Physically Realistic Estimates of Electric Water Heater Demand Response Resource

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Why demand response? What kind?

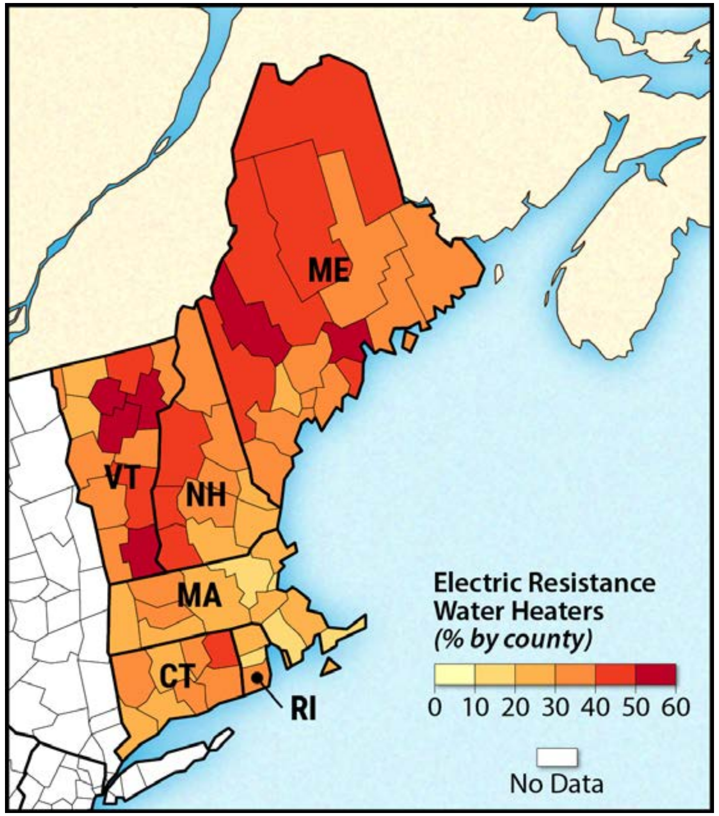
Table 10. 2017 ISO-NE Market Settlements Summary[a]

		Billing ($ Million)	Percentage
Energy	Energy markets total	4,522	49.50%
Capacity	Forward capacity market payments	2,244	24.56%
Transmission	Regional network service	2,163	23.68%
	Reserve markets total	70	0.77%
	Net commitment-period compensation	52	0.57%
	Regulation market	32	0.35%
	Financial transmission rights (FTRs)	20	0.22%
	Black-start	12	0.13%
	Volt-ampere-reactive capacity cost	20	0.22%
	Demand-response payments	1	0.01%
	Total	**$9,136**	**100.00%**

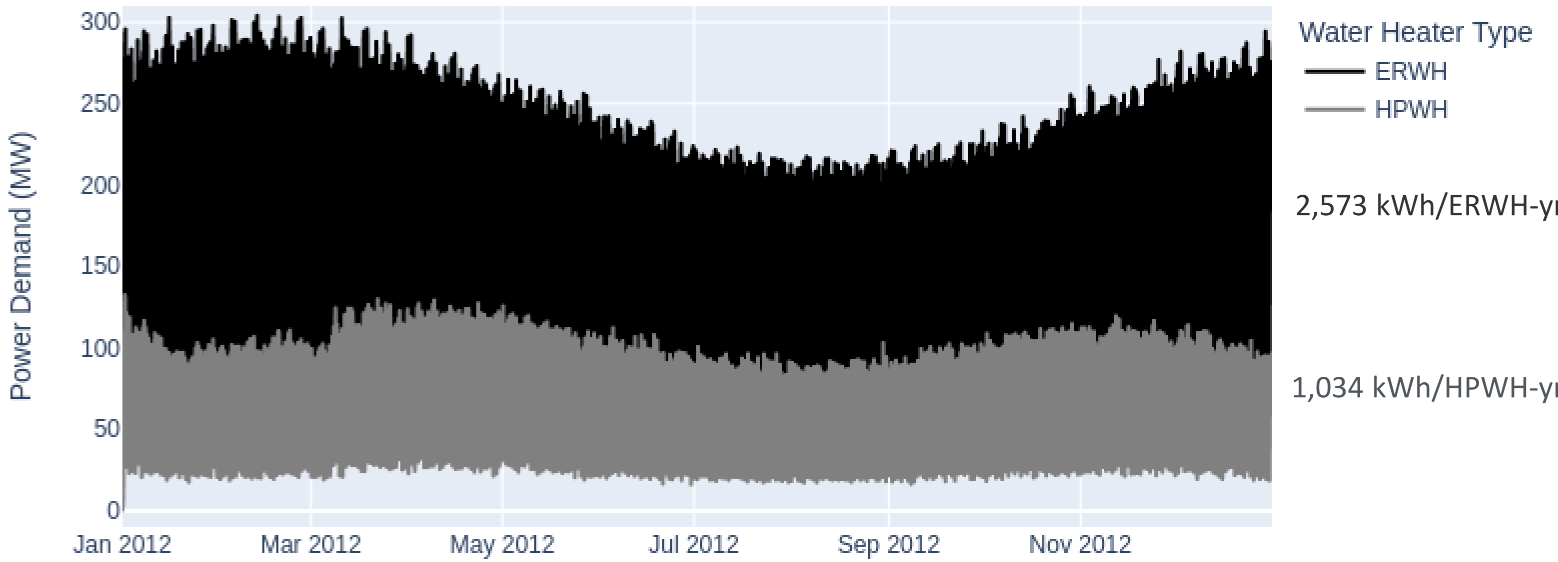
Table from:
P. Denholm, Y. Sun, T. Mai. 2019. An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind. NREL/TP-6A20-72578. https://doi.org/10.2172/1505934.
Data from:
[a] Independent System Operator–New England (ISO-NE). 2018a. 2017 Annual Markets Report. Holyoke, MA. https://www.iso-ne.com/static-assets/documents/2018/05/2017-annual-markets-report.pdf.

- Electricity supply and demand must balance at all timescales
- Demand response can provide energy, capacity, and ancillary services
- Energy, capacity, and transmission represent most system costs (> 95%)
- Residential demand response is often a capacity resource called on to reduce load at peak times and compensated through an incentive payment
- With more variable renewable energy and clean energy goals, there is potentially a larger role for demand response to play in future power systems

What grid services can water heaters provide?



ResStock-simulated power demand of 620,000 electric water heaters



2,573 kWh/ERWH-yr

1,034 kWh/HPWH-yr

- ResStock[1] estimates about 620,000 electric water heaters in New England, predominantly electric resistance water heaters (ERWHs) with tanks. What grid services can those water heaters realistically provide? What if they were heat pump water heaters (HPWHs) instead?
- Although there are aggregators currently providing regulation reserve with water heaters now, we focus on capacity and energy (shifting) service as the most valuable and important services for renewables integration.

[1] Wilson, E., C. Christensen, S. Horowitz, and H. Horsey. 2016. "A High-Granularity Approach to Modeling Energy Consumption and Savings Potential in the U.S. Residential Building Stock". *IBPSA-USA Journal* 6 (1).

How has the question been answered before?

In previous large-scale grid simulation studies

- Rough assumptions about how much water heater load might be sheddable (e.g., all participating load [personal communication] or an assumption of 25% "based on research to date"[1]) or shiftable and for how long
- No direct measurement/estimate of total power capacity and no energy loss during shifting due to dissipation[2]
- No consideration for heat pump water heaters and how their efficiency and power capacity varies with tank and ambient temperatures[2]

In pilot projects and laboratory tests

- Bonneville Power Administration (BPA) CTA-2045 water heater controller tests:[3]
  - 1, 2, and 3 hour shed events in different seasons and with both ERWHs (0.4 – 0.6 kW reductions) and HPWHs (0.1 – 0.2 kW reductions)
  - Shift events characterized by how much load was shed during the 2 to 4 hour shed portions of the shifting protocol, normalized to average reduction for a 3-hour shed (0.2 – 0.5 kWh for HPWH, 0.4 – 1.2 kWh for ERWH, with variations due to time of day)
- Laboratory tests of an 85 gallon ERWH and an 80 gallon HPWH subject to the same water draw profiles under baseline, peak load reduction (6 hour event), short-term response (1 hour event), and very short-term response (frequency regulation signal following). Impacts on tank temperature and size of response were measured for both water heaters on seven different days and then averaged.[4]
- Simulation study of HPWH shifting with models calibrated to lab testing data for water heaters from multiple vendors and of multiple sizes. Shifting based on price-taking analysis using marginal energy costs or a time-of-use tariff, and with different control strategies (on-off, set-point schedule, optimal price-based set-points). Compare R134a and CO_2 refrigerants.[5]

[1] Olsen, D.J., Matson, N., Sohn, M.D., Rose, C., Dudley, J., Goli, S., Kiliccote, S., Hummon, M., Palchak, D., Denholm, P., Jorgenson, J., Ma, O., Sep. 2013. *Grid Integration of Aggregated Demand Response, Part 1: Load Availability Profiles and Constraints for the Western Interconnection*. Technical Report LBNL-6417E, Lawrence Berkeley National Laboratory, Berkeley, California.

[2] Hale, Elaine T., Brady L. Stoll, and Joshua E. Novacheck. 2018. "Integrating Solar into Florida's Power System: Potential Roles for Flexibility." Solar Energy 170 (August): 741–51. https://doi.org/10.1016/j.solener.2018.05.045. (This is just one of several example studies)

[3] BPA. 2018. *CTA-2045 Water Heater Demonstration Report including A Business Case for CTA-2045 Market Transformation*. Technical Report BPA Technology Innovation Project 336. Bonneville Power Administration (BPA). https://www.bpa.gov/EE/Technology/demand-response/Documents/Demand%20Response%20-%20FINAL%20REPORT%20110918.pdf.

