

Implications of Electrifying Residential Space Heating in Cold Climates with Heat Pumps, Envelope Improvements, and Thermal Storage

Sven Mumme, US DOE Building Technologies Office, Presenter

Co-authors:

Fredericka Brown, US DOE Building Technologies Office

Brett Bass, Bo Shen, Som Shrestha, Joshua R. New, and Kyle R. Gluesenkamp, Oak Ridge National Laboratory

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Getting to Net Zero by 2050 -- Building heating electrification is key

- Replace furnaces with heat pumps (HP)
- Focus on cold climates
 - Homes in cold climate zones comprise 34% of homes in the US, yet consume 60% of fossil fuels for heating

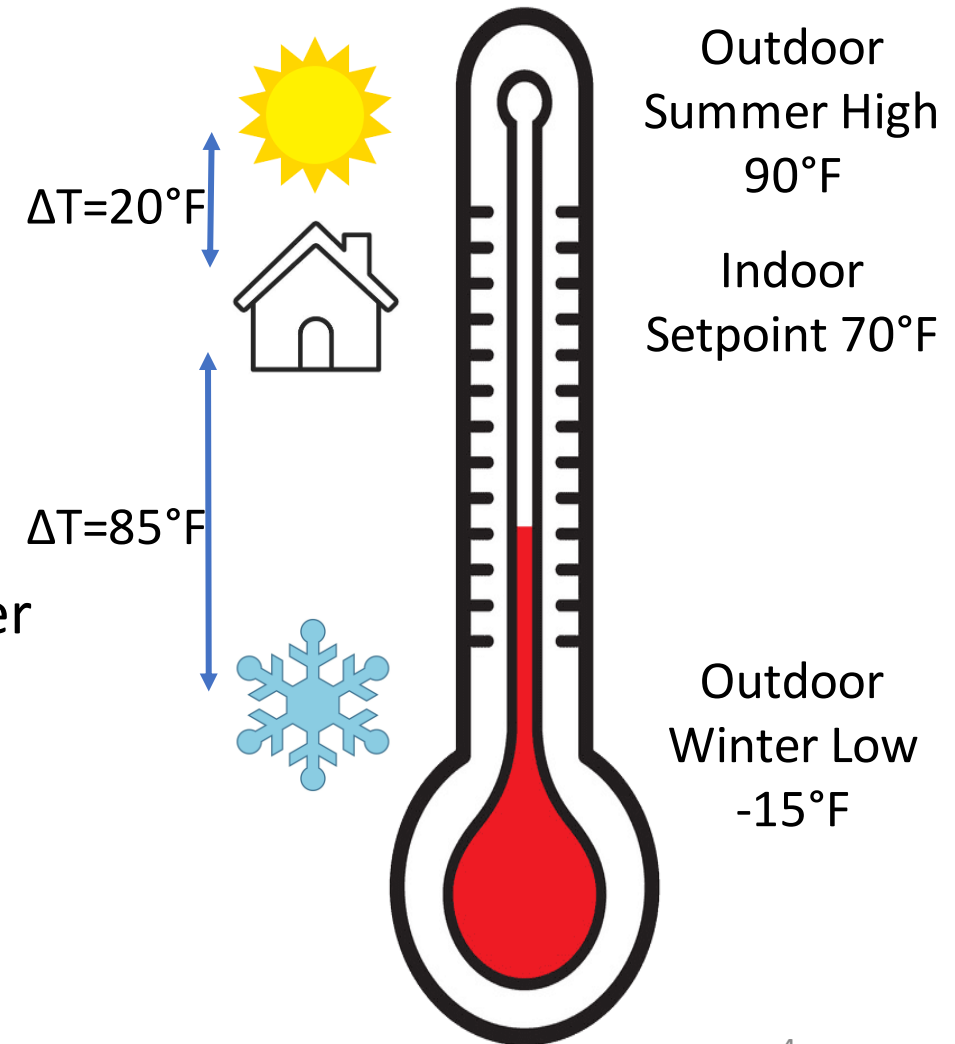


Overview of this work

- *Motivation*: improving envelope and HPs in cold climates is critical to mitigate increased electricity demand for heating.
- *Approach*: we conducted original modeling work in cold climates:
 - Three measures modeled: envelope improvements, cold climate heat pumps (CCHP), and thermal energy storage (TES) with CCHP
 - Results compiled for carbon emissions, peak demand, and cost of energy

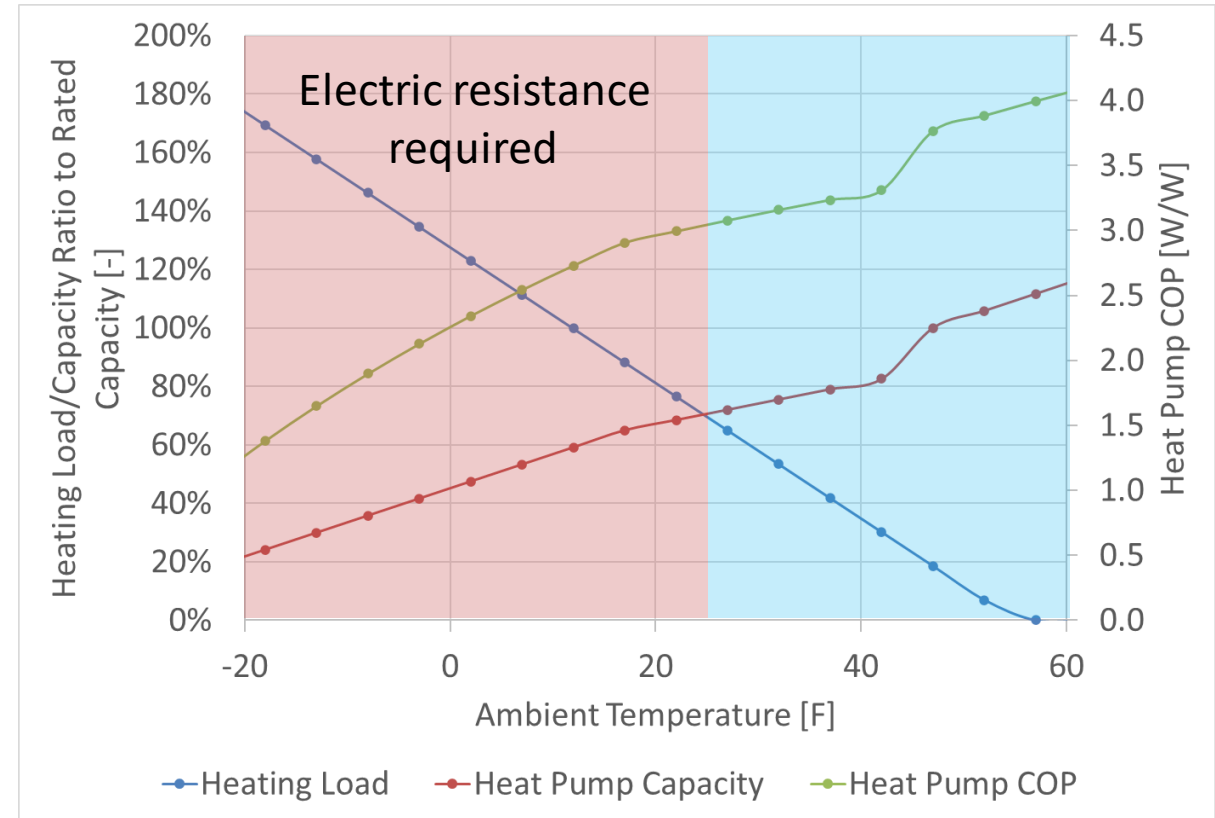
Challenges with heating electrification: Peak

- Many utilities' annual peak demand will occur in winter when heating is electrified
- Winter HP vs. summer AC:
 - Energy consumption is 10 – 46 times higher in winter
 - Peak demand is 2.5 – 6.75 times higher in winter
- Heating electrification leads to much higher winter electrical grid loads



