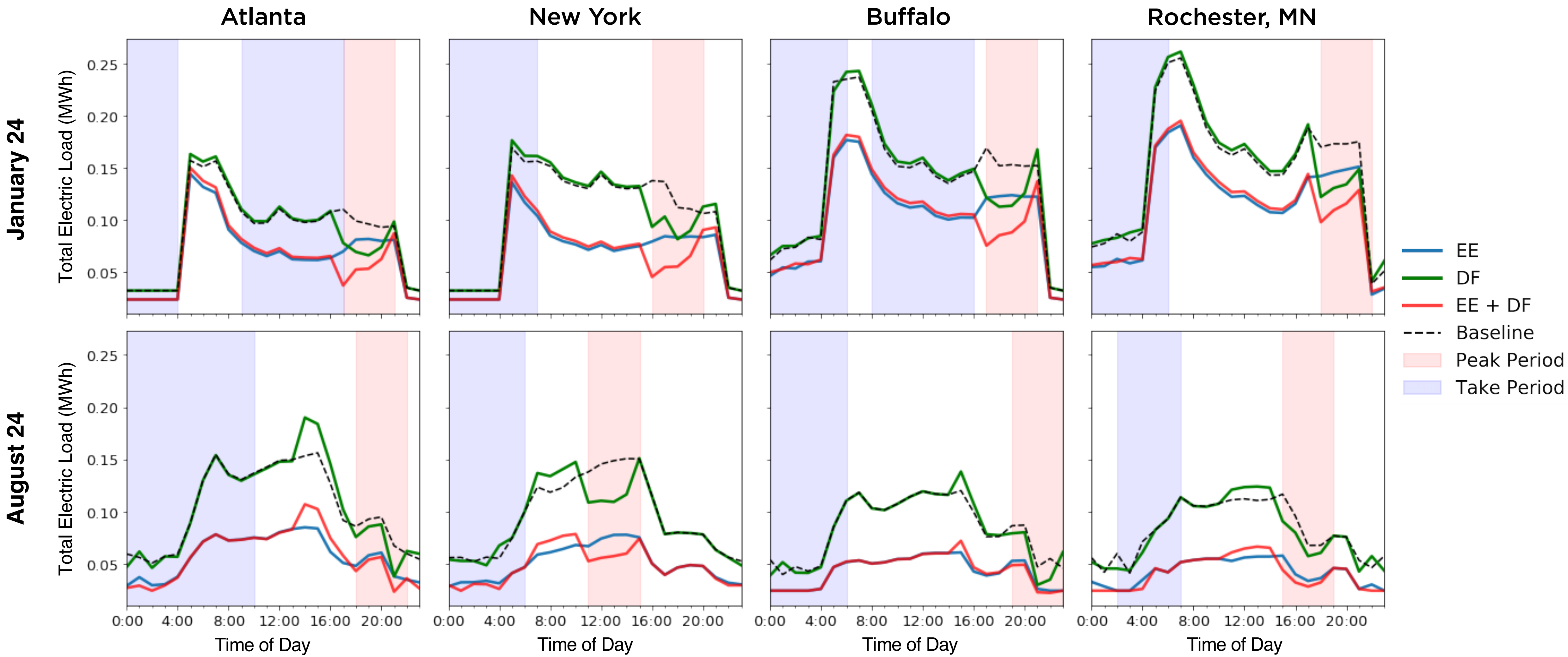


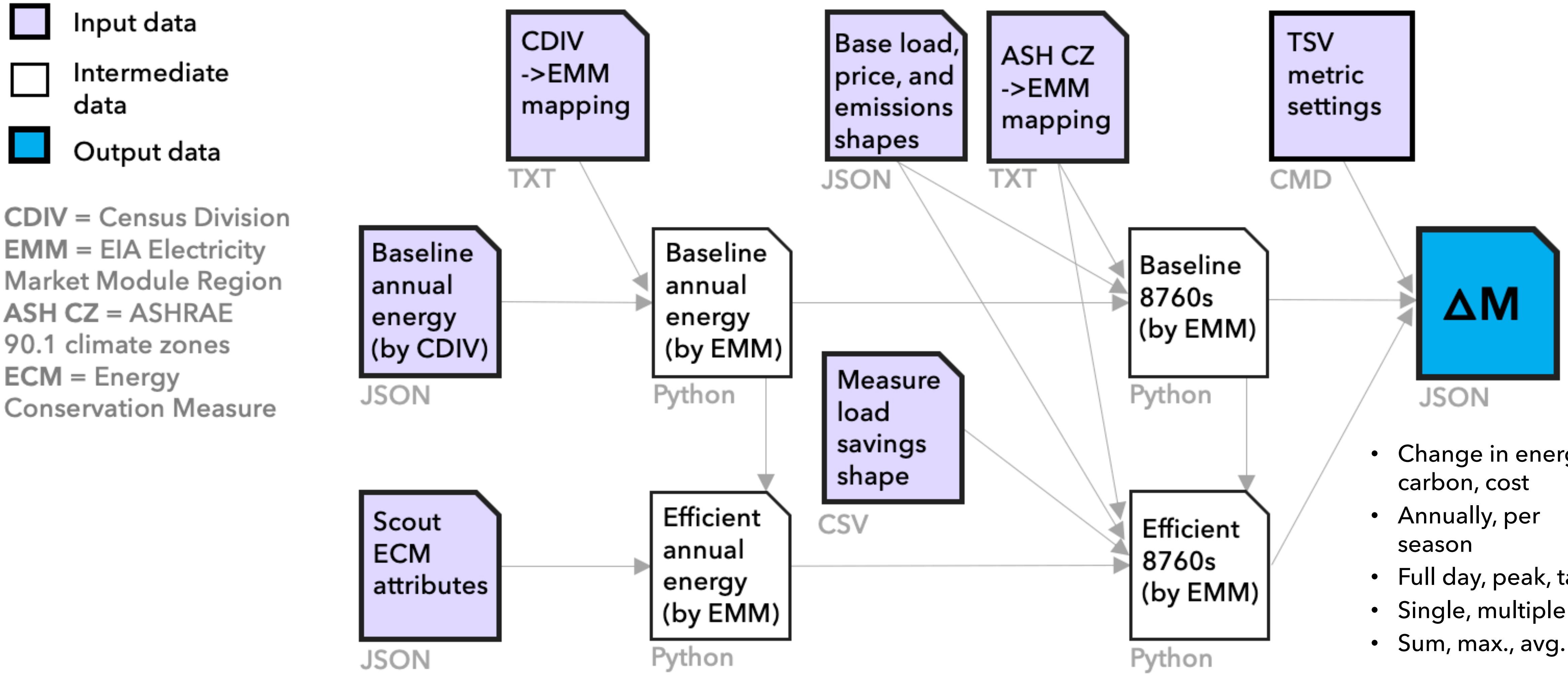
Data: EnergyPlus/OpenStudio Commercial Prototypes, GEB Measures

Commercial EE and DF measures: key assumptions

EE Measure	Approach
Envelope	*Medium and Large Offices upgrade to follow AEDG 50% guidelines for floor, roof, and exterior walls for medium offices. Large Hotel uses the AEDG 50% for highway lodging. Warehouse uses the AEDG 30% for small warehouses. Retail Stand-Alone uses the AEDG 50% for medium and big-box retail.*
Lighting	*Upgrade to follow AEDG guidelines on lighting using the same building type mapping as the envelope upgrade.*
Plug loads	*Upgrade to follow AEDG guidelines on equipment power density according to the same building type mapping as the envelope upgrade.*
HVAC	*Upgrade to higher COP HVAC equipment. Large Hotel already has an efficient air-cooled chiller. Large Office chiller is upgraded to 7 COP. All other building types (e.g., medium office, retail, and warehouse) have their 2-speed DX cooling unit upgraded to 4 COP and its burner efficiency to 0.99.*
Refrigeration	*Upgrade to match "high" commercial refrigeration performance in "EIA Updated Buildings Sector Appliance and Equipment Costs and Efficiency Appendix C," 2018.*
Water heating	*Upgrade to match "high" commercial heat pump water heater performance in "EIA Updated Buildings Sector Appliance and Equipment Costs and Efficiency," 2018.*