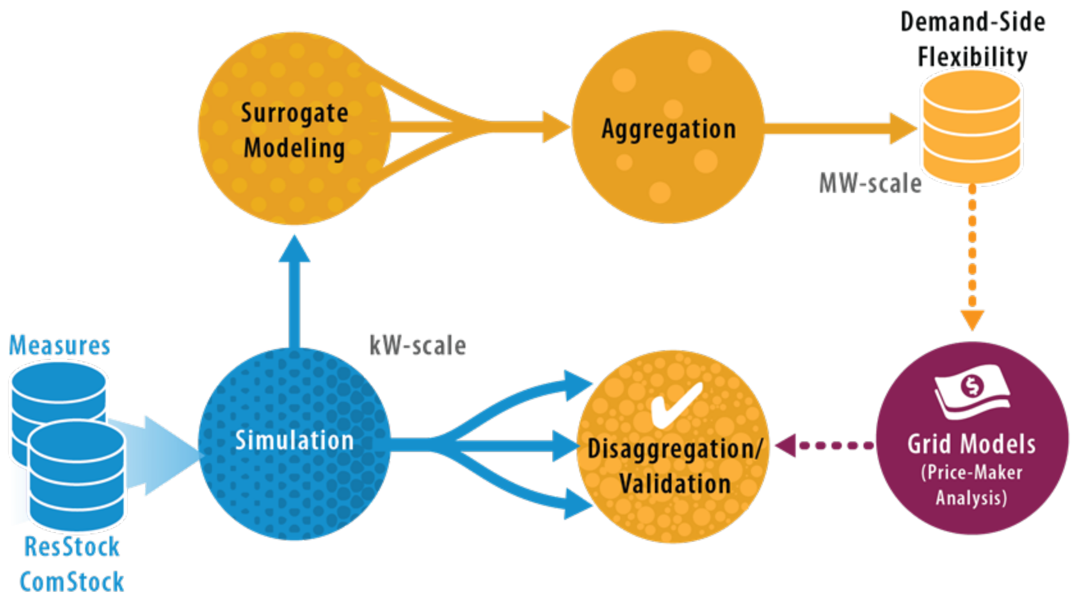
[4] Mayhorn, E., S. Widder, S. Parker, R. Pratt, and F. Chassin. 2015. Evaluation of the demand response performance of large capacity electric water heaters . Technical Report PNNL-23527. Richland, Washington: Pacific Northwest National Laboratory. https://labhomes.pnnl.gov/documents/PNNL_23527_Eval_Demand_Response_Performance_Electric_Water_Heaters.pdf.

[5] Carew, Nick, Ben Larson, Logan Piepmeier, and Michael Logsdon. 2018. "Heat Pump Water Heater Electric Load Shifting: A Modeling Study." Ecotope. https://ecotope-publications-database.ecotope.com/2018_001_HPWHLoadShiftingModelingStudy.pdf.

Study Approach

Water heaters (at 1 kW to 5 kW) are too small to directly participate in power system dispatch (FERC Order 2222 applies 100 kW minimum and ISO dispatch software cannot represent quantities smaller than 0.1 MW)

In this study, we use detailed models of single-family housing stock in New England (ResStock) and the bulk power system (PLEXOS) and bridge them with surrogate modeling, aggregation, and disaggregation/validation



Real-world aggregators operate similarly, except they are continually aggregating and disaggregating and working with measured data and physical controls.

Water Heater Flexibility

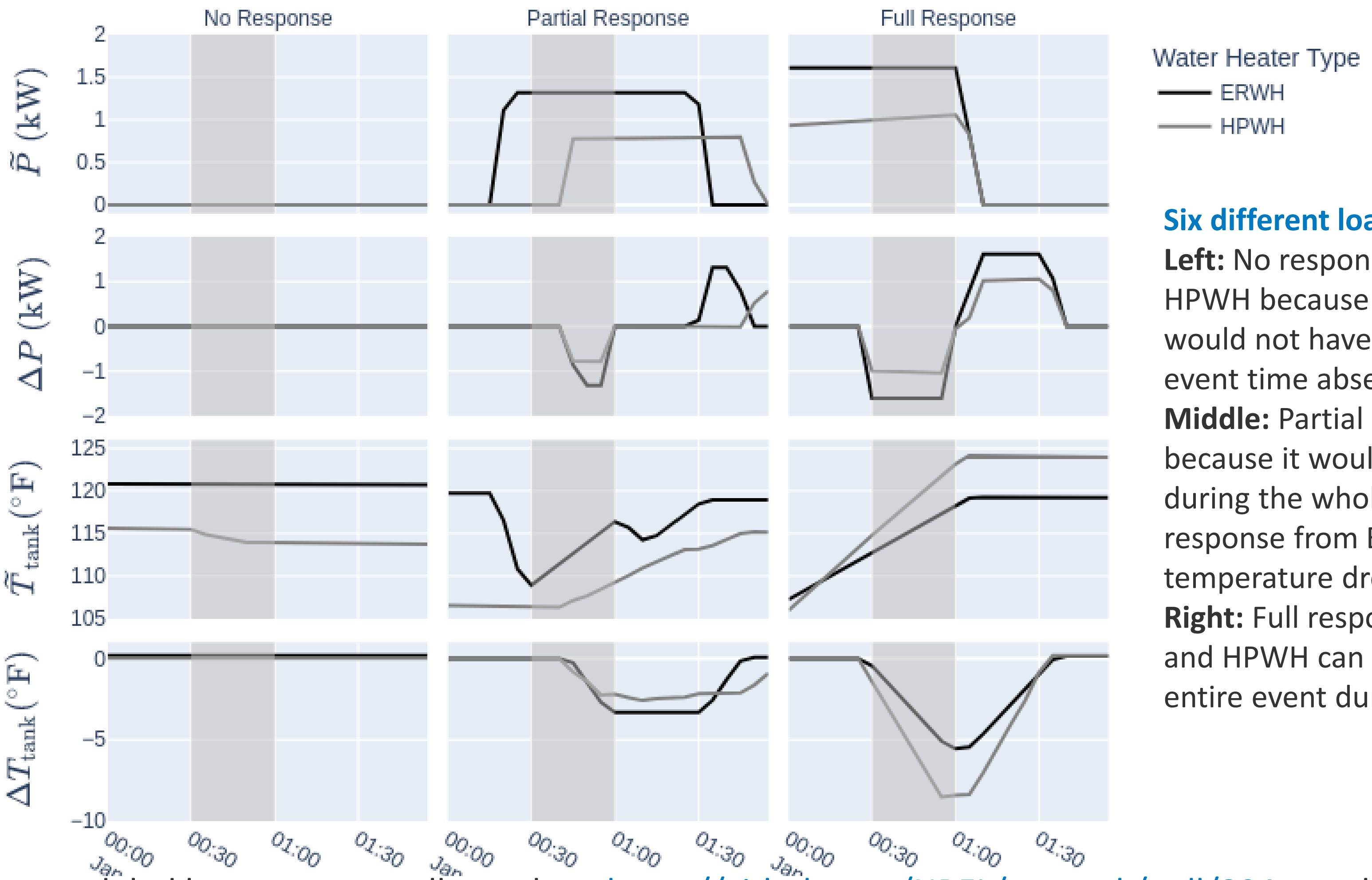
ResStock/EnergyPlus ERWHs and HPWHs Perform Differently

Baseline Power Draws

Change in Power Draw due to Shed Event

Baseline Average Tank Temperatures

Change in Average Tank Temperatures due to Shed Event



Six different load shed responses:

Left: No response from ERWH or HPWH because the water heaters would not have been on during the event time absent the event.

Middle: Partial response from HPWH because it would not have been on during the whole event. Partial response from ERWH because tank temperature drops too low.

Right: Full responses because ERWH and HPWH can drop load for the entire event duration.

- The ERWH power capacities modeled here are generally too low: https://github.com/NREL/resstock/pull/804; resulting in cycles that are about 3 times too long and potentially impacting average outlet temperatures/delivered thermal energy
- ERWH average tank temperature differs significantly from, and is often higher than, temperature measurements used to control heating elements

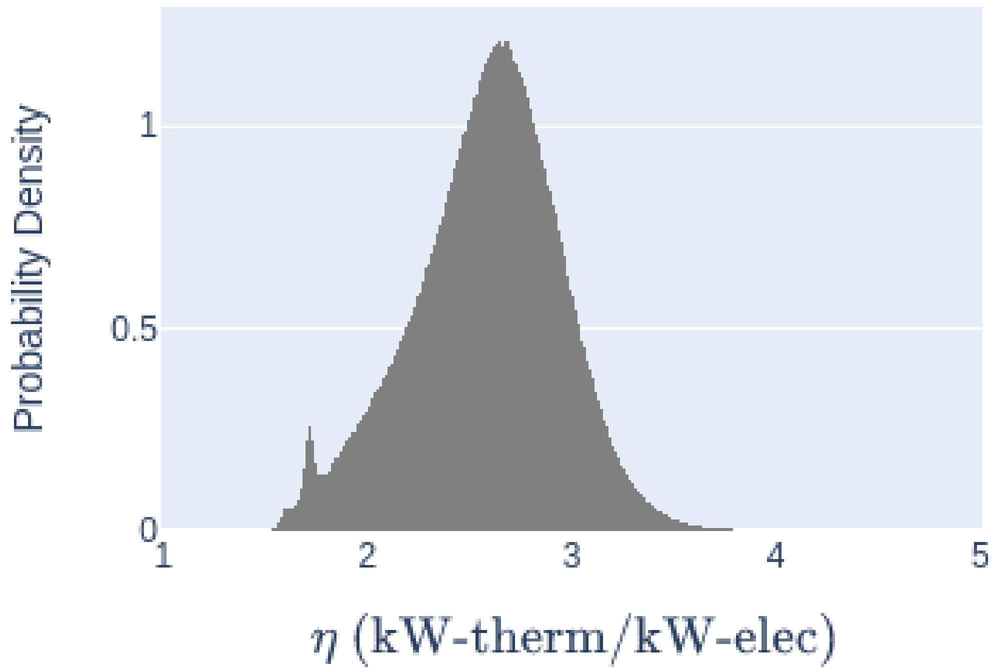
Surrogate Flexibility Model

- Dynamic battery-like model per water heater
  - Power bounds capture ability to turn water heaters on or off relative to baseline
  - Energy bounds capture how long the water heater can be kept off or turned on before reaching a temperature bound
- Two “flavors” of surrogate model:
  - **Simple** assumes that the tank is always at set point under baseline conditions
  - **TankT** accounts for the actual average tank temperature during the baseline ResStock run