Challenges with heating electrification: Performance

- Coefficient of performance (COP) and capacity drop drastically at low ambient temperatures for a conventional HP
- Electric resistance is required below 25°F for conventional HP

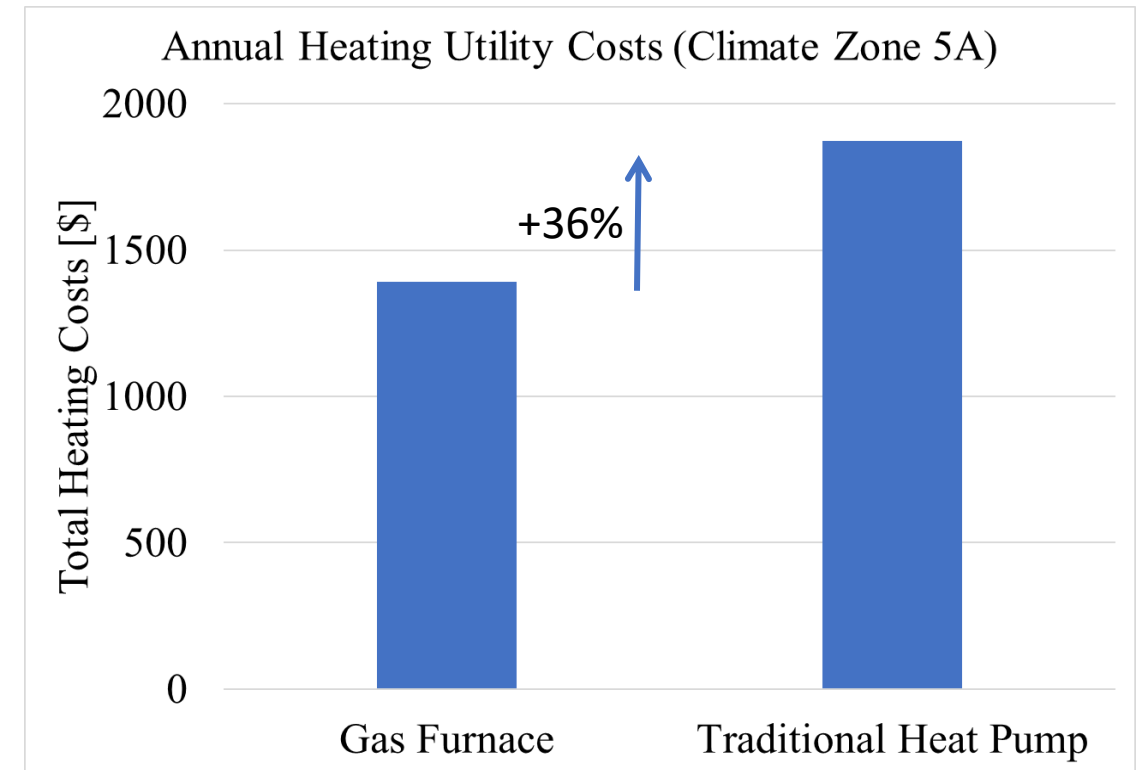


A regular single-speed heat pump in a residential home¹

Challenges with heating electrification:

Operating Costs

- Traditional heat pump has higher utility costs than a gas furnace in cold climate zones:
 - Use of electric resistance is a major driver
 - Differential in energy prices (gas vs. electric) also contributes
- Increased utility cost exacerbates the energy cost burden for low-income households
 - From 8.1% to 9.2% of income, for 36% increase in HVAC utility cost

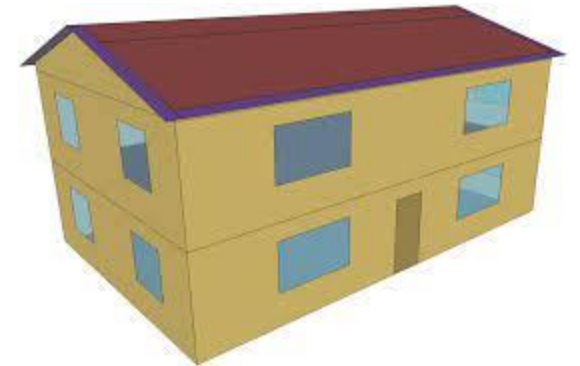


Analysis & Modeling Approach & Scope

- 40 scenarios were analyzed (see table)
- Simulation results for each building were scaled by the number of buildings in each region to estimate regional impact



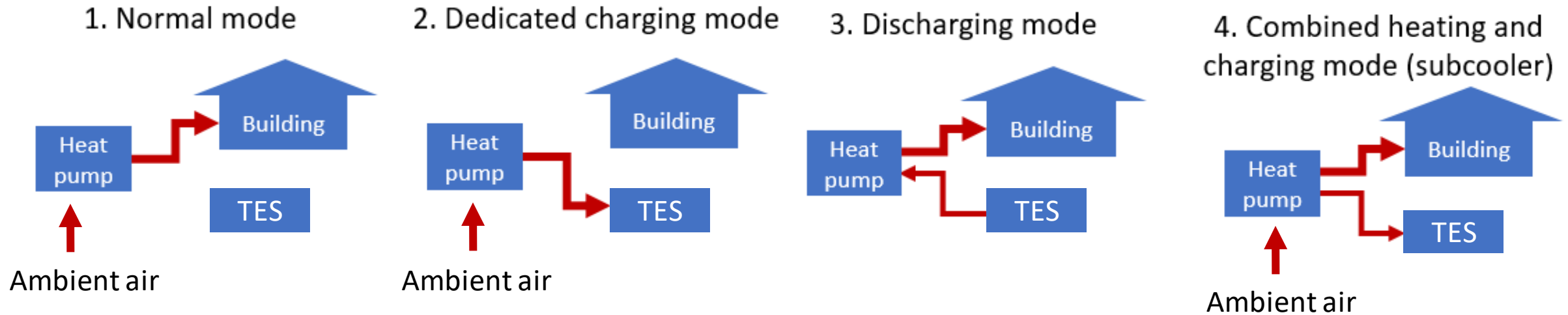
HVAC types	Climate zones (representative cities)	Building vintages
1. Gas furnace (gas, 80% fuel efficiency)	1. 5A (Buffalo, New York)	1. Pre-
2. Traditional HP	2. 5B (Denver, Colorado)	1990
3. CCHP	3. 6A (Rochester, Minnesota)	2. IECC
4. CCHP+TES, discharging TES at 2% lowest ambient temperature at a COP of 6.0.	4. 5B (Great Falls, Montana)	2021
	5. 7 (International Falls, Minnesota)	



Three HVAC models considered in this work

	Conventional Heat Pump	Cold Climate Heat Pump (CCHP)	CCHP + Thermal Energy Storage (TES)
Compressor type	Single-speed	Three speed Capacities: 100%/67%/45%	(same as CCHP)
Rated COP at 47°F outdoor 70°F indoor	3.7	3.8 @ 100% speed 4.0 @ 67% speed 4.1 @ 45% speed	(same as CCHP)
Sizing (autosized by EnergyPlus)	Match building's design cooling load	Middle speed (67%) matches building's design cooling load; top speed reserved to increase capacity at low ambient temperatures.	TES is sized to meet a 4-hour peak load