DF Measure	Approach
Lighting	*Reduce lighting loads by 30% for occupied spaces and 60% for unoccupied spaces during the peak hours.*
Plug loads	*Reduce plug loads by 20% for occupied spaces and 100% for unoccupied spaces during the peak hours.*
Global temperature adjustment	*Increase global temperature by 5°F in the summer and decrease by 2°F in the winter. The adjustment occurs during peak hours.*
Pre-cooling	*Pre-cool by 2°F four hours before the peak period. Passive pre-cooling applies to the Medium Office, Stand-Alone Retail, and Warehouse prototypes.*
Ice storage	*Implement a 6.7 COP charging chiller and ice storage on the HVAC plant loop. Charge ice storage 12AM to 6AM. Discharge ice storage during the peak period. The active ice storage option applies to the Large Hotel and Large Office prototypes.*

Integration of data inputs and outputs in Scout



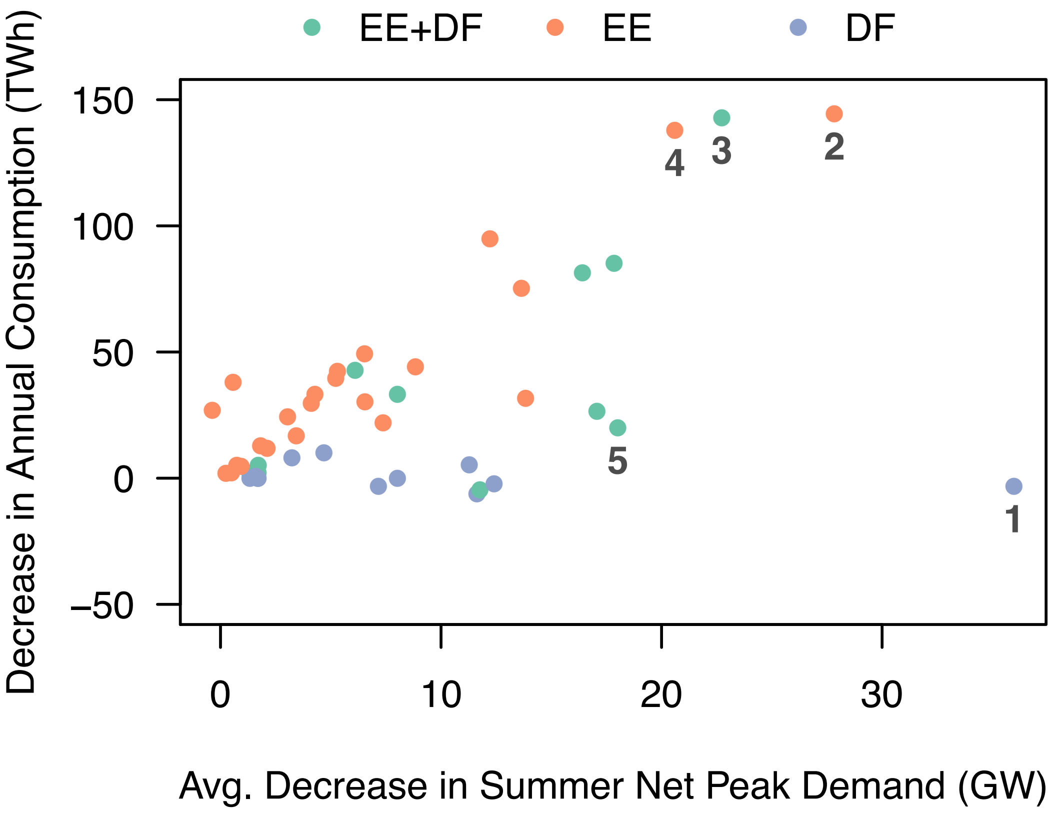
CDIV = Census Division
EMM = EIA Electricity Market Module Region
ASH CZ = ASHRAE 90.1 climate zones
ECM = Energy Conservation Measure

- Change in energy, carbon, cost
- Annually, per season
- Full day, peak, take
- Single, multiple hrs.
- Sum, max., avg.

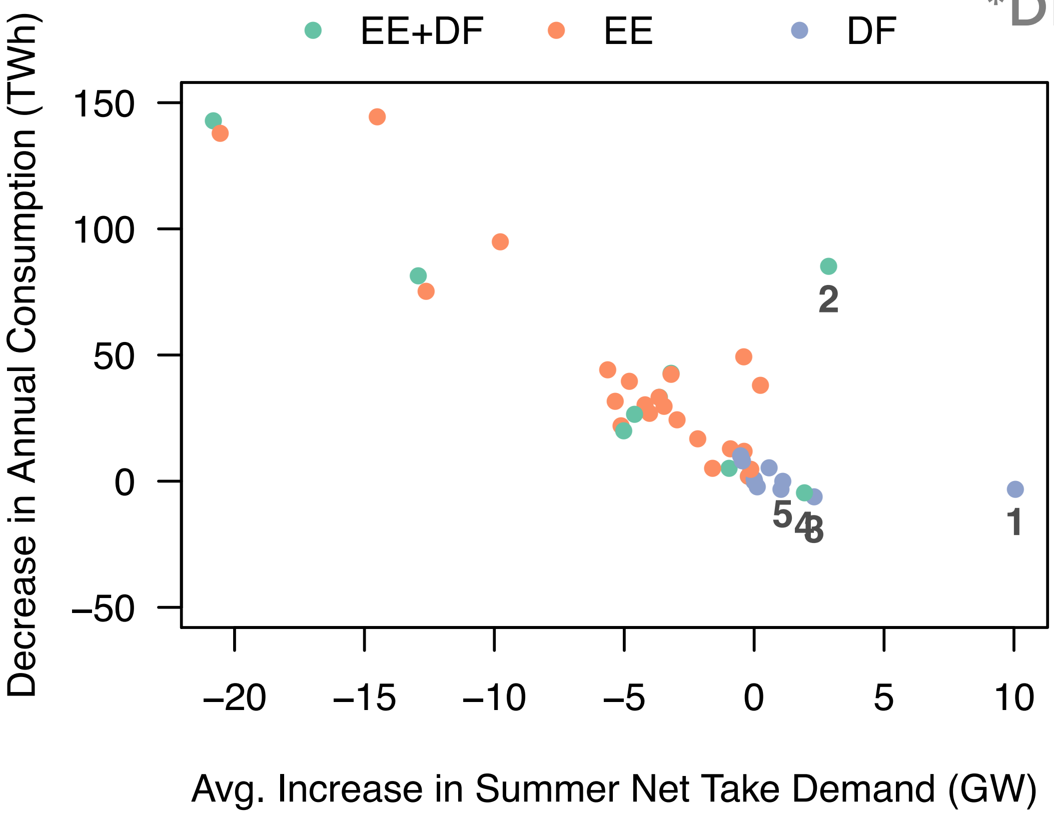
Additional results

Individual measure impacts during the summer

DRAFT



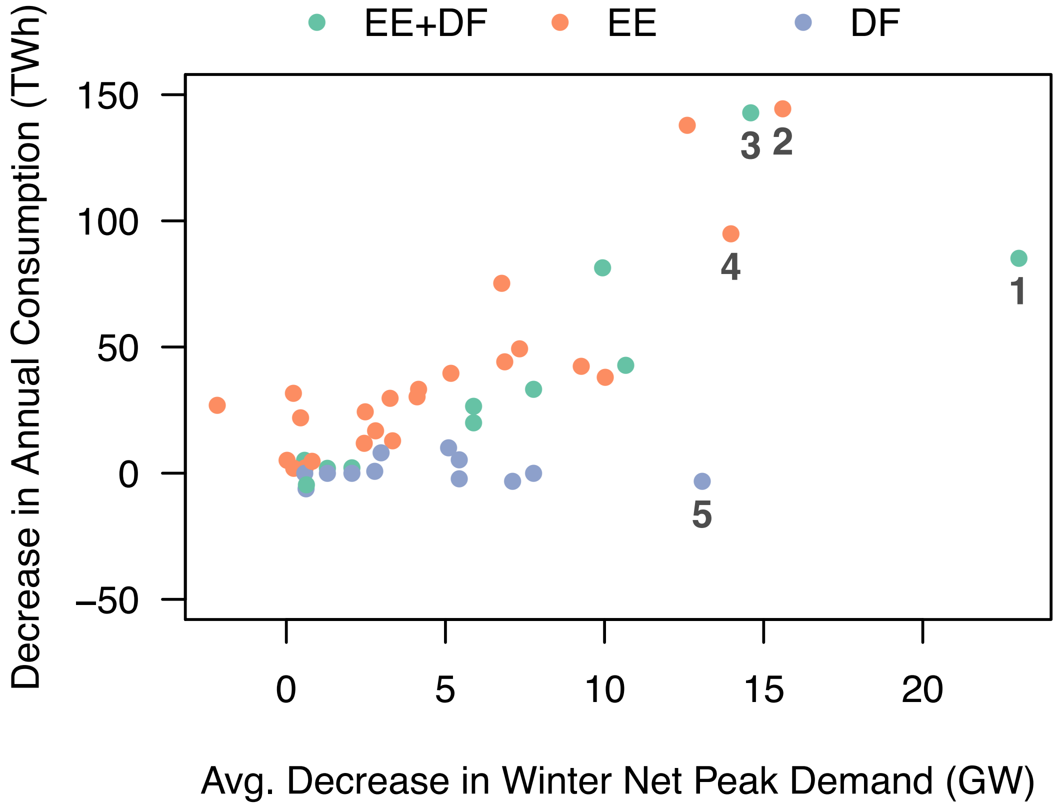
1 Preconditioning (DF−R)
2 ASHP (EE−R)
3 Plug Loads (EE+DF−C)
4 Plug Loads (EE−C)
5 HVAC+GTA+Precool (EE+DF−C)