Efficiency (η) and Tank losses

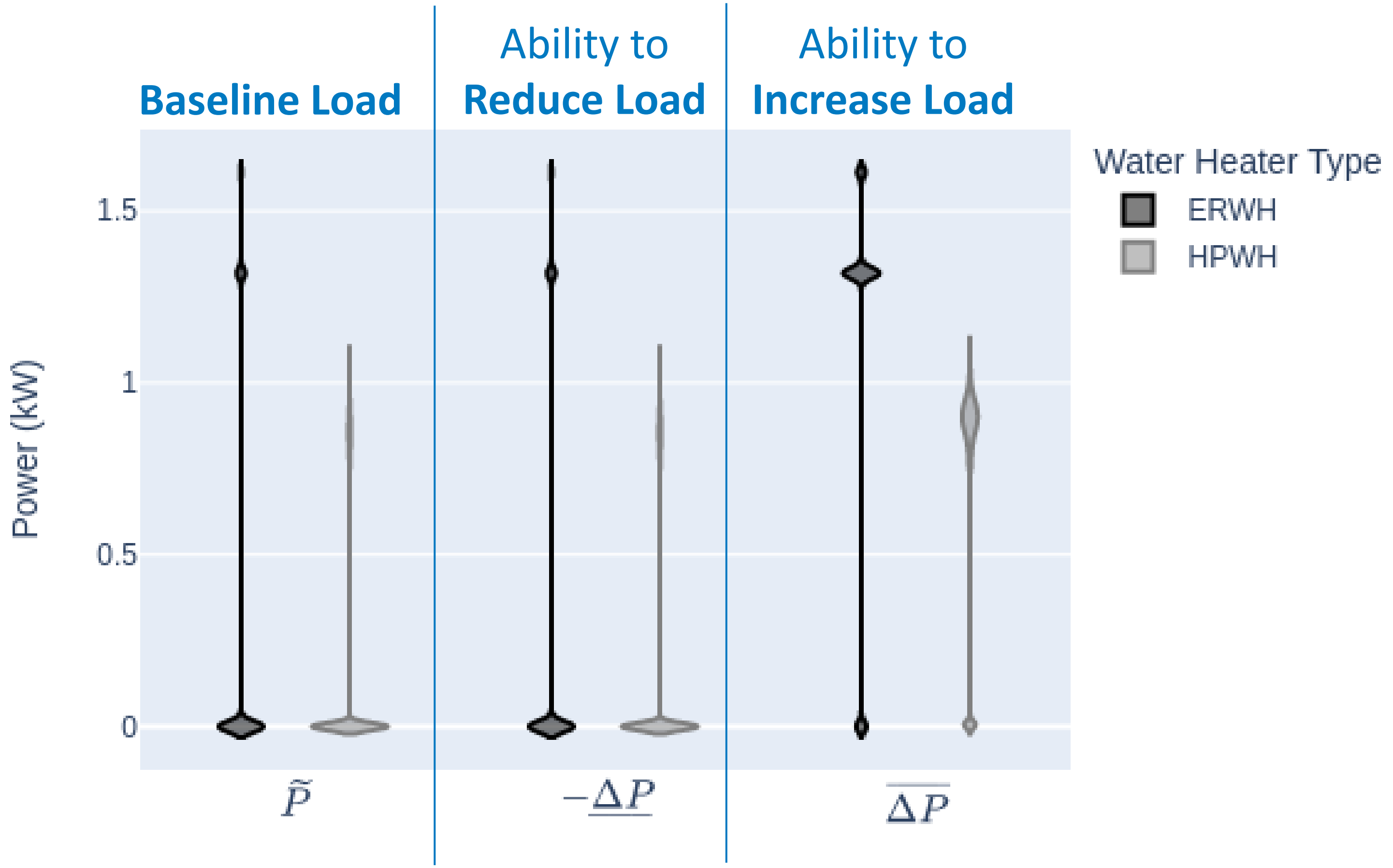
- ERWH efficiency (η) is 1
- Tank losses are less than 1%/hour for all water heater models
  - ERWH scenario has two models each installed with 5 different tank volumes, from 20 to 60 gallons
  - HPWH scenario has one 80-gallon model

HPWH Efficiency



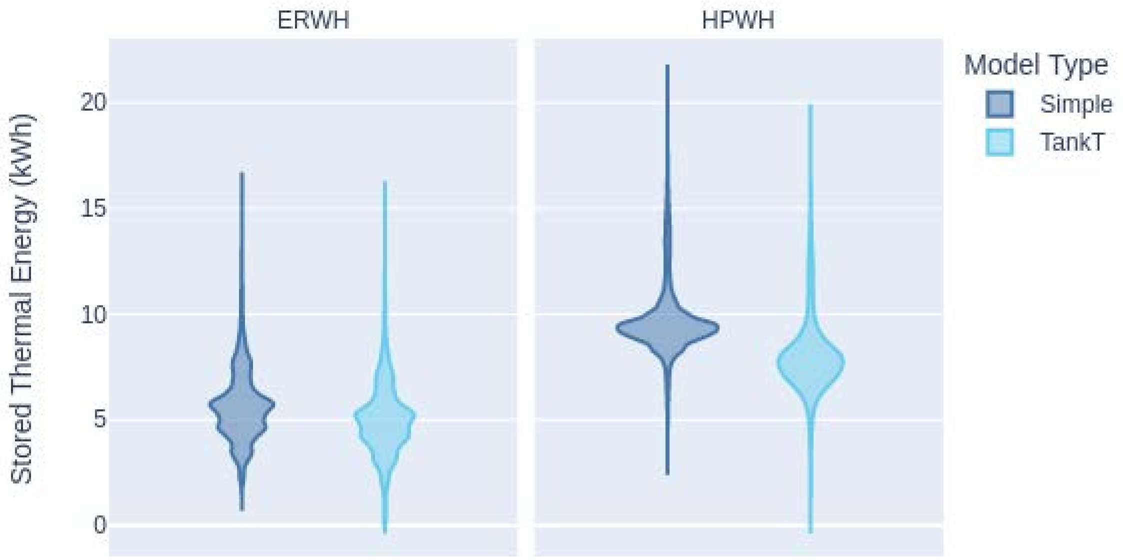
Power Bounds

- As modeled, ERWHs have maximum power draws of 1.3 kW or 1.6 kW
  - Per https://github.com/NREL/resstock/pull/804 these capacities should be 4.5 kW or 5.5 kW
  - Impact at hourly timescale is likely modest, but at this time is not precisely known
- HPWHs pull a little less than 1 kW, typically
- Only baseline power draws can be reduced ($-\underline{\Delta P} = \tilde{P}$)
- Ability to increase load is power capacity minus baseline load ($\overline{\Delta P} = P_{max} - \tilde{P}$)



Stored Thermal Energy & Energy Bounds

- Stored thermal energy is thermal capacitance (proportional to tank volume) times difference in tank and ambient temperature
- Stored thermal energy is measured differently (e.g., relative to water mains temperature) for different applications