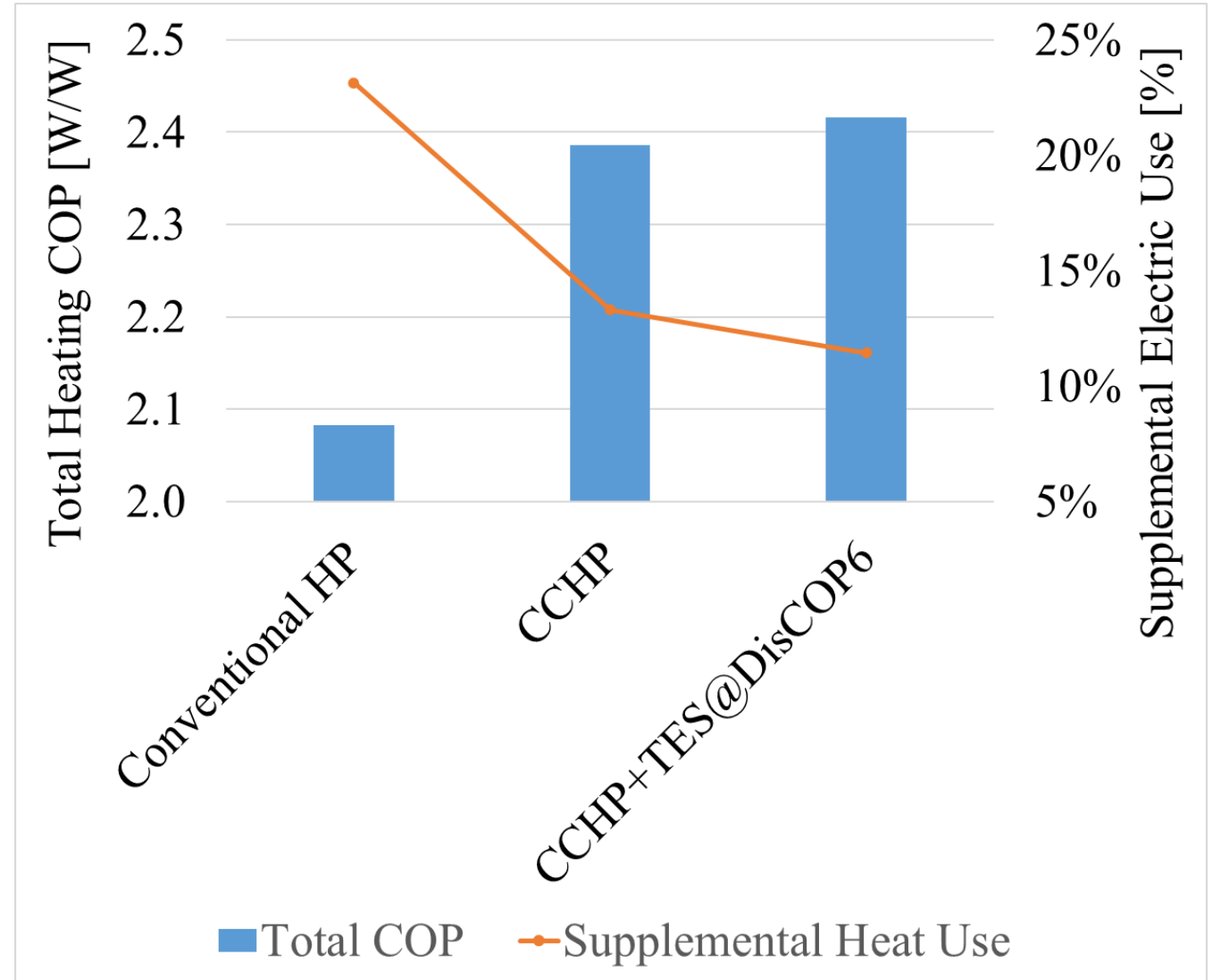
Charging/discharging controls for CCHP+TES



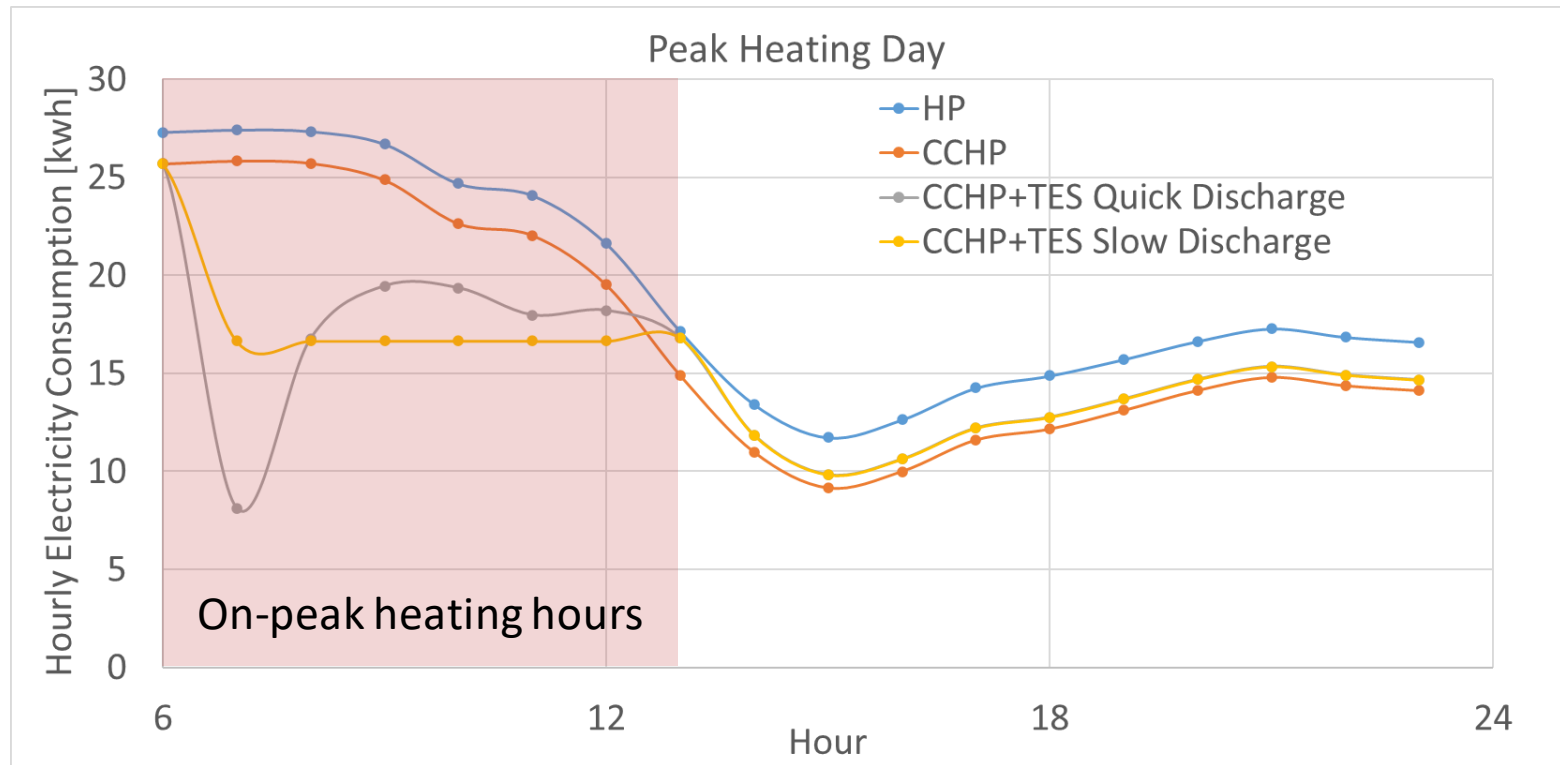
- The TES introduces additional operating modes: the TES must be charged off-peak, and discharged on-peak
- Two charging modes are possible:
 - mode 2 charges fast (using 100% of heating capacity) but less efficiently
 - mode 4 charges slowly (using 10% of heating capacity) but more efficiently
 - Fix bullets to animate same as mode 2!!!