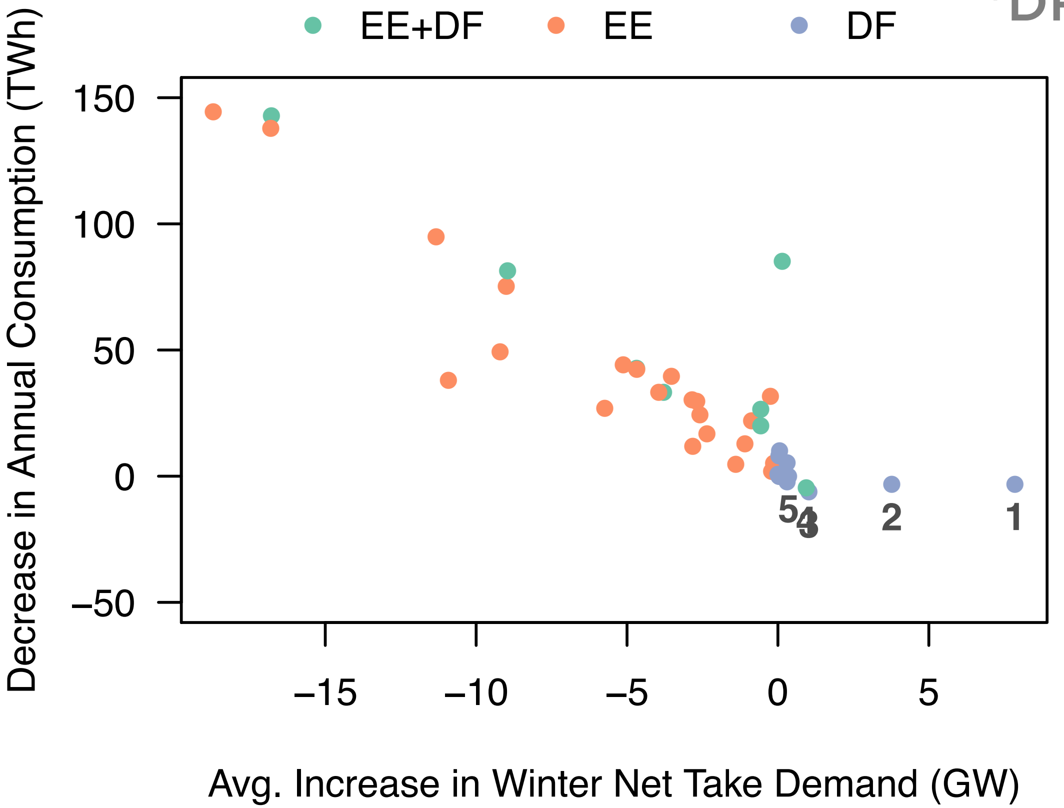
1 Water Heater (DF−R)
2 HPWH (EE+DF−R)
3 Ice Storage (DF−C)
4 HVAC+Ice (EE+DF−C)
5 Pool Pump (DF−R)