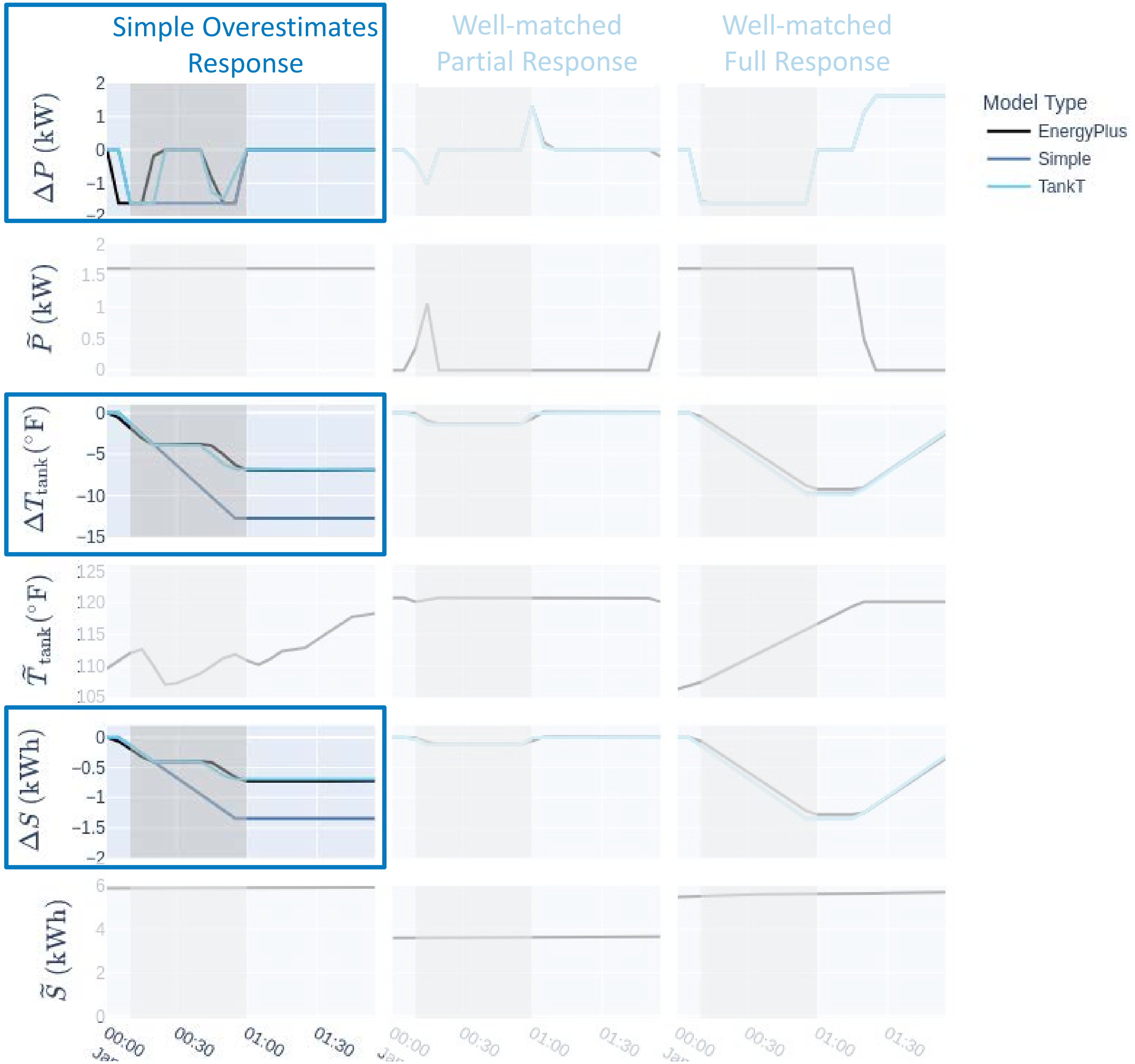
Baseline Stored Thermal Energy

- ERWH Simple model allowed reductions: 1 to 3 kWh
- HPWH Simple model allowed reductions: approx. 3.5 kWh
- TankT assumptions reduce these quantities to:
  - About 0.5 to 1.8 kWh for ERWHs
  - About 1 to 2.5 kWh for HPWHs

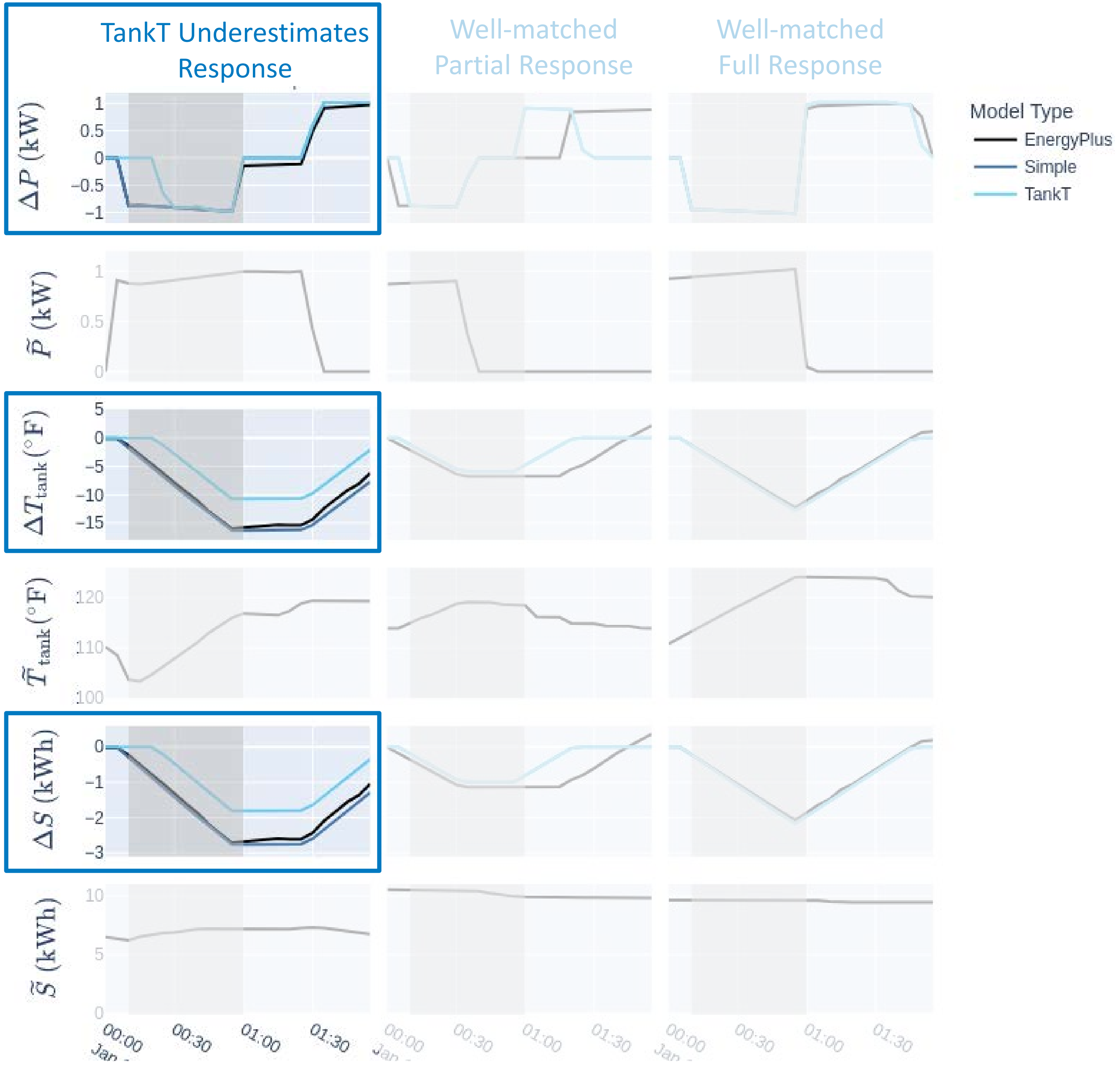
Validation of Surrogate Models

TankT surrogate model better represents ERWH shed responses

For these “Claim10” (50 minute) responses, both models do well for the “Partial” and “Full” responses, but TankT better matches EnergyPlus simulation in the left-hand column

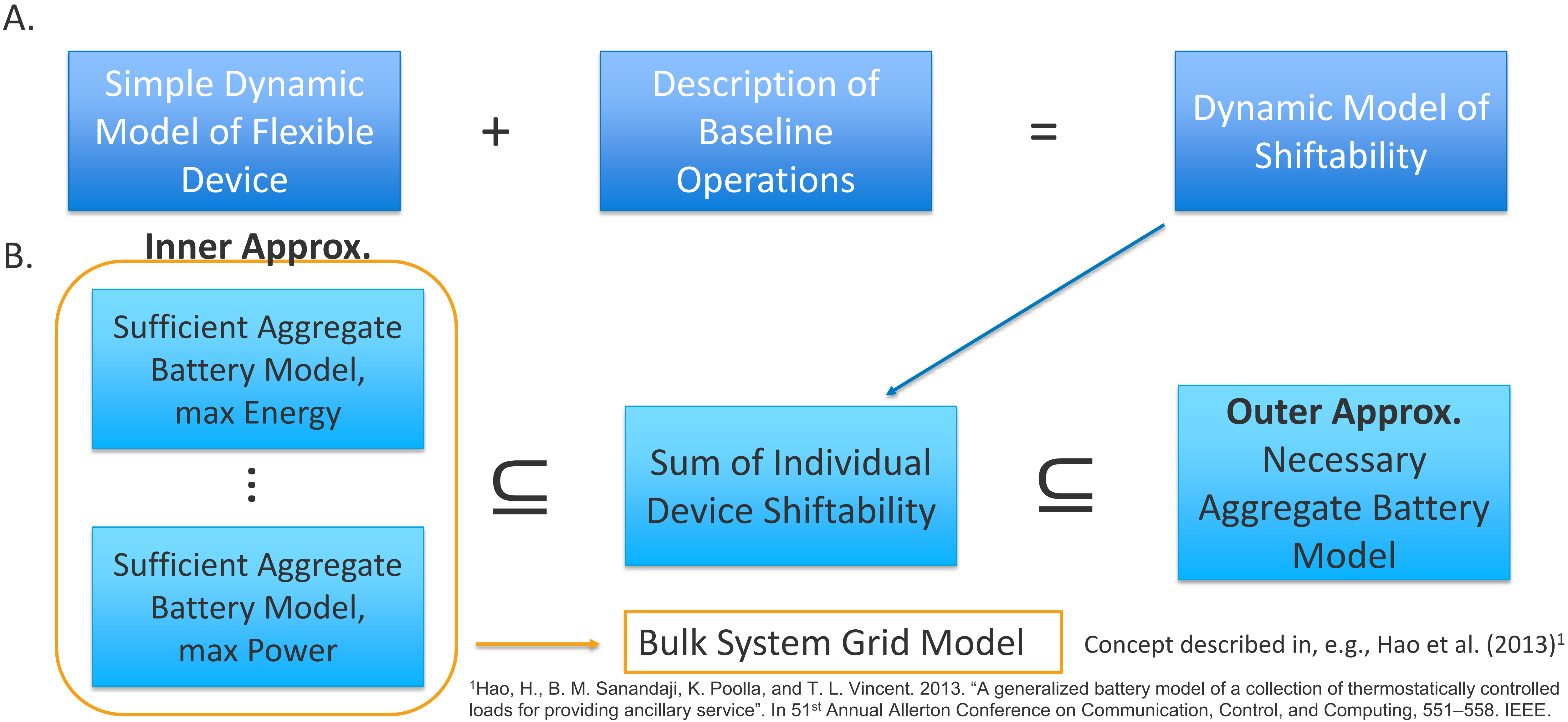


Simple surrogate model better represents HPWH shed responses



For these “Claim10” (50 minute) responses, both models do well for the “Partial” and “Full” responses, but Simple better matches EnergyPlus simulation in the left-hand column

Conceptual Framework for Aggregation



[1]Hao, H., B. M. Sanandaji, K. Poolla, and T. L. Vincent. 2013. "A generalized battery model of a collection of thermostatically controlled loads for providing ancillary service". In 51st Annual Allerton Conference on Communication, Control, and Computing, 551–558. IEEE.