Results: Conventional HP \rightarrow CCHP \rightarrow CCHP + TES

- CCHP is more efficient
 - Reduces supplemental resistance heat at low ambient temperatures (due to larger sizing)
 - Reduces cyclic losses at moderate temperatures (due to low-speed capability)
- TES can reduce supplemental electric resistance heat use and thus slightly improve the total seasonal heating COP

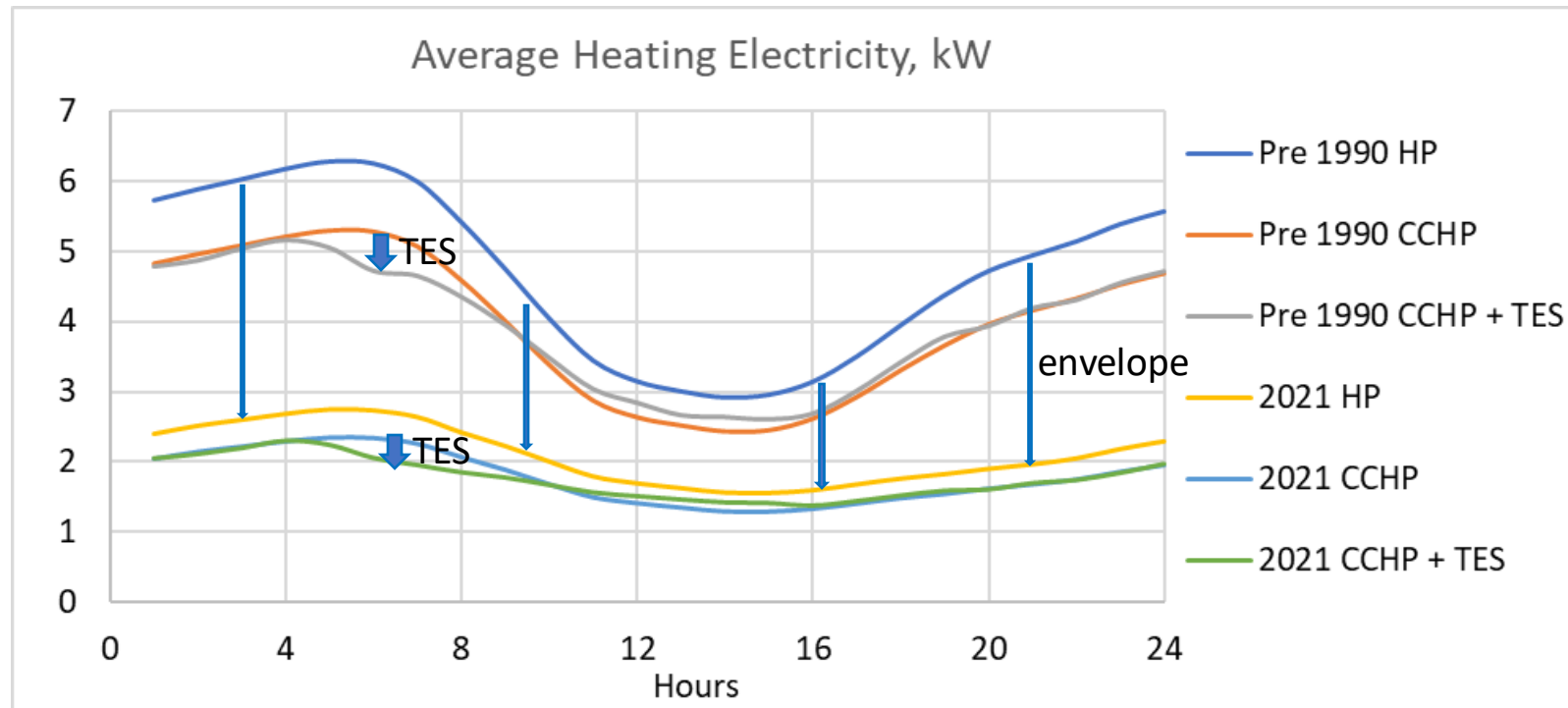


Peak Power Reduction



- Quick discharge to obtain all source energy from the PCM tank during the first peak hours – weather forecast control – 28% peak power reduction
- Slow discharge to average the TES energy use in all the peak hours for 1 day – model-predictive control – up to 40% peak power reduction
- TES not fully charged during peak heating days due to inadequate heat pump capacity.

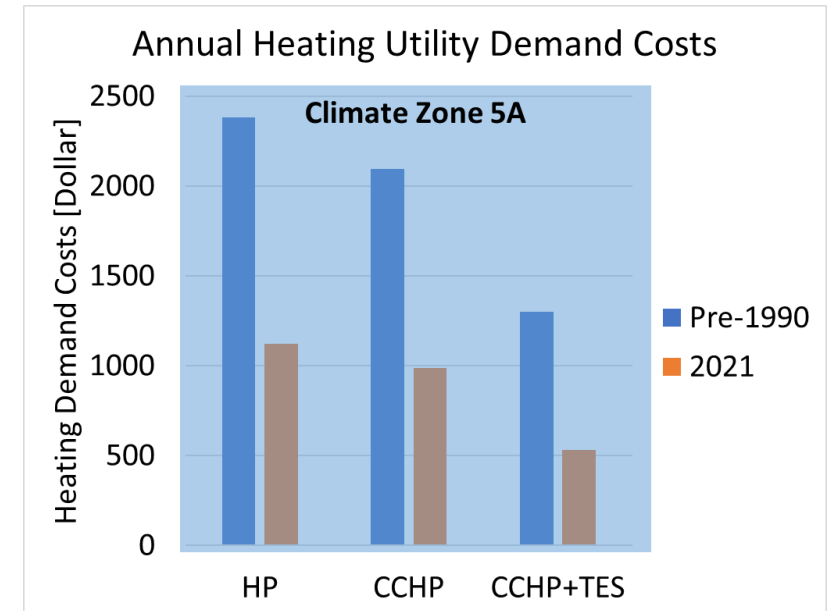
Seasonal Average 24-Hour Heating Power



- 55% reduction in overall heating energy from the envelope improvements |||
- Envelope improvements reduce the peak-to-valley load ratio by about 20%
- TES further reduces peak demand ↓
- Fix animation in PPT!!!!!!!!!!

Utility Cost (Demand)

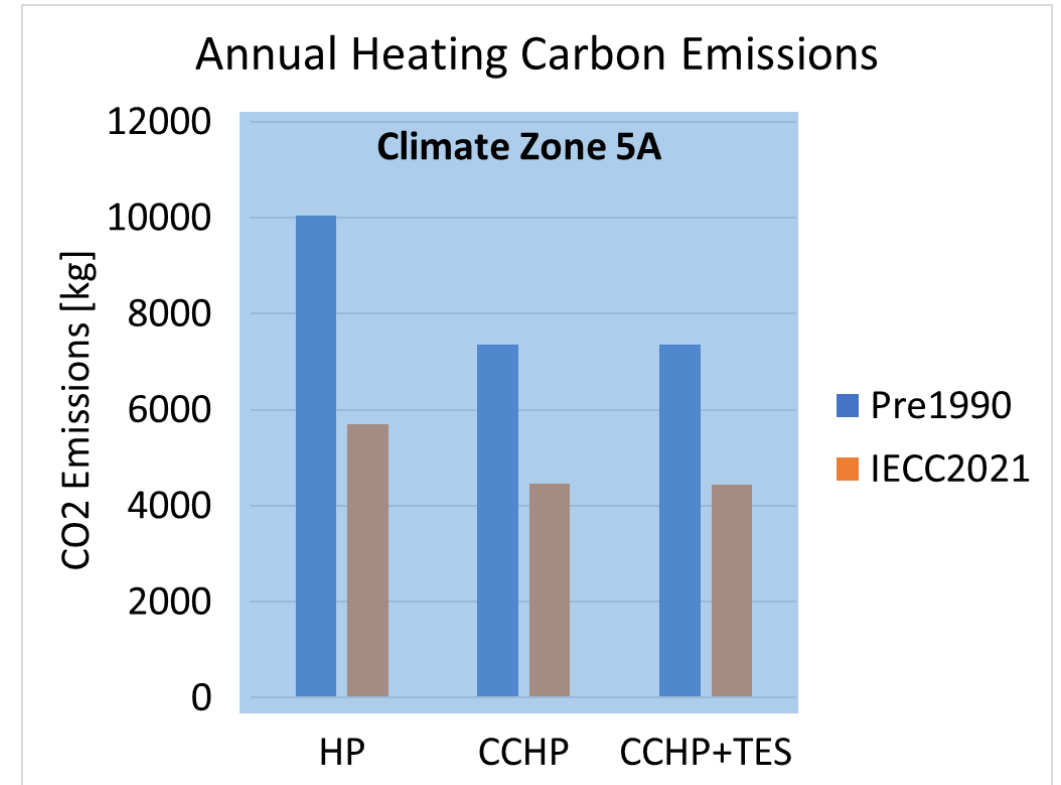
- Demand charges are not present in today's residential electric rates, but here we compute their impact in a residential tariff.
- TES provides significant demand charge savings
- Savings are small in the coldest zones (zones 6 and 7) due to:
 1. A lack of spare capacity for charging
 2. Limitations of the simple modeled control strategy
- About 50% savings switching from HP to CCHP+TES