Individual measure impacts during the winter

DRAFT

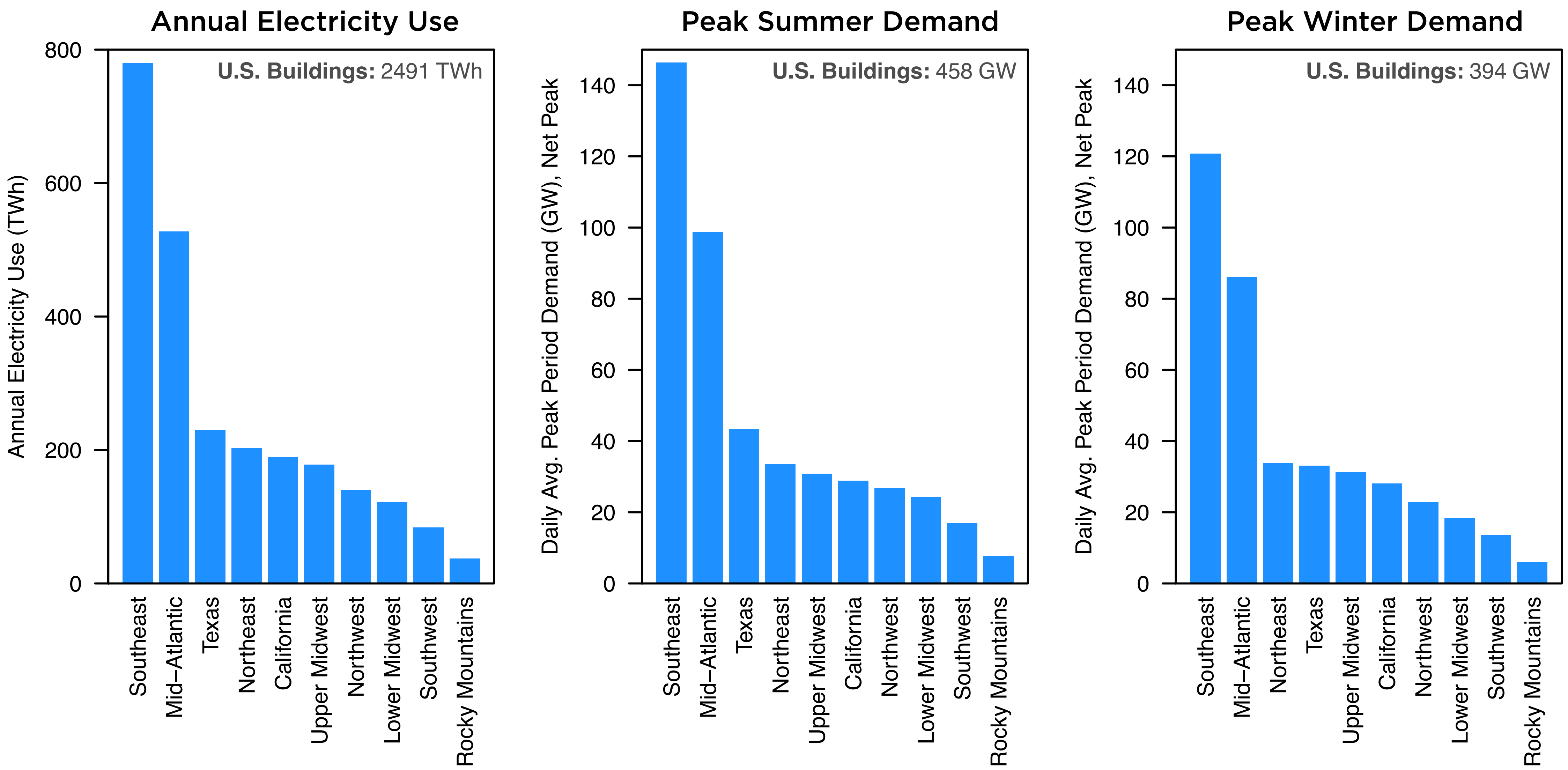


1 HPWH (EE+DF−R)
2 ASHP (EE−R)
3 Plug Loads (EE+DF−C)
4 HPWH (EE−R)
5 Preconditioning (DF−R)



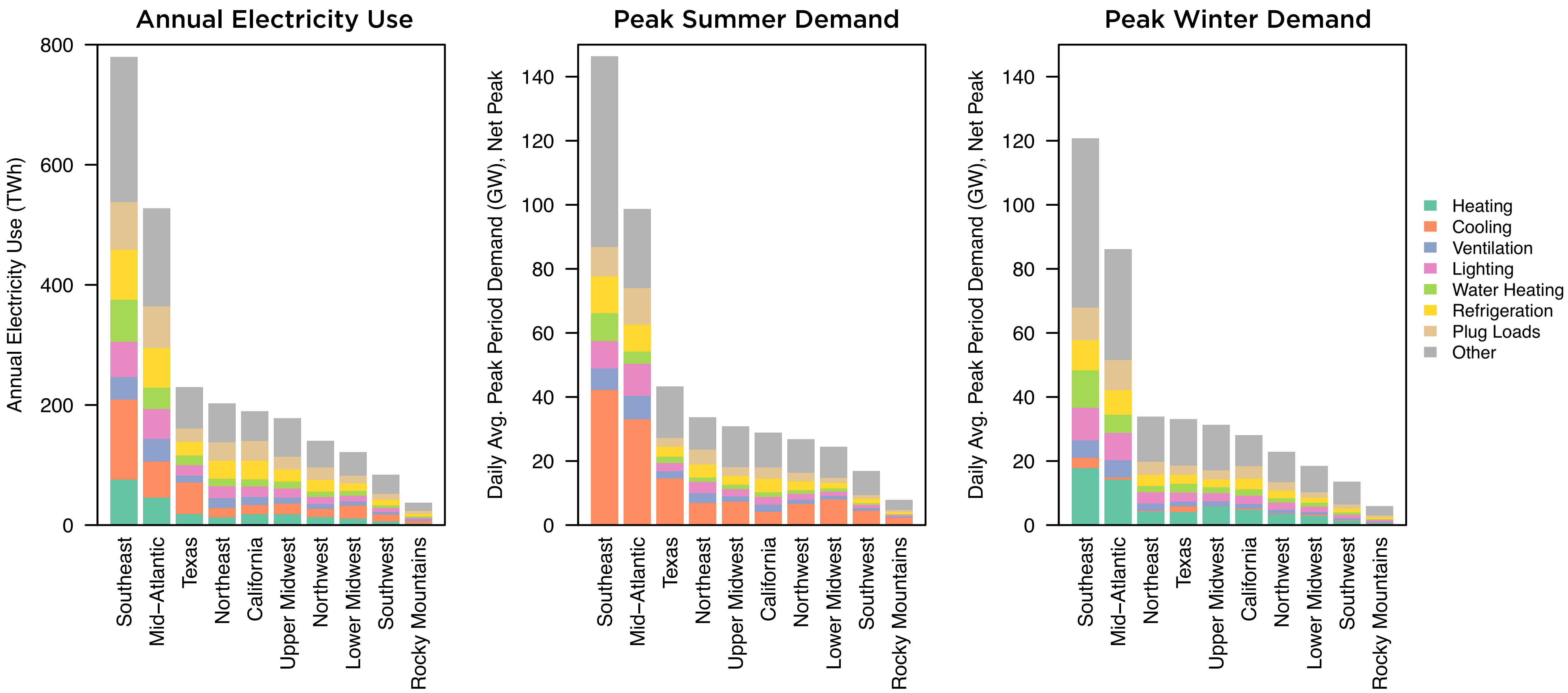
1 Water Heater (DF−R)
2 Preconditioning (DF−R)
3 Ice Storage (DF−C)
4 HVAC+Ice (EE+DF−C)
5 Clothes Dryer (DF−R)

Baseline electricity use in 2020 varies widely by region of the U.S.