Aggregation Overview

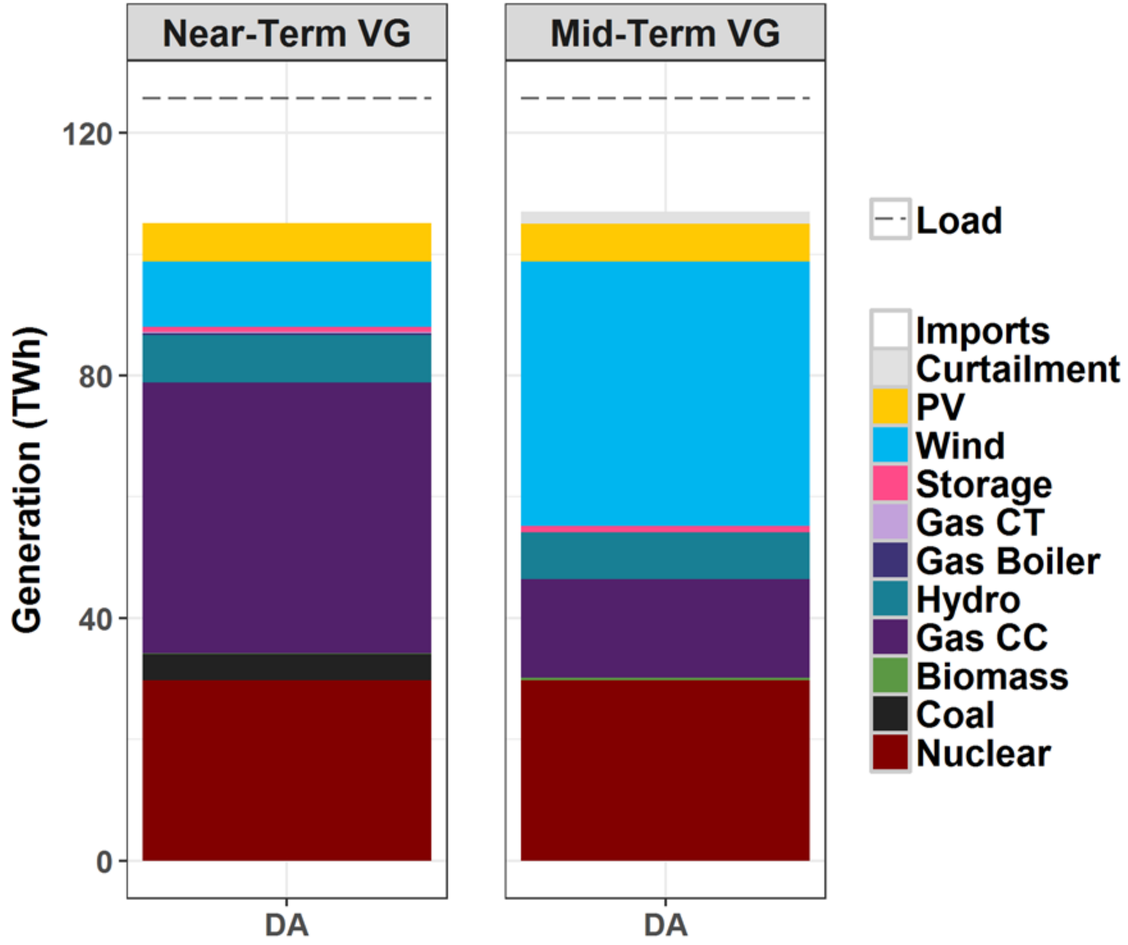
- Naïve aggregation by summing flexibility of water heaters overestimates resource
  - Although difference was not apparent in this study for HPWH contingency responses because they could hold response for full event period
- We can compute provably dispatchable “inner approximations” of aggregate resource
  - Works reasonably well for single time points and constant parameters
  - At least given the mathematics we have now, produces overly conservative estimates for energy shifting, when we can compute them at all (only done for ERWH in this study)

Contingency Resource & Grid Impact

Two models of possible future power systems for ISO-NE

- Production cost (operational) PLEXOS models of ISONE extracted from SEAMS Study[1] (2024 and 2038)
- Wind and solar are the predominant forms of variable generation (VG)

[1]https://www.nrel.gov/analysis/seams.html



Clean Share (%)	52	82
RE Share (%)	24	56
VG Share (%)	16	49

Contingency (Spinning) Reserves

- Contingency reserve resources must be ready to increase generation or reduce load in response to unexpected outages
- Response needs to be fast—within 10-30 minutes
- Response duration is typically on the order of 1 hour
- Magnitude of resource might be reasonable proxy for capacity credit, after filtering down to highest net-load* hours

Question: How much could electric resistance water heaters contribute to spinning reserves in ISO-NE?

*Net-load is often calculated by subtracting variable renewable (VRE) generation from load