\$16.82/kW electrical demand charge

Carbon Emissions

- Electricity emissions factors were averaged over cold-climate states
- CCHP leads to lower emissions in moderate cold climate zones (5, 6)
- Regular HP increases emissions for cold climates with current CO₂ emission factor
- About 25% emissions savings switching from HP to CCHP



Average emission factors for cold climate states:
417 g CO₂/kWh electricity
181 g CO₂/kWh natural gas

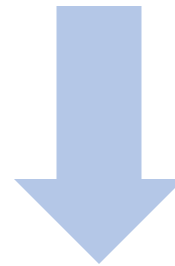
Regional impact

1. **300k tons CO₂** and **\$85 billion** can be saved by updating single-family envelope to newest standard
2. About **15%** energy savings from switching from HP to CCHP
3. About **40%** monthly demand savings from adding TES to CCHP in January
 1. Our analysis showed variable demand savings in different months and climate zones

		Gas furnace (Natural gas)	Heat pump (Electricity)	CCHP (Electricity)	CCHP+TES (Electricity)
Pre-1990	Energy use (TWh/yr)	2,765	1,302	1,111	1,105
	Peak heating demand (TW)	-	0.85	0.81	0.47
	Emissions (Tons CO ₂ /yr)	551,584,212	598,650,862	510,792,811	507,723,699
	Cost (billion \$/yr)	\$137.9B	\$178.7B	\$152.4B	\$151.5B
IECC 2021	Energy use (TWh/yr)	1,265	584	503	499
	Peak heating demand (TW)	-	0.44	0.42	0.24
	Emissions (Tons CO ₂ /yr)	252,436,396	268,590,849	231,390,106	229,169,273
	Cost (billion \$/yr)	\$63.1B	\$80.2B	\$69.1B	\$68.4B

Advanced TES Controls

	Demand reduction with basic controls	
	Zones 5a 5b	Zones 6 and 7
Typical moderate heating day	big	big
Typical cold heating day	big	small
Coldest hour of the year	none	none



Advanced Controls

**TES savings in all climate
zones and all peak days**

Conclusions

- Switching to electric heating requires additional electrical generation, in addition to other electrification efforts.
- Coupling of envelope improvements, cold climate heat pumps, and TES can reduce by over 65% of the amount of new electricity generation required to electrify heating.
- Policies that incentivize coupling of envelope improvements, cold climate heat pumps, and thermal storage can enable electrification.
- Cold climate heat pumps can reduce carbon emissions with today's grid carbon emission factors in cold climate states (conventional heat pumps do not).
- TES charging is challenging at the coldest winter temperatures
 - TES controls are easiest with large diurnal temperature swings. However, the coldest week in the coldest climate can have very small diurnal swings.

Fredericka: Adjust phrasing of bullets to reflect future work
(note from Kyle: I rephrased these as I was working on the transition slide "overview of this work")
Kyle: I've adjusted the phrasing

Future work

- Consider a variety of residential building types (this work focused only single-family homes), as dwelling types vary when accounting for energy burden
- Implement advanced TES control scheme to be based on utility peak
- Develop a framework that will inform electrification policies across the United States as HPs, TES, and high-performance envelope measures are used to facilitate building electrification in cold climates.

Questions?

ACEEE Paper Slide Deck

Outline

- I. Background – Basis for the Study
- II. Methodology – TES and Control Scheme
- III. Scope – How Analysis was conducted in different climate zones
- IV. Results and Discussion – Include individual subsections (cost, energy savings, demand response)
- V. Conclusion – Next steps for Energy Policy Research

Questions to consider:

Gas price vs. electricity price

There is a lot of talk about electricity prices are increasing... (importance of envelope upgrades)

In summer, yes electricity is increasing. We'll see in the winter if gas prices will spike as well (EIA projections for gas prices)

Demand charge for electricity in heating season – can not prepare for that trend; might make it worse without TES

Only 1% of residential buildings have a demand charge (future work – commercial buildings do currently have demand charges. This makes this work applicable to them immediately)

Modeled single family homes, but for underserved communities we should also have a focus on multifamily homes (this is an extension)

Results would be consistent in other home types; TES systems might not be as large

Can extend analysis to other building types as well

Per building – increased savings with increased loads based on the size of the systems

CO2 emissions – heat pumps are worst in climate zones 6 or 7 vs. natural gas

reduce emission from heat pumps with a cleaner grid causing a shift

How will electricity consumption skyrocket? Not a huge difference based on the figure in the paper. (make this clear in the presentation)

Figure 3. Gas furnace is high compared to everything else

Comparing gas and electricity in kWh –

If you magically convert all natural gas furnaces over a time period you will need X% more of your electricity generation on the building side; prime opportunity to ensure that additional generation capacity will be clean

Since it's 3Xs as much that means that it is practically a clean grid because it dilutes everything else (the non-clean stuff)

Gas is more reliable than electricity – for example in natural disaster cases; thoughts on resiliency?

Continued improvement in smart grid technologies; TES can add resilience if heat pumps are developed with resilience modes; especially if you can use a partial capacity with TES and with some battery storage

Gas furnaces also need electricity to run blowers

Anisotropic building envelope energy resilience study

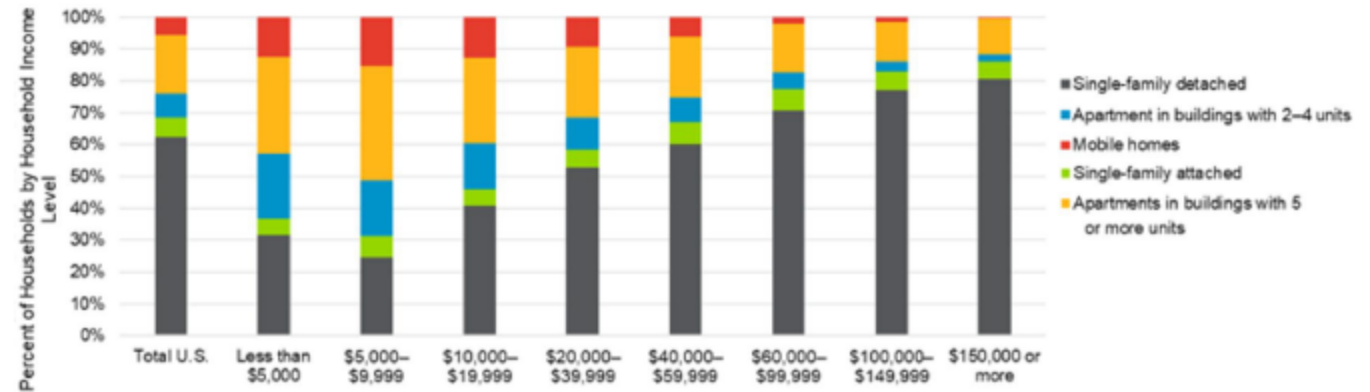
Section Assignments

- Bo
 - Methodology
 - Demand Results
- Brett
 - Outline
 - Energy Results
 - Cost Results
 - Regional Results
- Som
 - Outline
 - Demand Results
- Fredericka
 - Background/Motivation