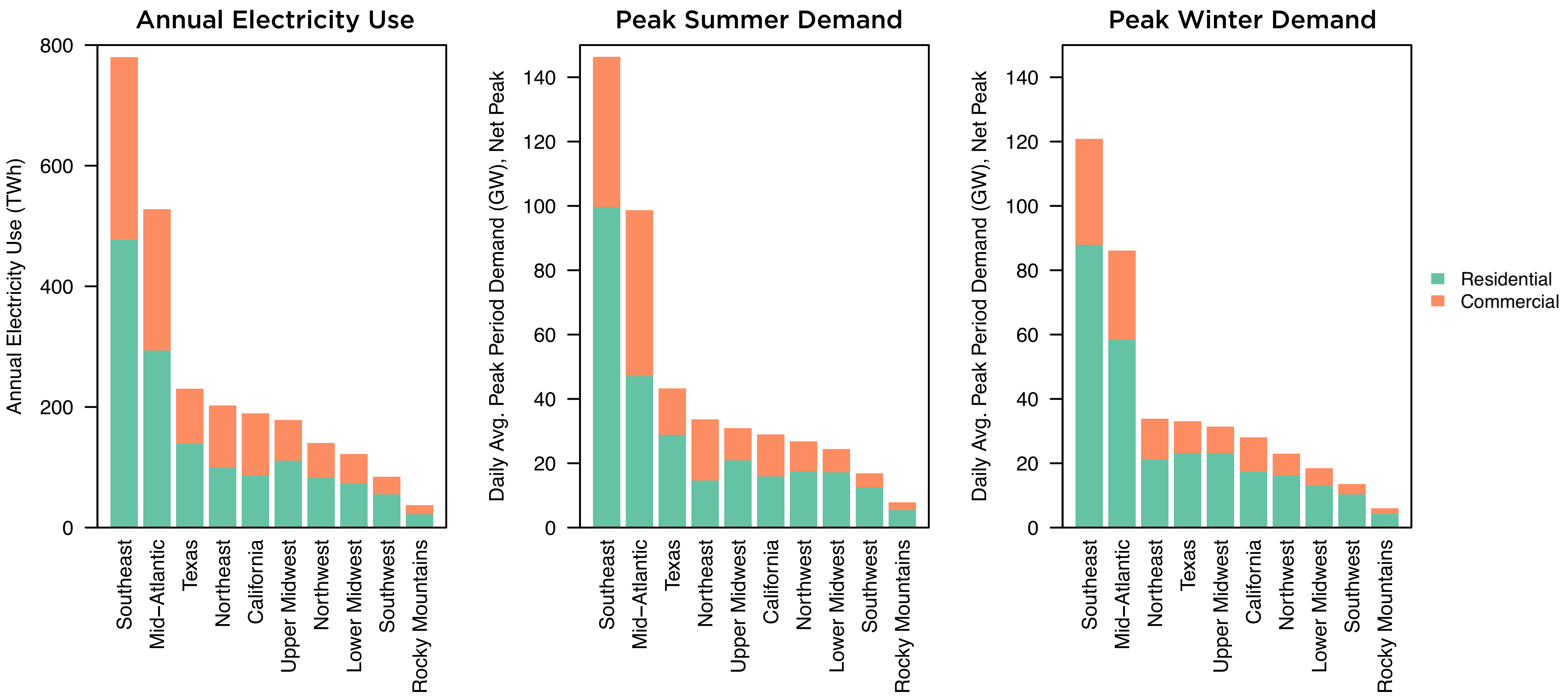
Data: EIA EMM, AEO; Scout

Electricity use differences between regions are driven by end uses



Data: EIA EMM, AEO; Scout

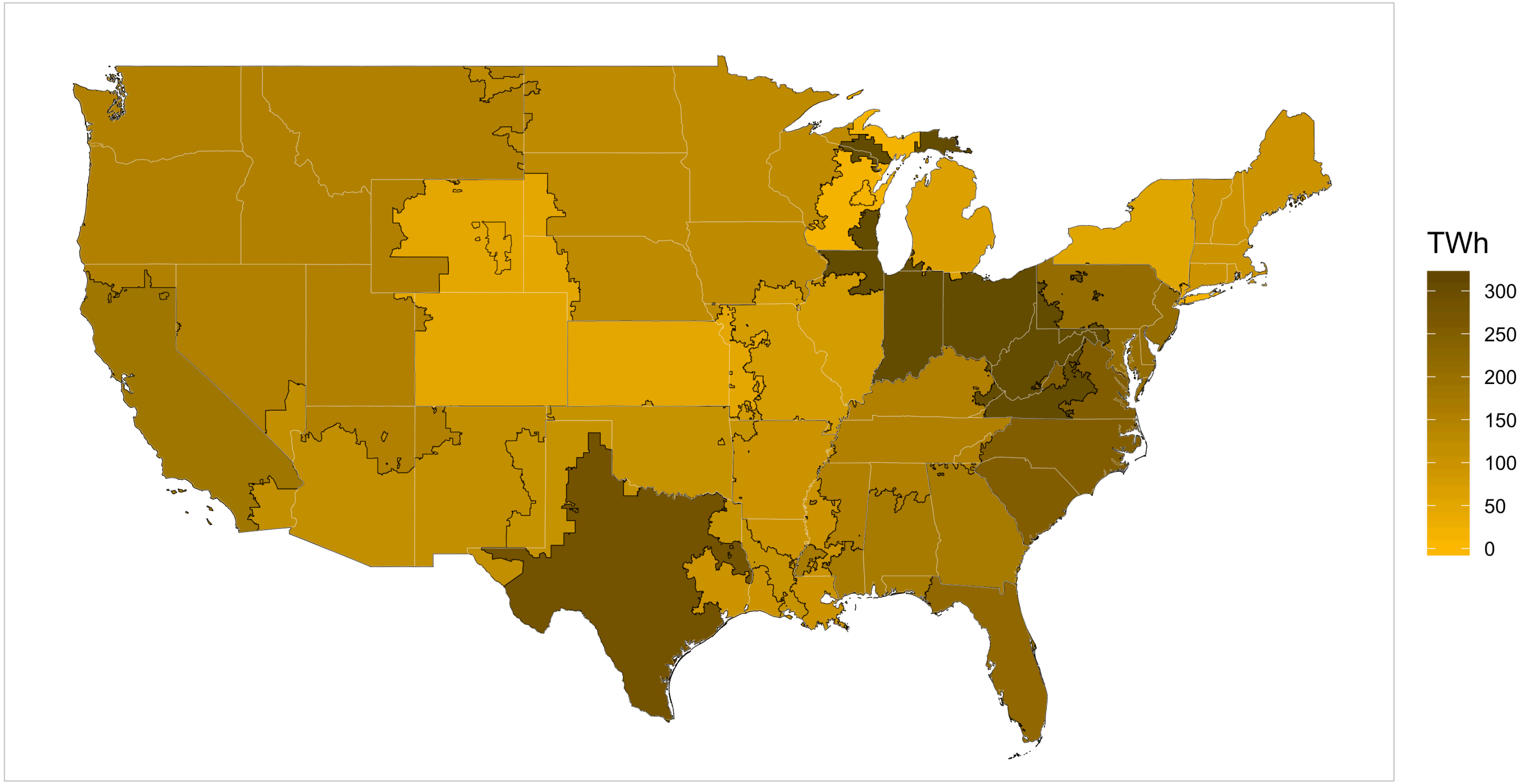
The share of electricity use by building sector also varies by region



Data: EIA EMM, AEO; Scout

The buildings sector drives U.S. annual and peak electric loads

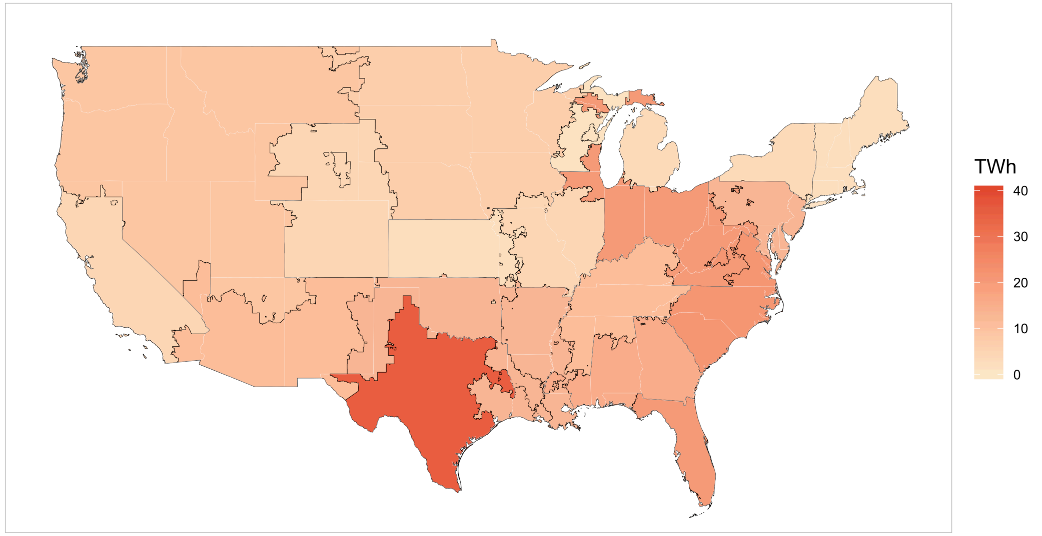
Total annual U.S. building electricity consumption



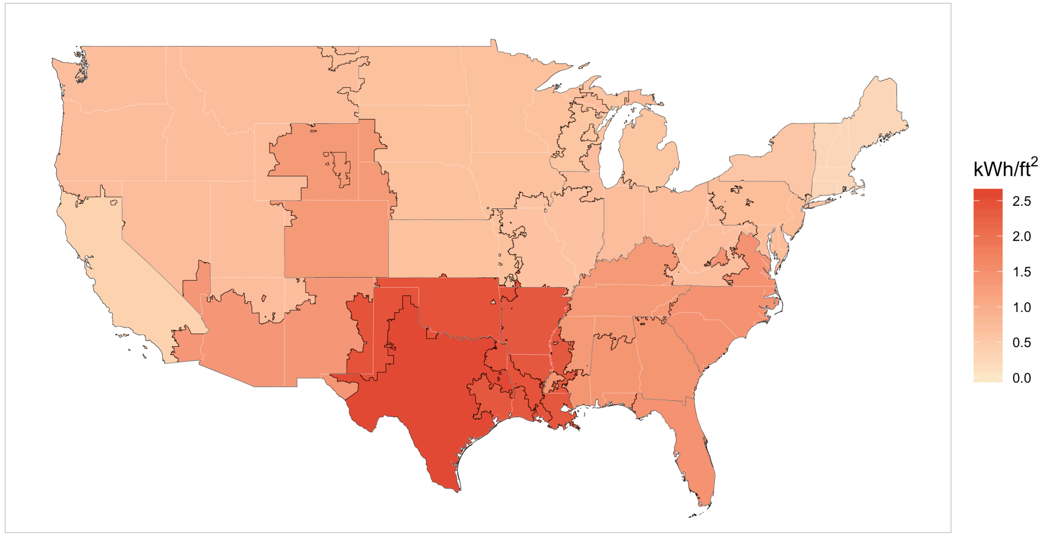
Data: EIA EMM/AEO, Scout

The buildings sector drives U.S. annual and peak electric loads

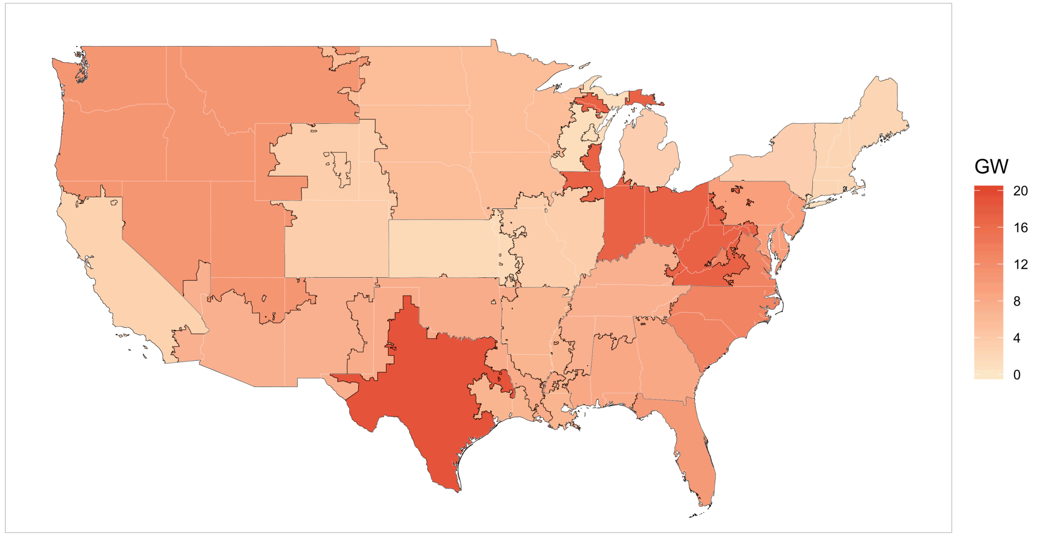
Total annual electricity use, residential cooling