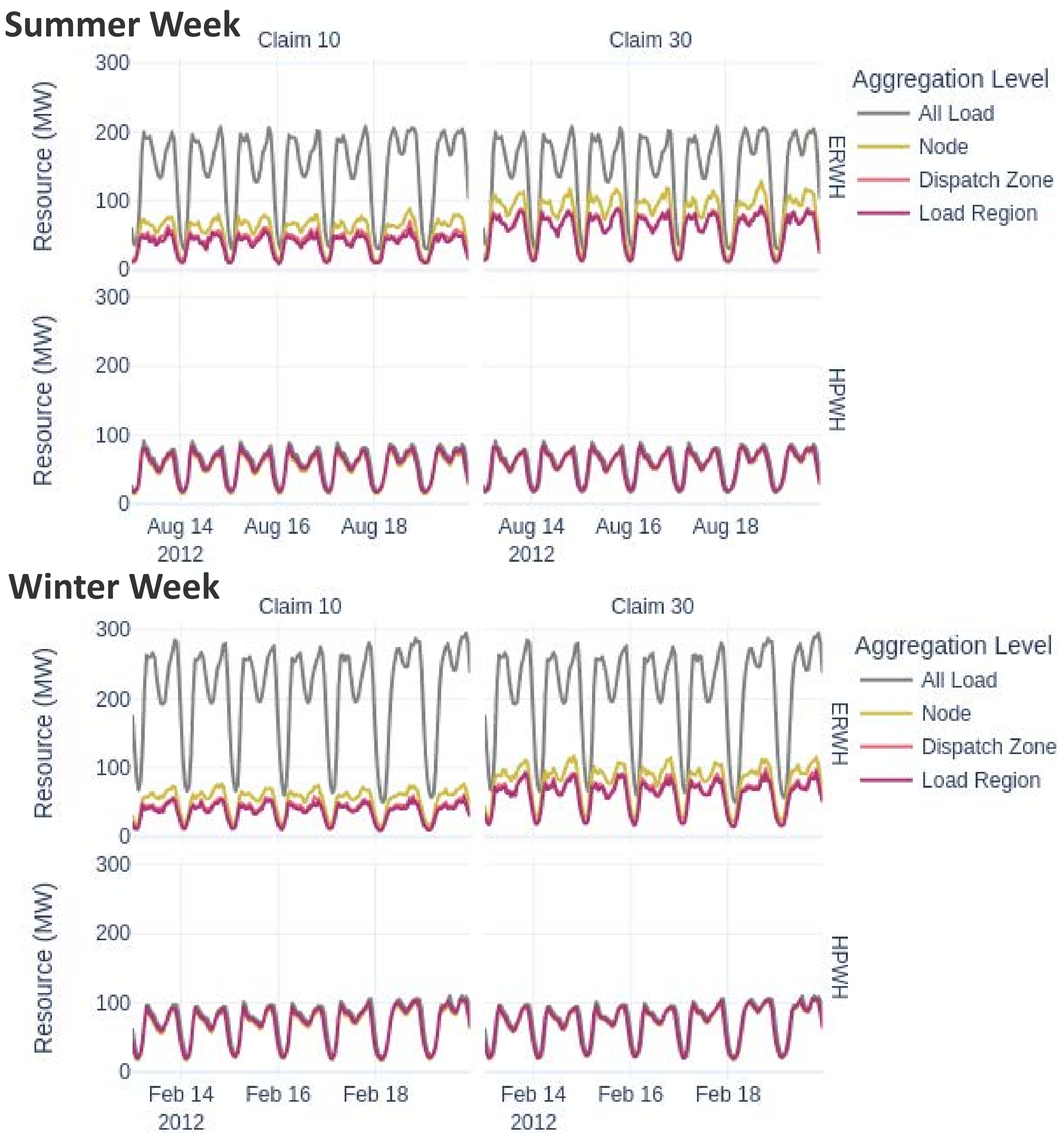
Resource Profiles

Annual Contingency Reserve Resource Summary

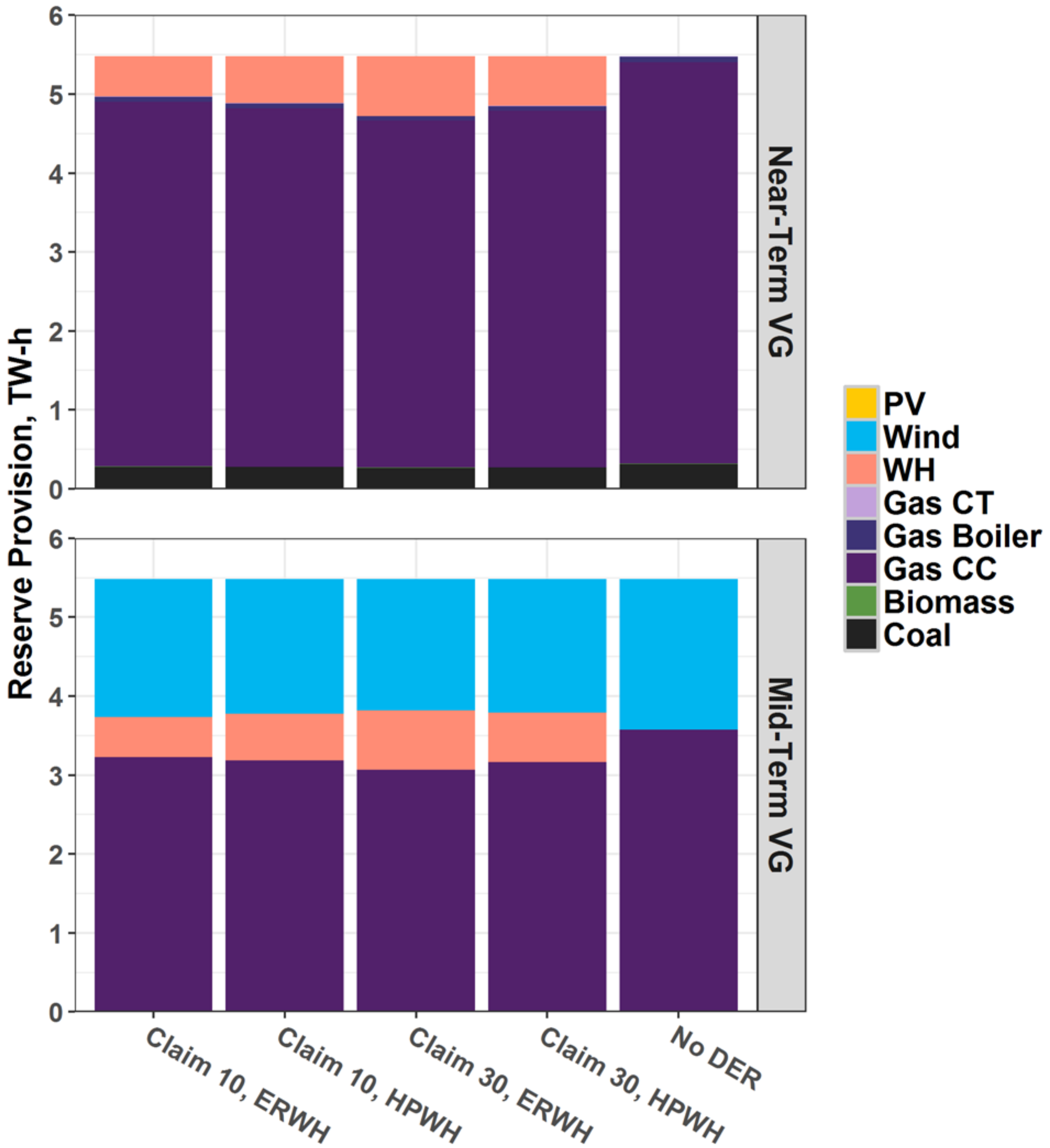
- ERWH nodal resource 0.81 – 1.2 MWh/water heater
- HPWH regional resource 0.96 – 0.99 MWh/water heater

Capacity Value

- Resource profiles like those shown here could be used to estimate ability of water heaters to reduce (net-)peak load



Water heaters provide contingency reserve, displacing Gas CC and Wind generators



Shifting Resource & Grid Impact

Evaluation of Shifting Service

- Create individual surrogate models with $\overline{T}$ = 145°F and $\underline{T}$ = 105°F
- Create aggregate ERWH surrogate models
  - Much more difficult and complex than for contingency because we need a consistent aggregation across a whole day
  - Worst-case parameter selection necessitates clustering heaters with similar profiles and still results in very conservative estimates
- Dispatch individual surrogate models and aggregate surrogate models against day-ahead prices from our ISONE models
- Dispatch aggregate models directly in the day-ahead ISONE models
- Evaluate supply-side impacts by running real-time ISONE models with load changes induced by water heater energy shifting

Shifting Resources and Mid-Term VG Price-taking Results

FERC Order 2222 Minimum Size is 0.1 MW

Water Heater Type	Aggregation	No. Models	Weight	Shiftable Load (GWh)	Shiftable Load (%)	Shifted Load (GWh)	Shifted Load (%)	Median Energy Capacity (MWh)	Median Power Capacity Up (MW)	Median Power Capacity Down (MW)	Profit per Water Heater ($/WH-yr)
HPWH	None	2708	228.6	640	100	336	52	0.003	0.001	0.001	23
ERWH	None	2640	228.6	1547	100	653	42	0.002	0.001	0.001	40
ERWH	k240	240	1	537	35	77	14	38	4.5	30.0	4

- HPWHs (all 80 gallons) use 60% less energy but capture about 50% of value compared to ERWHs (20 to 60 gallons)
- ERWH aggregation creates MW-scale resources, but they underperform in terms of value capture (10% of profits with 35% of shiftable load)
- ***ERWH results subject to change based on ResStock ERWH power capacity fix (Slide 10).***

Price-taking Dispatch Profiles

- Energy use is shifted away from morning and evening residential peaks
- There are some differences by season and grid condition
- Aggregate resource is not able shift as much as represented load would indicate because of energy bounds

Conclusions

Key Findings - 1

- The difference in physical configuration and control logic between ERWHs and HPWHs in ResStock EnergyPlus simulations significantly impact flexibility estimates (and methods). **These results were also impacted by a ResStock bug that assigned too-small power capacities to ERWHs (https://github.com/NREL/resstock/pull/804).**
- Physically accurate and validated (against EnergyPlus) aggregation methods enable realistic 8760 estimates of contingency resource from electric water heater load reductions based on a single ResStock run
- **ERWHs could provide 0.8 MWh/yr to 1.2 MWh/yr of contingency reserve per water heater** depending on expected length of response (50 minutes to 30 minutes, respectively) and subject to revision once power capacities are fixed.
- **HPWHs could provide about 1 MWh/yr of contingency reserve per water heater**, subject to the caveat that in this study all HPWH models were 80 gallons.

Key Findings - 2

- Aggregating flexibility for energy shifting service is significantly more challenging. If we group ERWHs by baseline power and energy profiles and then aggregate in a provably dispatchable way, we can present up to 35% of the load for energy shifting but dispatching the flexibility in a price-taking sense only captures about 10% of the profits captured by dispatching the individual water heaters' flexibility.
- **Shifting ERWH energy use could capture about $40/yr in price-taking profits per water heater and shifting HPWH energy use could capture about $20/yr in price-taking profits per water heater**, based on dispatching individual flexibility against modeled day-ahead prices (which tend to be less volatile than real-world prices).
- **Overall, based on the current version of ResStock, our models of ISONE grid operations, and various assumptions made in this study, HPWHs tend to over-perform as flexibility resources relative to the amount of load they present to the system as compared to ERWHs**. That is, HPWHs use 60% less energy than ERWHs, but can provide similar amounts of contingency reserves and 50% of the energy shifting profits per water heater. However, this finding might be more attributable to this study's HPWHs' large tank sizes (80 gallons compared to the ERWHs' 20 to 60 gallons), rather than to HPWHs generally.

Thank You

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NREL/PR-6A40-82082

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Backmatter

Surrogate Flexibility Model

ΔS = change in stored thermal energy

Change in State of Charge

$$\Delta S_{t+1} = (1 - \alpha \Delta t)\Delta S_t + \eta \Delta P \Delta t$$

Energy Bounds

$$\underline{\Delta S} = C(\underline{T} - \tilde{T}) \leq \Delta S \leq C(\overline{T} - \tilde{T}) = \overline{\Delta S}$$

Power Bounds

$$\underline{\Delta P} = -\tilde{P} \leq \Delta P \leq P_{max} - \tilde{P} = \overline{\Delta P}$$

Physical parameters

Behavioral parameters

Surrogate Flexibility Model: Simple

$$\Delta S_{t+1} = (1 - \alpha\Delta t)\Delta S_t + \eta\Delta P\Delta t$$

$$\underline{\Delta S} = C(\underline{T} - \tilde{T}) \leq \Delta S \leq C(\bar{T} - \tilde{T}) = \underline{\Delta S}$$

$$\underline{\Delta P} = -\tilde{P} \leq \Delta P \leq P_{max} - \tilde{P} = \underline{\Delta P}$$

$\tilde{T}$ = 125°F (set point)

$\bar{T}$ = 125°F

$\underline{T}$ = 105 °F

$\tilde{P}$ = EnergyPlus baseline power

Surrogate Flexibility Model: Tank T

$$\Delta S_{t+1} = (1 - \alpha\Delta t)\Delta S_t + \eta\Delta P\Delta t$$

$$\underline{\Delta S} = C(\underline{T} - \tilde{T}) \le \Delta S \le C(\bar{T} - \tilde{T}) = \underline{\Delta S}$$

$$\underline{\Delta P} = -\tilde{P} \le \Delta P \le P_{max} - \tilde{P} = \underline{\Delta P}$$

$\tilde{T}$ = **EnergyPlus baseline tank temperature**

$\bar{T}$ = 125°F

$\underline{T}$ = 105 °F

$\tilde{P}$ = EnergyPlus baseline power

Inner Aggregations

- For the aggregate
  - $L(t)$ represents change in storage level (aggregate over $\Delta S_k(t)$ for individual water heaters k)
  - $U(t)$ is similarly analogous to $\Delta P_k(t)$
- Provable disaggregation by assigning each water heater k a fraction β_k of the aggregate's dispatch and setting $L(t)$ and $U(t)$ bounds in a worst-case sense, e.g.