Presentation Guidance

- Your Panel Leader may ask to preview your presentation and may have other helpful suggestions.
- 1. Length of Presentation:
 - For sessions with three (3) presentations, you will be allowed 20 minutes for the presentation and 10 minutes for questions and answers. We recommend no more than a maximum of 20 slides for a presentation (one per minute).
- 2. Presentation Format:
 - a. no more than five (5) bullet points per slide
 - b. no less than 20 pt. size for text
 - c. high contrast background with text (black text on white or white text on dark blue, etc. as long as the contrast is sharp)
 - d. simplified graphics – avoid complex backgrounds

Note from Kyle: This figure was in the future work side – does it really belong there?



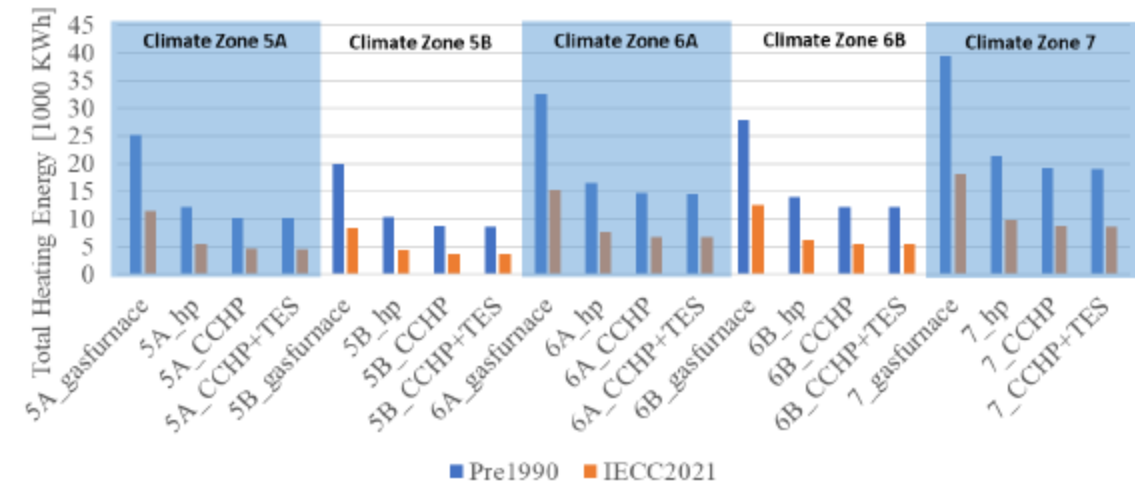
Data from EIA 2022b, figure from Young et al. 2022.

TES ambient temperature-based control

- . Weather forecasts a temperature range (0%–100%, from lowest to highest temperature) in the next 24-hr.
- . Run discharging mode when the TES is not fully discharged, the hourly ambient temperature is below 2% (coldest time), and the building is calling for space heating.
- . Run combined space heating and subcooler charging when there is a space heating call, and the TES is not full.
- . Run dedicated charging when there is no space heating call and ambient temperature is 80%–100%.
- . Run normal heating mode all other times when responding to a space heat call; supplemental heater will be called if needed.

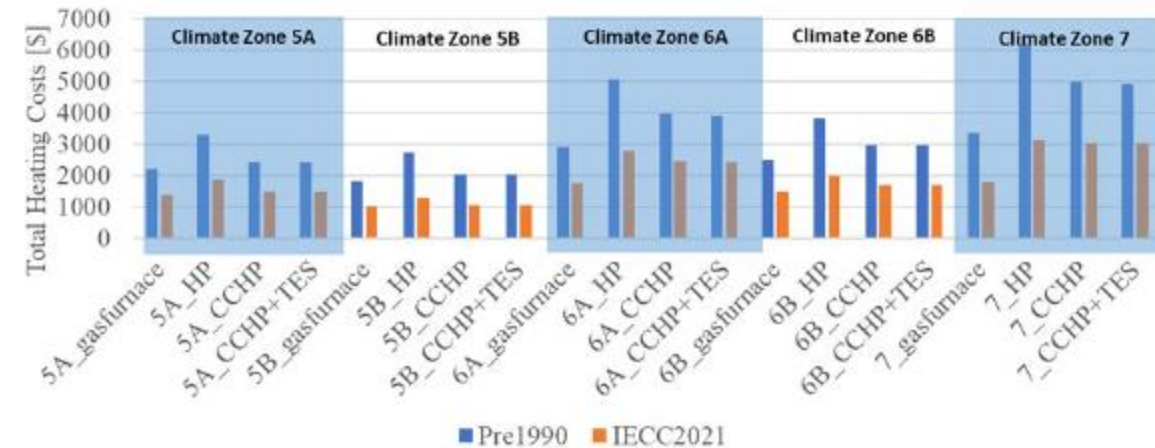
Heating Energy Use

- Gas furnace uses most energy for each climate zone
- Significant energy savings (~50%) by upgrading building to newest standard
- No major difference between CCHP, CCHP+TES for annual energy consumption



Utility Cost (Energy Consumption)

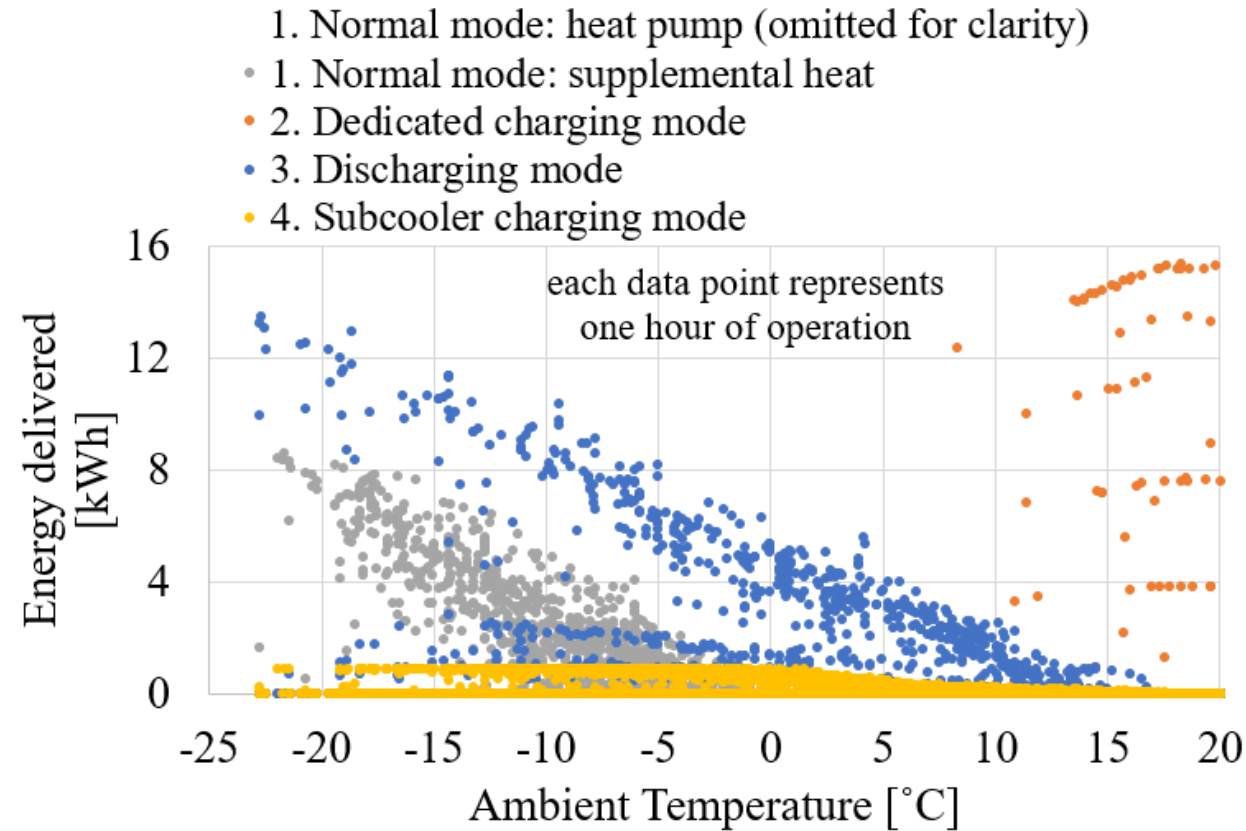
- No demand cost included
- Gas furnace currently most cost effective (especially in coldest climate zones)