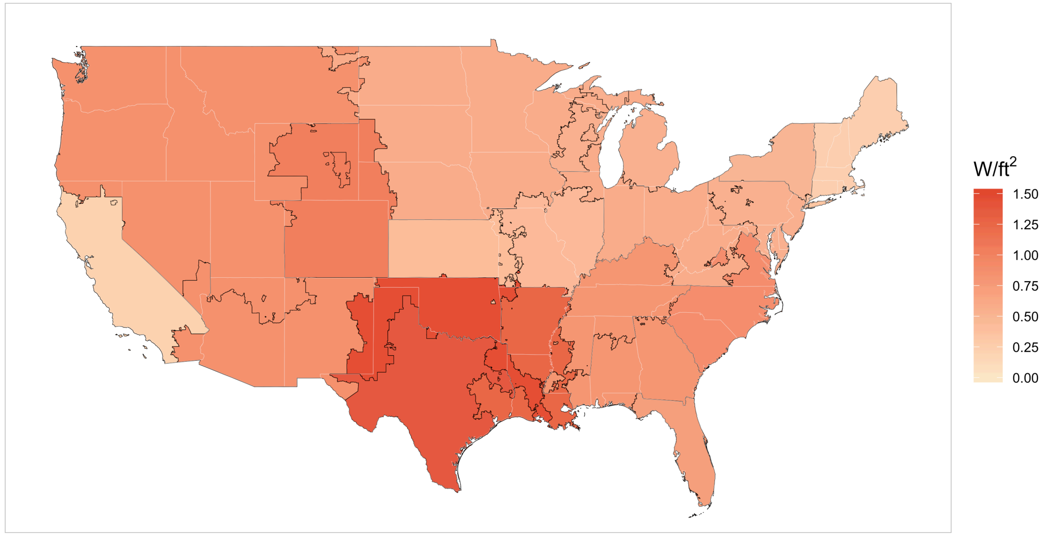
Total annual electricity use intensity, residential cooling