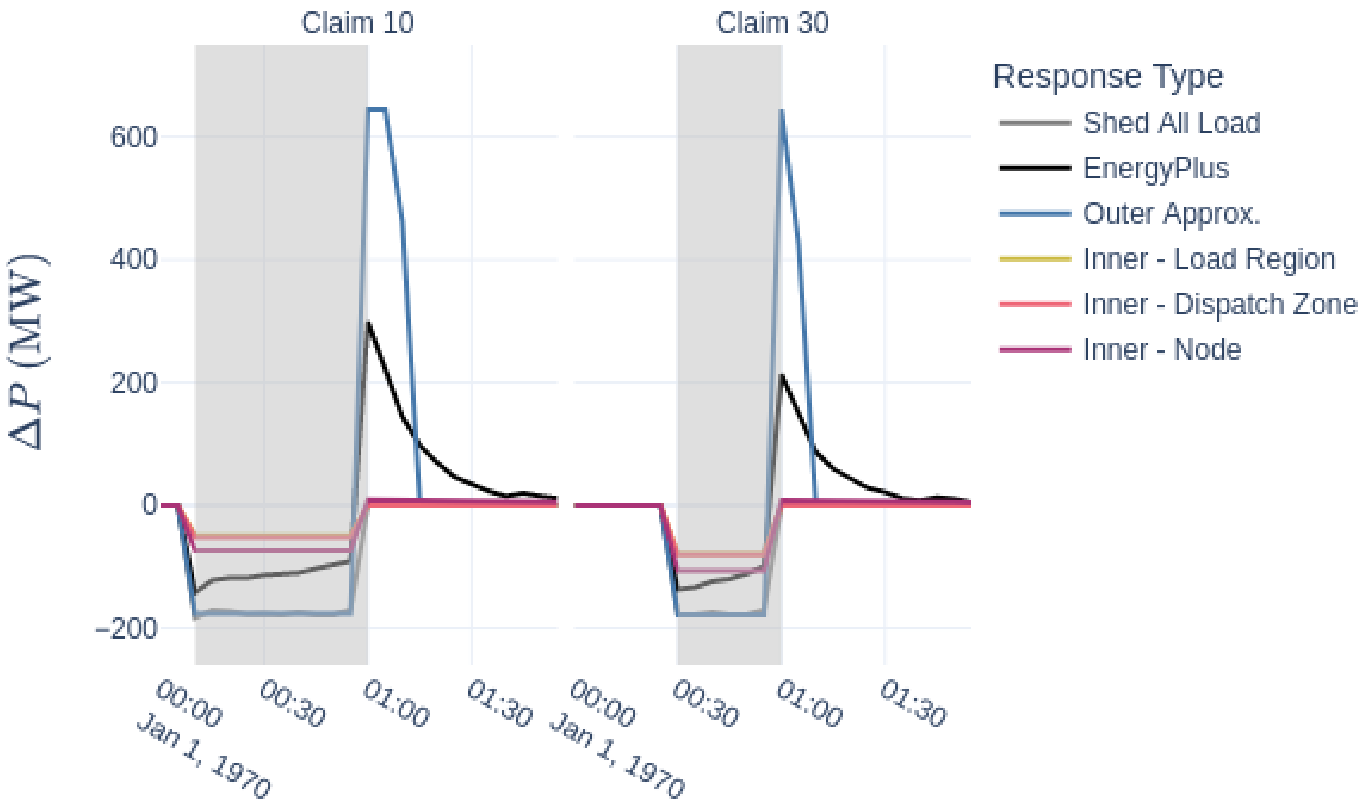
$$\beta_k \underline{L}(t) \leq \underline{\Delta S_k}(t) \quad \text{for all } k$$

- Can calculate β_k for each hour to maximize

$$w\left|\underline{L}\right| + (1-w)\eta\left|\underline{U}\right|,$$

where w is a weighting between energy and power capacity

Inner and Outer Aggregations bound ERWH response

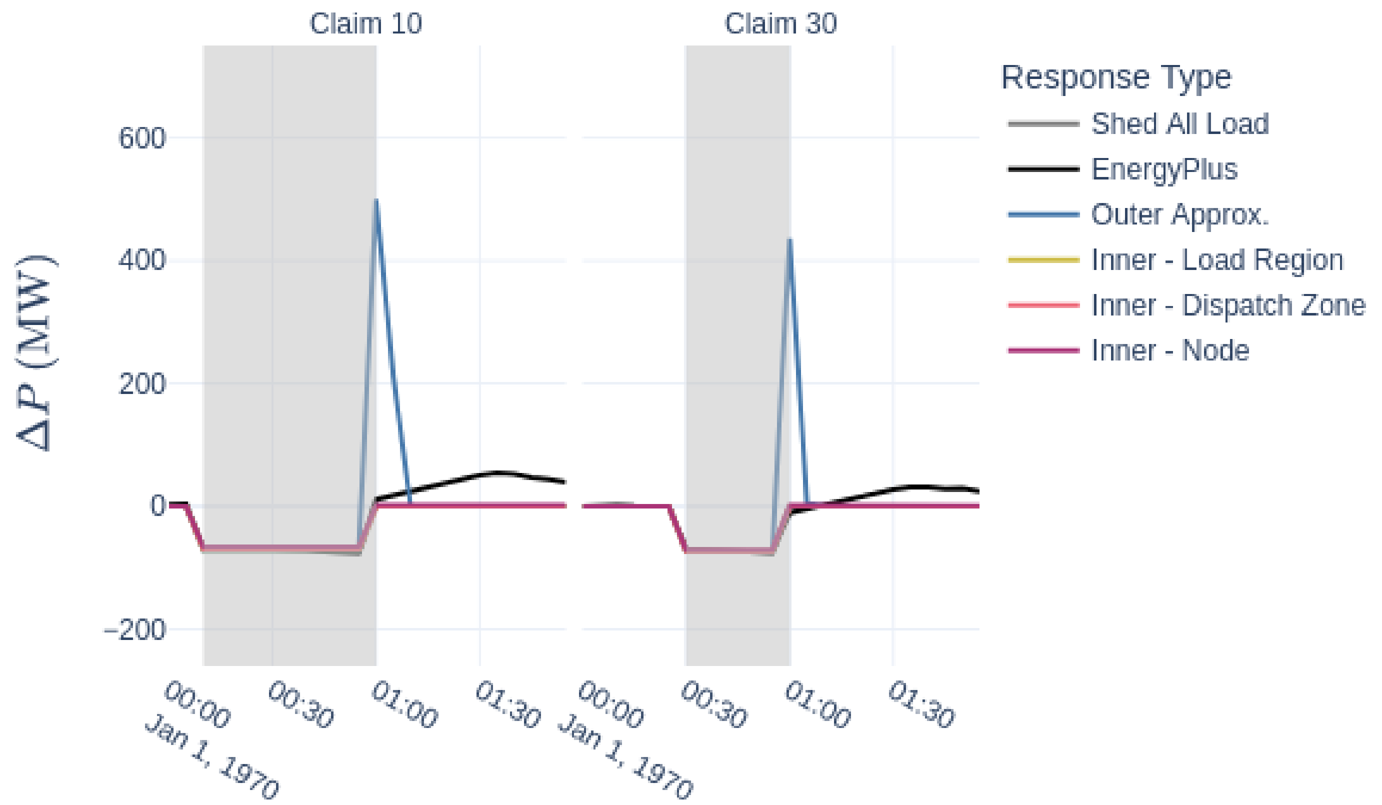


Less aggregation produces tighter inner bounds:

- Node has 783 resources
- Dispatch zone has 19
- Load region has 8

HPWH response well-represented by all aggregation types

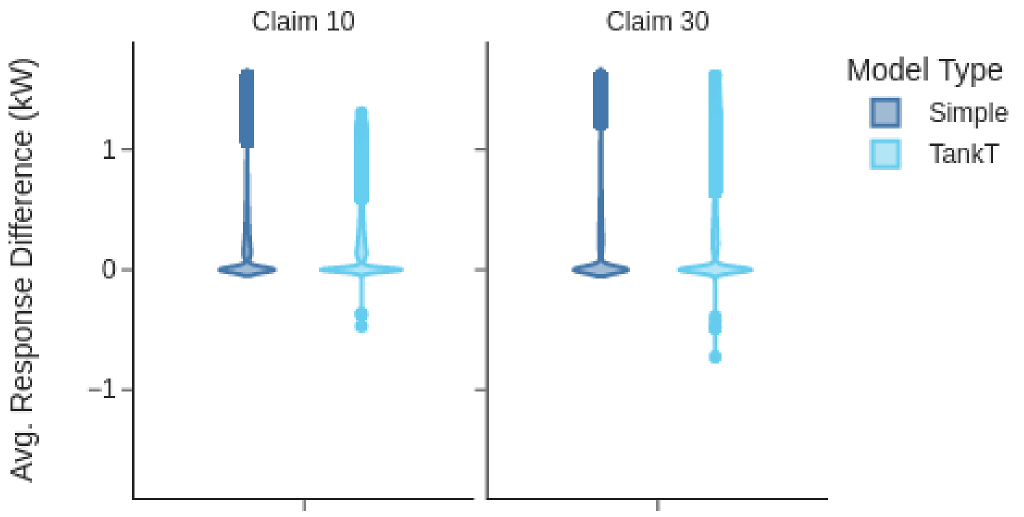
Outer approximation greatly overestimates rebound, but all approximations perform similarly during the response period



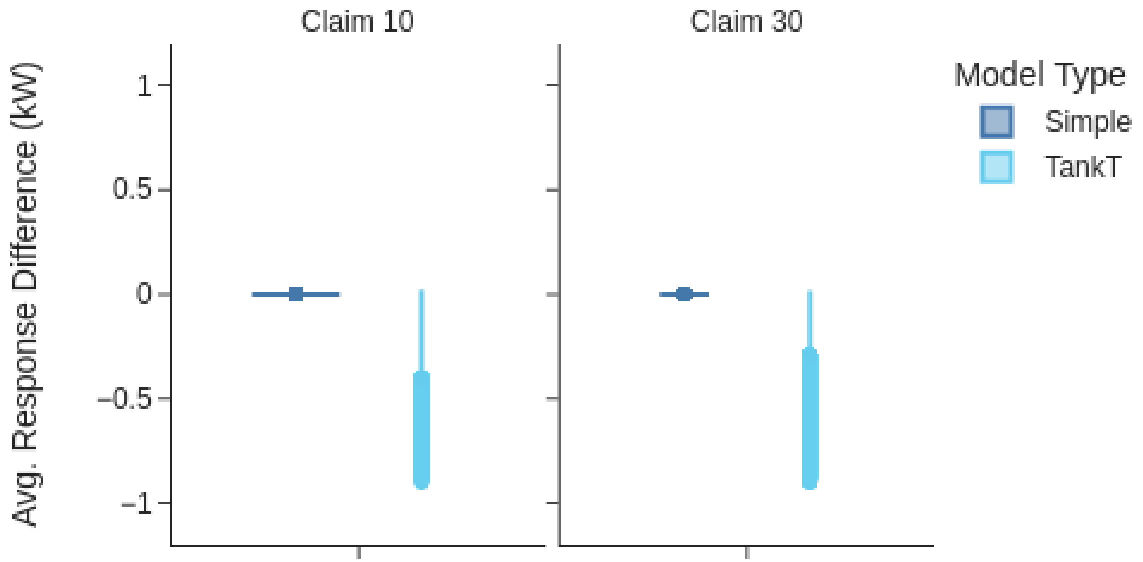
Example validation findings hold in the aggregate