13.72 cents/kWh electricity

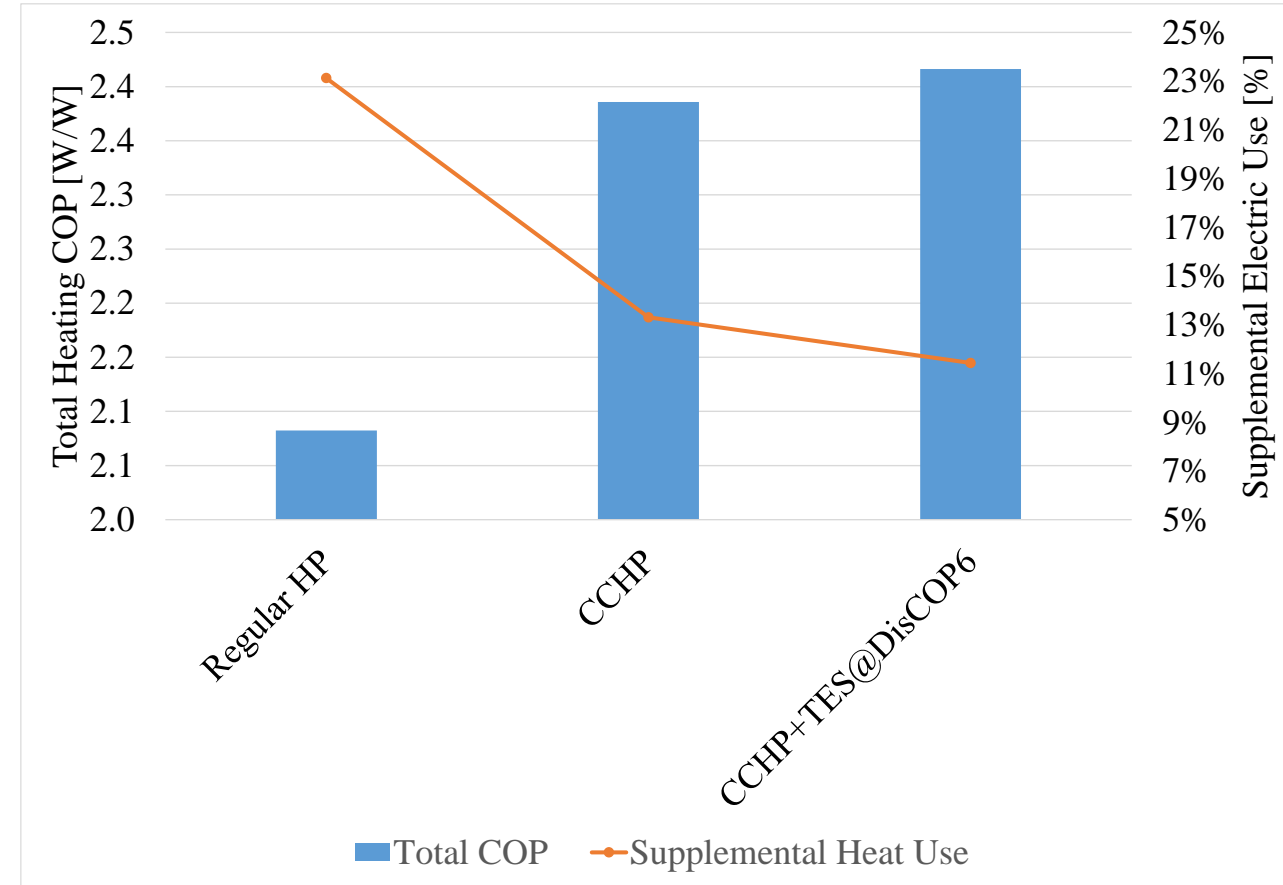
4.99 cents/kWh natural gas

Energy Allocation



Single-family house in Indianapolis, IN

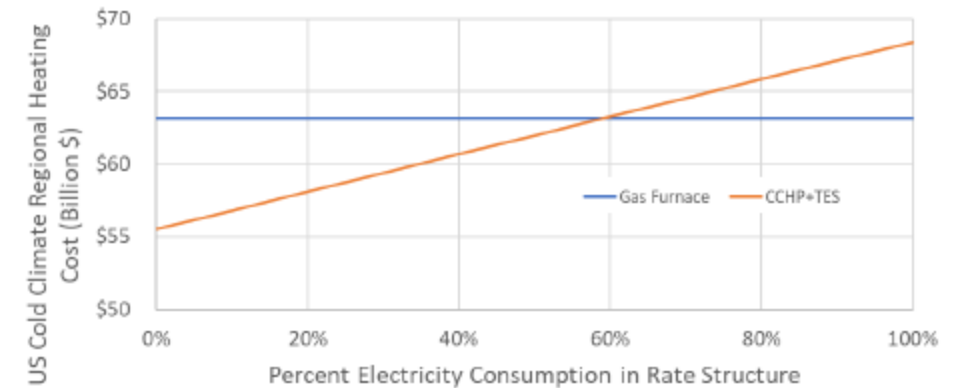
TES can reduce supplemental electric resistance heat use and thus slightly improve the total seasonal heating COP.



Regional Impact (Demand Charge)

- Electrical demand may become more common in future residential utility rate structures
 - Currently mainly commercial
- As the percent of demand in utility rate structure increases, TES becomes increasingly viable