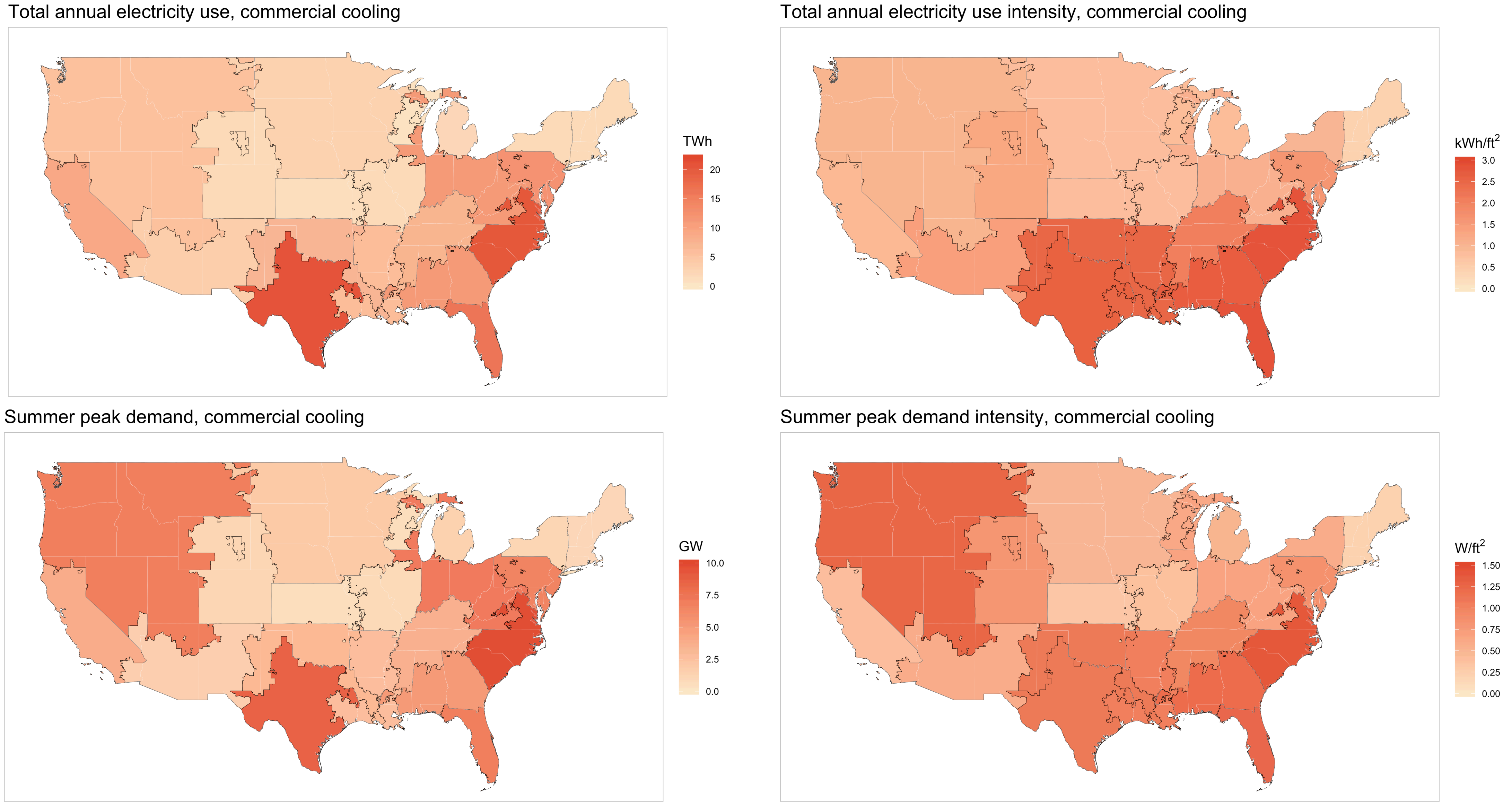
Summer peak demand, residential cooling



Summer peak demand intensity, residential cooling

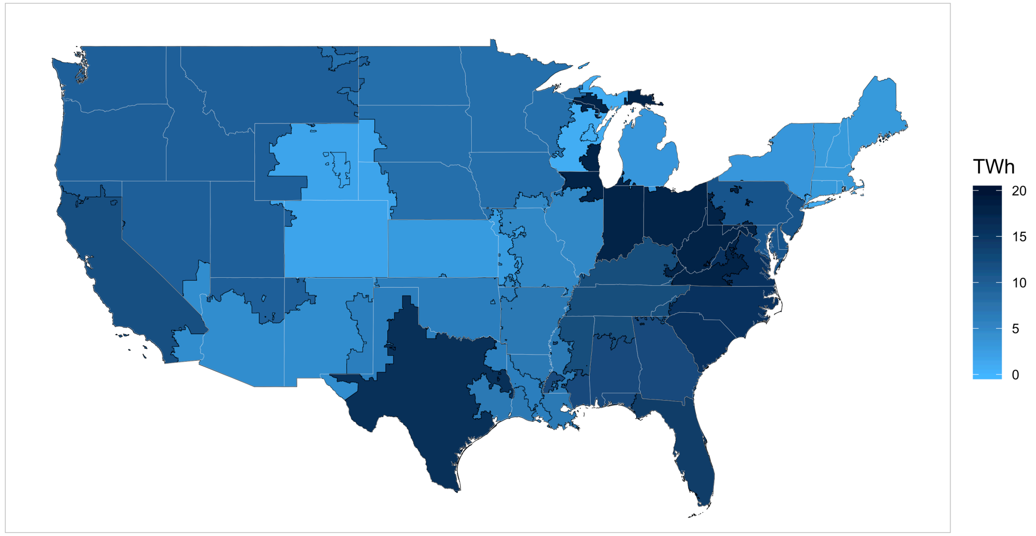


The buildings sector drives U.S. annual and peak electric loads

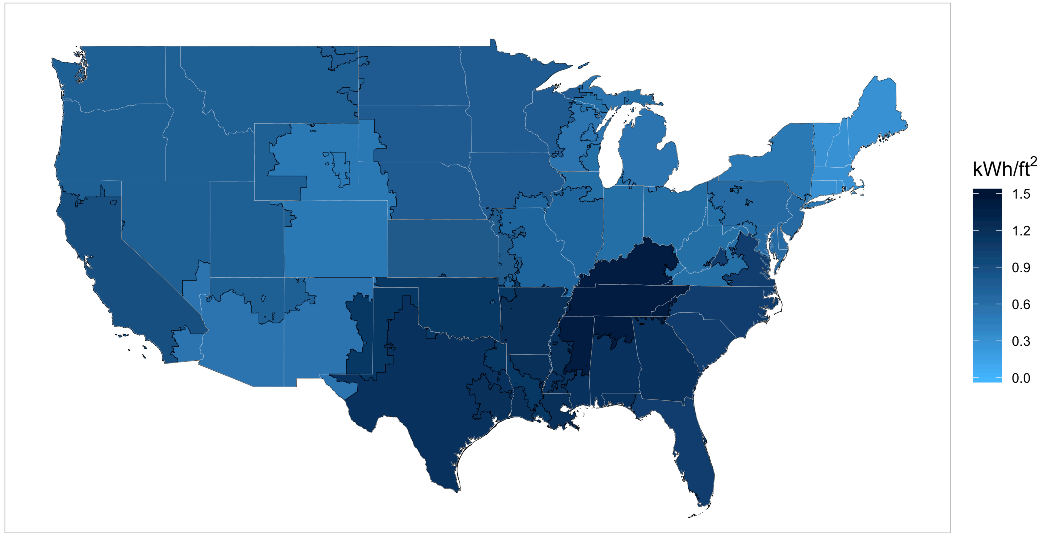


The buildings sector drives U.S. annual and peak electric loads

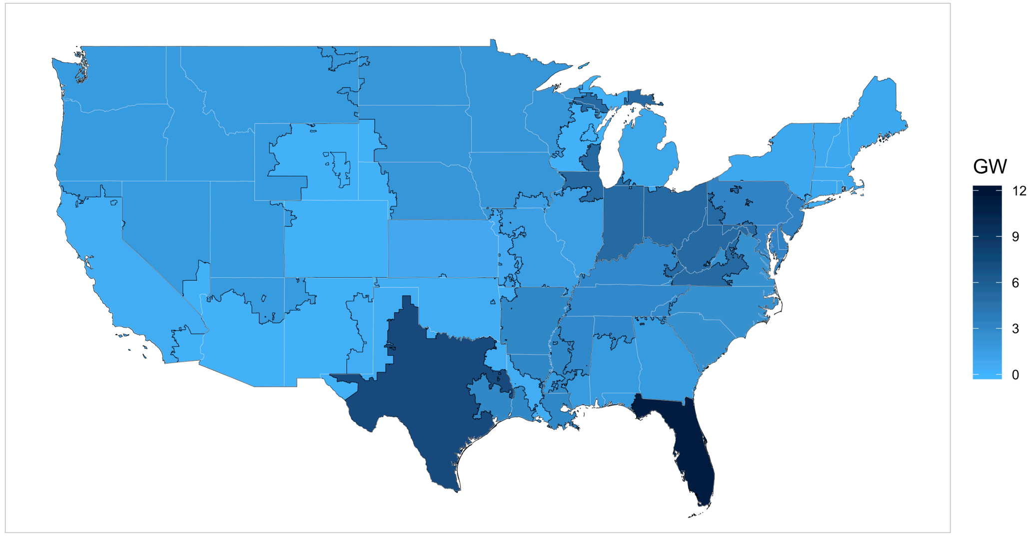
Total annual electricity use, residential heating



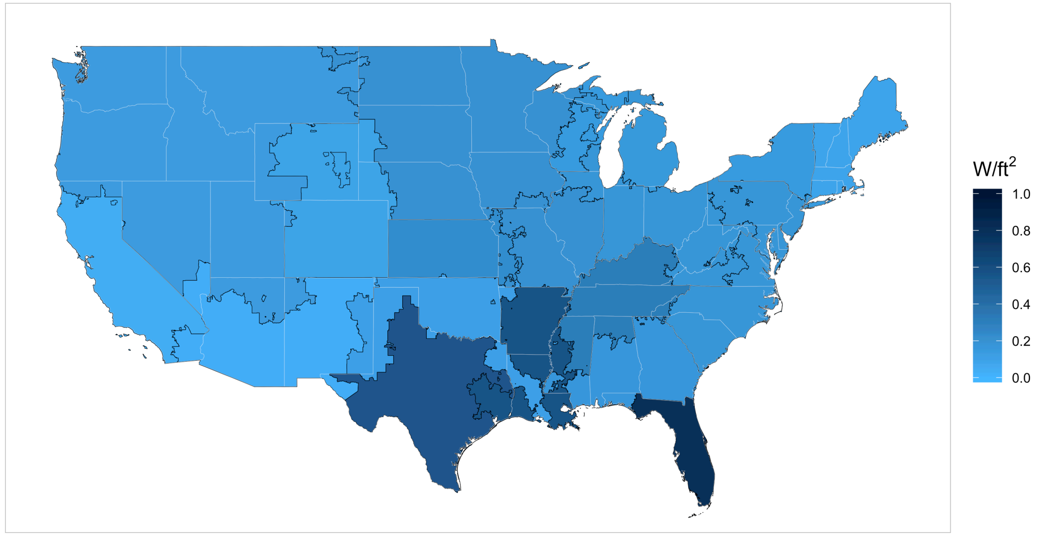
Total annual electricity use intensity, residential heating