Distributions of surrogate model minus EnergyPlus average kW reductions for events simulated in all hours of the day and for all ResStock portfolio buildings (~2000 samples)

ERWH Simple models always overestimate response whereas TankT models produce errors in both directions and have a higher density at zero error



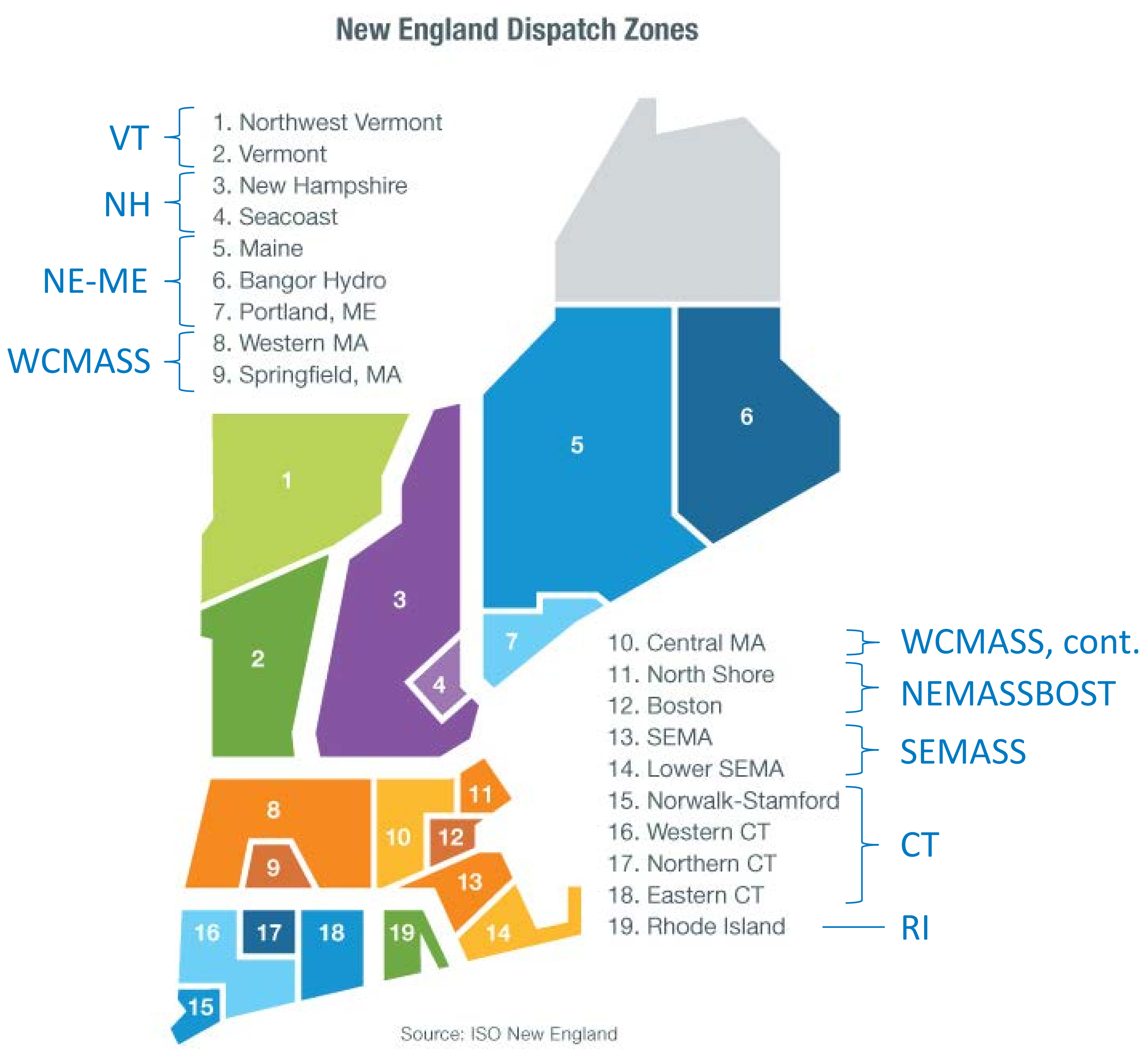
HPWH Simple models correctly capture ability to sustain load reductions for the whole response time; TankT models underestimate response



ISO-NE Power System Geography

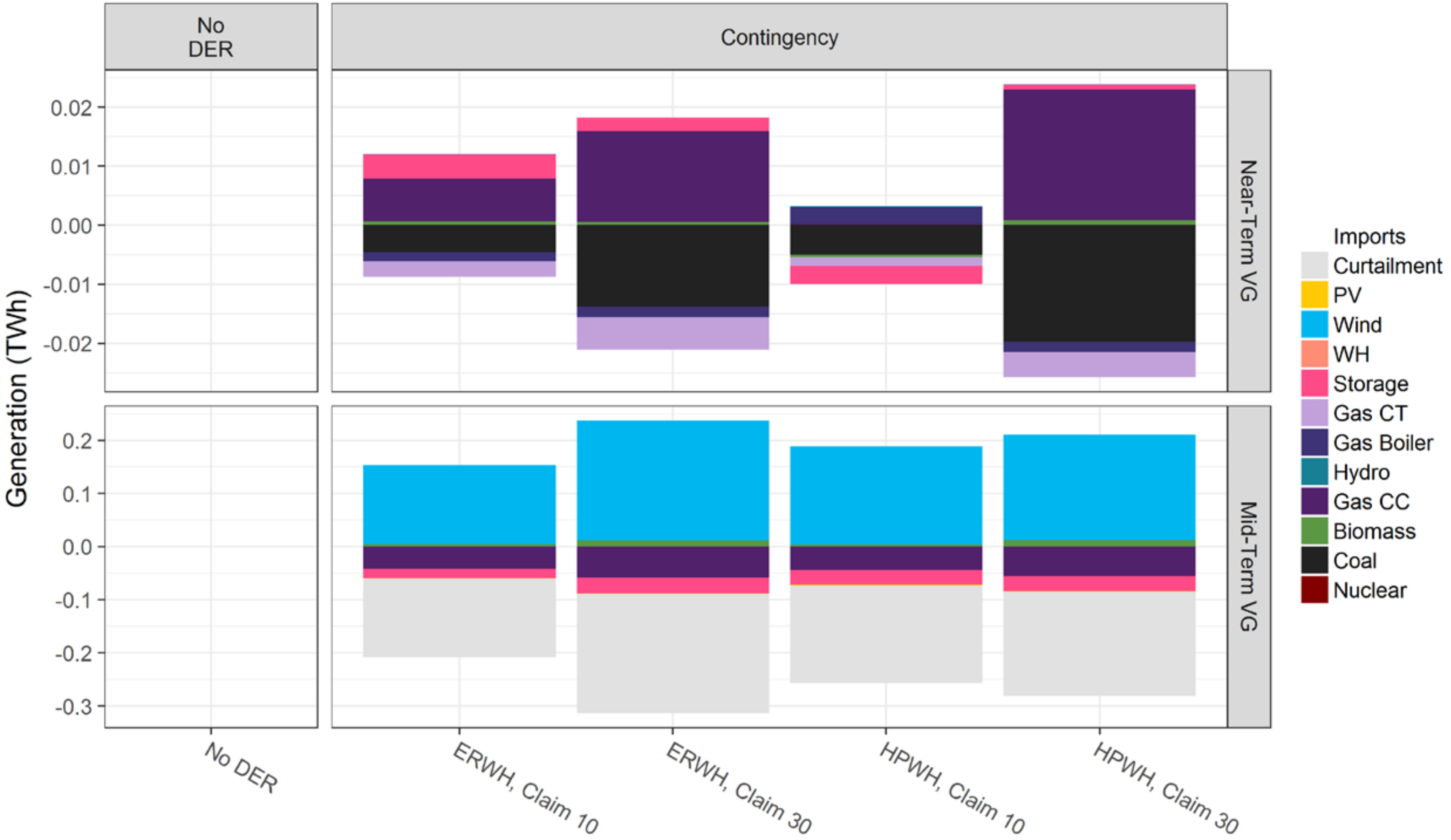
ISO-NE Quick Statistics

- Peak demand has declined from 28 GW in 2006 to 26 GW in 2018
- 121 TWh projected net annual demand (including EE and PV) this year (20 TWh savings from EE and PV)



Water heaters providing contingency reserves impact the ISONE dispatch

- Dispatch impacts are small and mostly displace coal under Near-Term VG conditions
- Dispatch impacts are larger and reduce wind curtailment under Mid-Term VG conditions



Aggregation of ERWHs for Shifting

- Mathematics for constructing provably dispatchable aggregates (a) does not yet apply to HPWHs, and (b) requires β_k constant for the duration of the service
- Worst-case assignment of aggregate bounds implies a need to group water heaters with similar power draw profiles
- **Aggregation procedure applied to ERWHs only:**
  - *Optionally* group water heaters by geography
  - Split timeseries data by day in anticipation of making different collections of aggregate resources per day
  - Apply *k*-means clustering to group water heaters with similar profiles
  - Aggregate resulting groups by assigning a constant fraction β_k to each participating water heater