Winter peak demand, residential heating

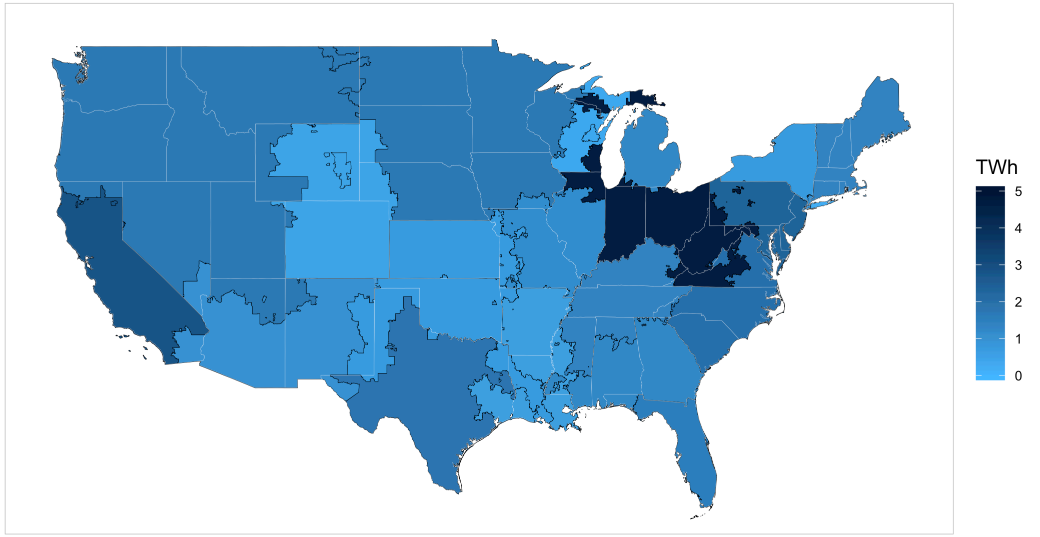


Winter peak demand intensity, residential heating

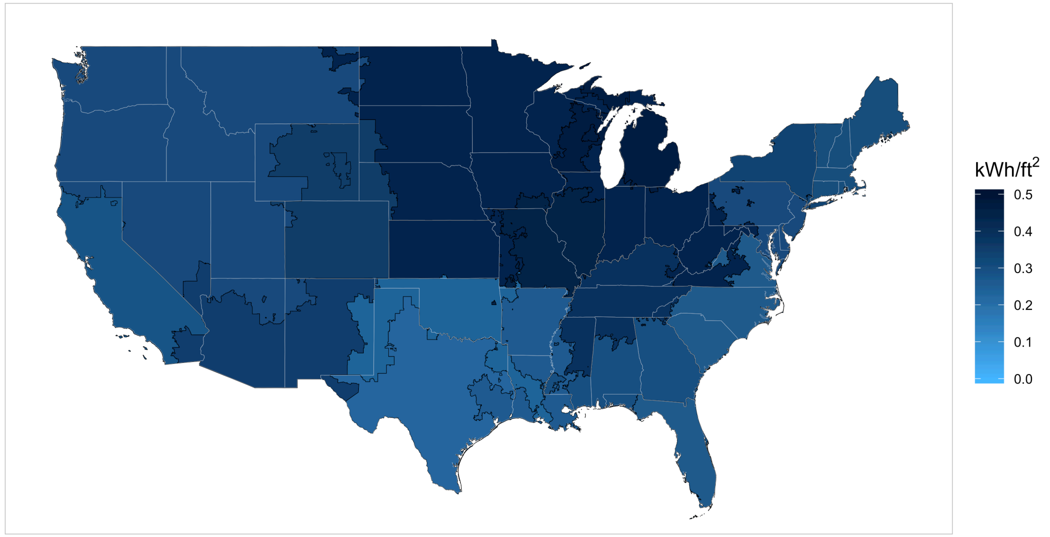


The buildings sector drives U.S. annual and peak electric loads

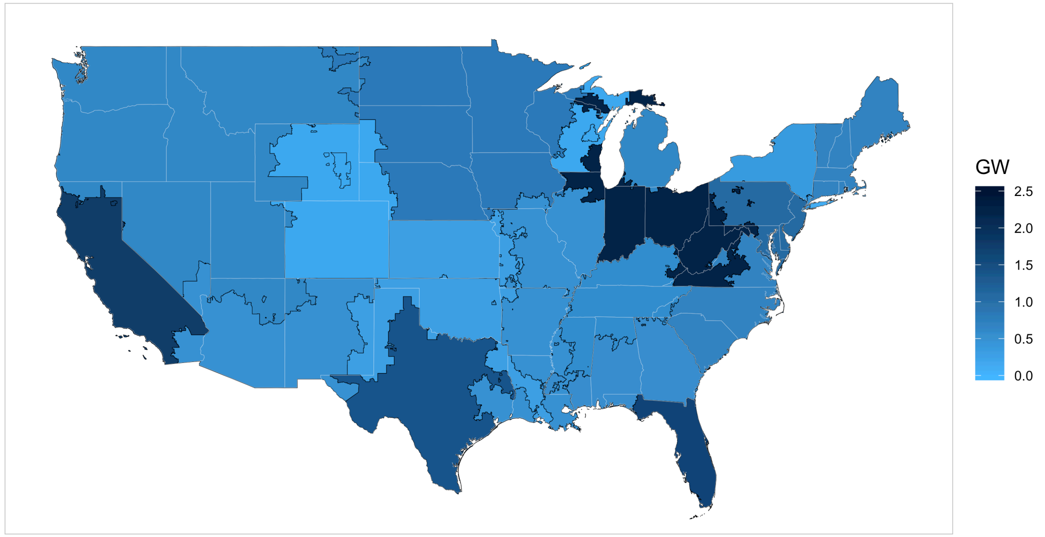
Total annual electricity use, commercial heating



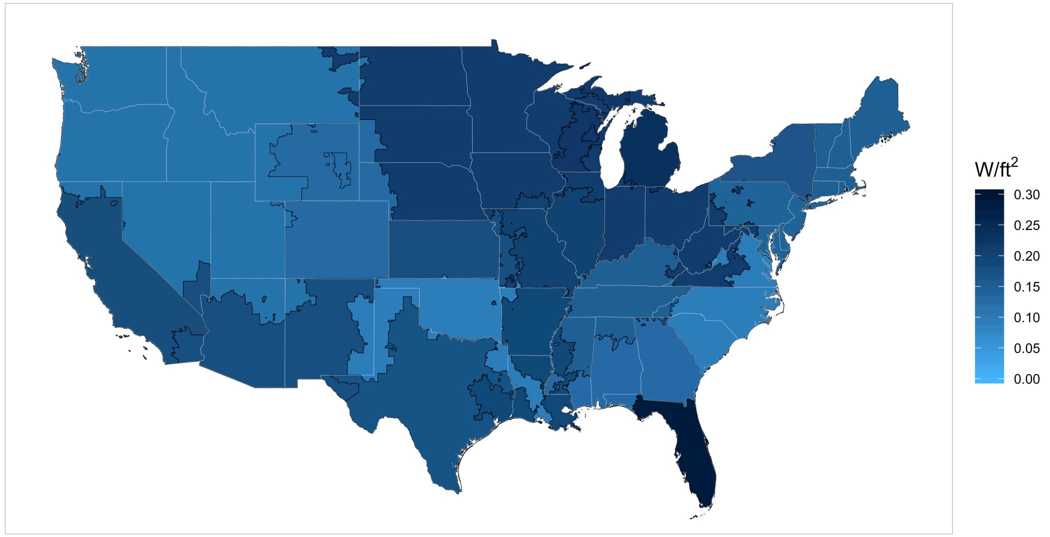
Total annual electricity use intensity, commercial heating



Winter peak demand, commercial heating



Winter peak demand intensity, commercial heating



Efficiency and flexibility are complementary and conflicting

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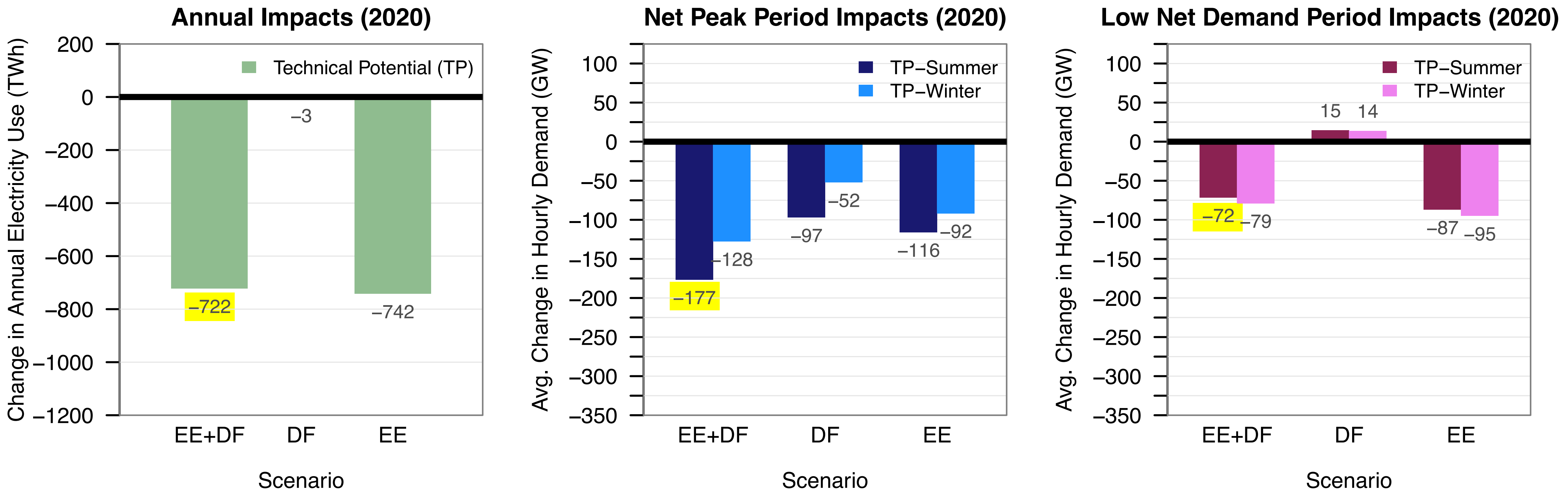

-722 TWh: *19% of total U.S. electricity use in 2020*

-177 GW: *24% of total summer U.S. non-coincident peak in 2020*

-72 GW: *Efficiency reduces opportunity to build load*

Data: Scout
Acronyms: Energy Efficiency (EE), Demand Flexibility (DF)