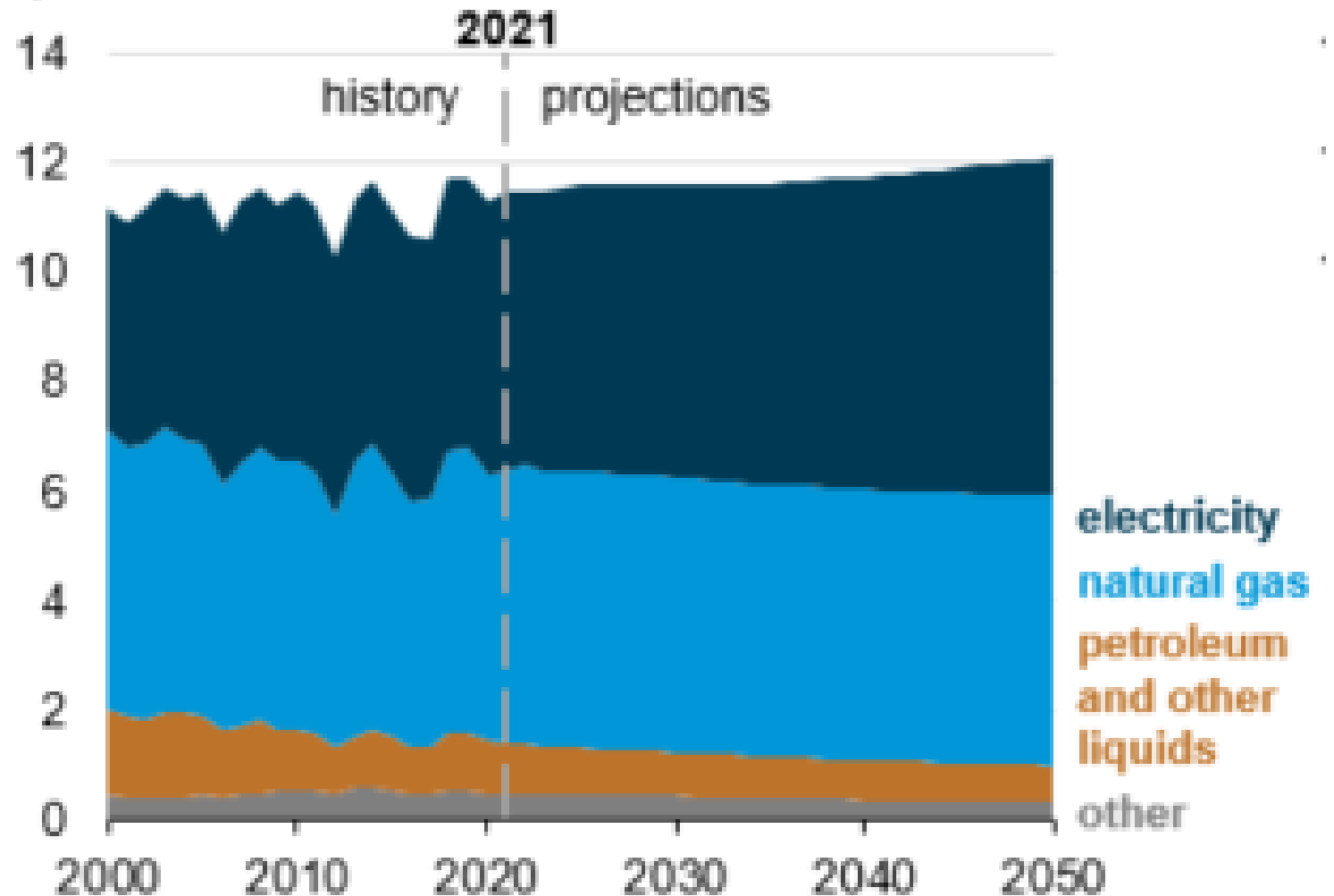
		Gas furnace (natural gas)	HP (electricity)	CCHP (electricity)	CCHP+TES (electricity)
Pre-1990	Energy use (TWh/year)	2,765	1,302	1,111	1,105
	Annual demand (TW)	-	5.12	4.67	3.56
	Emissions (tons CO ₂ /year)	551,584,212	598,650,862	510,792,811	507,723,699
	Cost (\$ billion/year)	137.9	178.7	152.4	151.5
IECC 2021	Energy use (TWh/year)	1,265	584	503	499
	Annual demand (TW)	-	2.43	2.22	1.59
	Emissions (tons CO ₂ /year)	252,436,396	268,590,849	231,390,106	229,169,273
	Cost (\$ billion/year)	63.1	80.2	69.1	68.4



Electricity Consumption

Residential sector delivered energy consumption AEO2022 Reference case

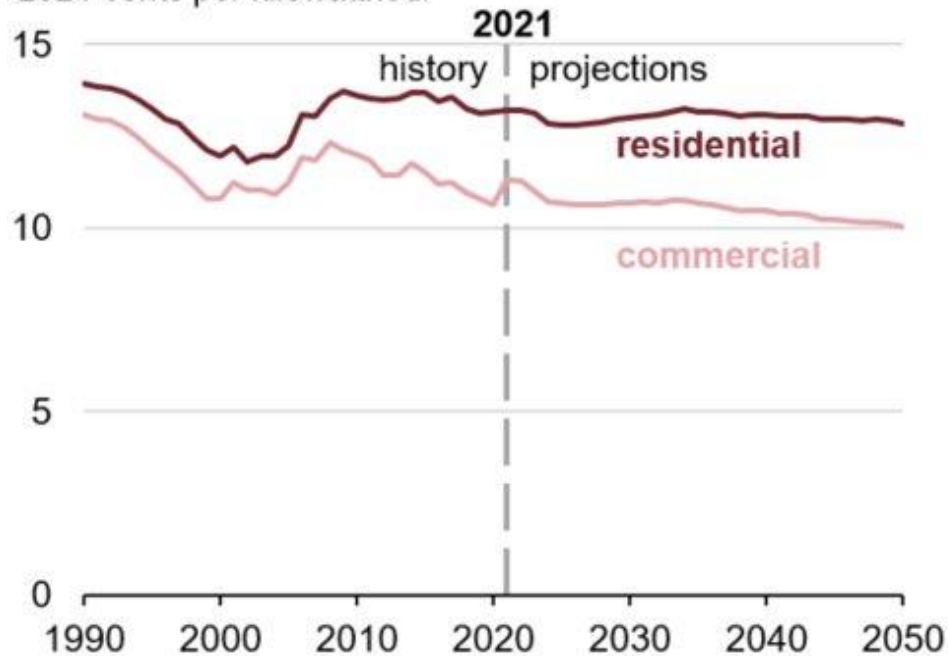
quadrillion British thermal units



Electricity prices in the residential and commercial sectors

AEO2022 Reference case

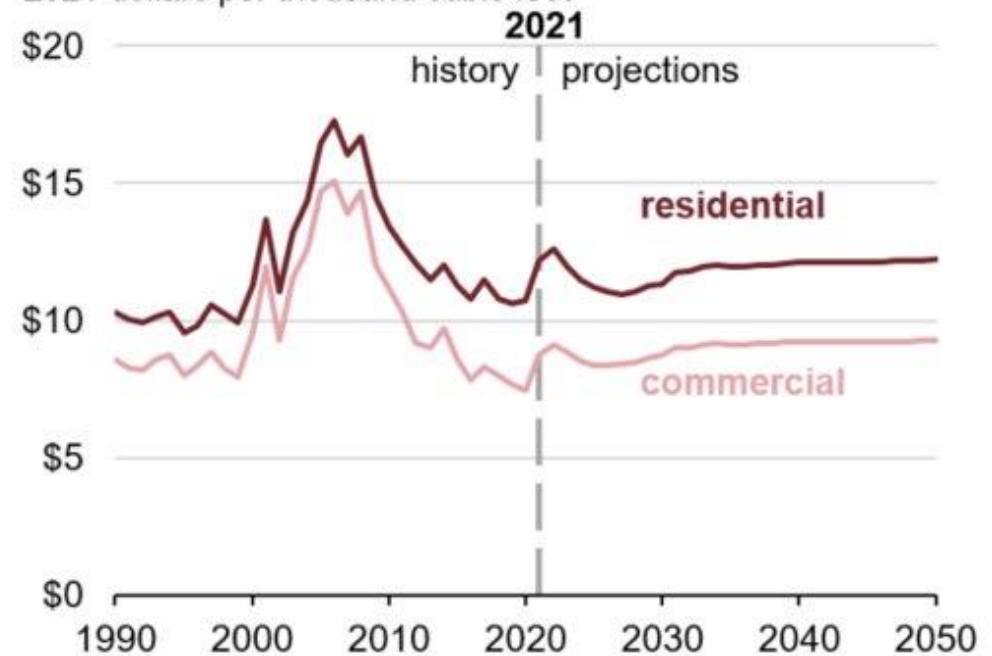
2021 cents per kilowatthour



Natural gas prices in the residential and commercial sectors

AEO2022 Reference case

2021 dollars per thousand cubic feet

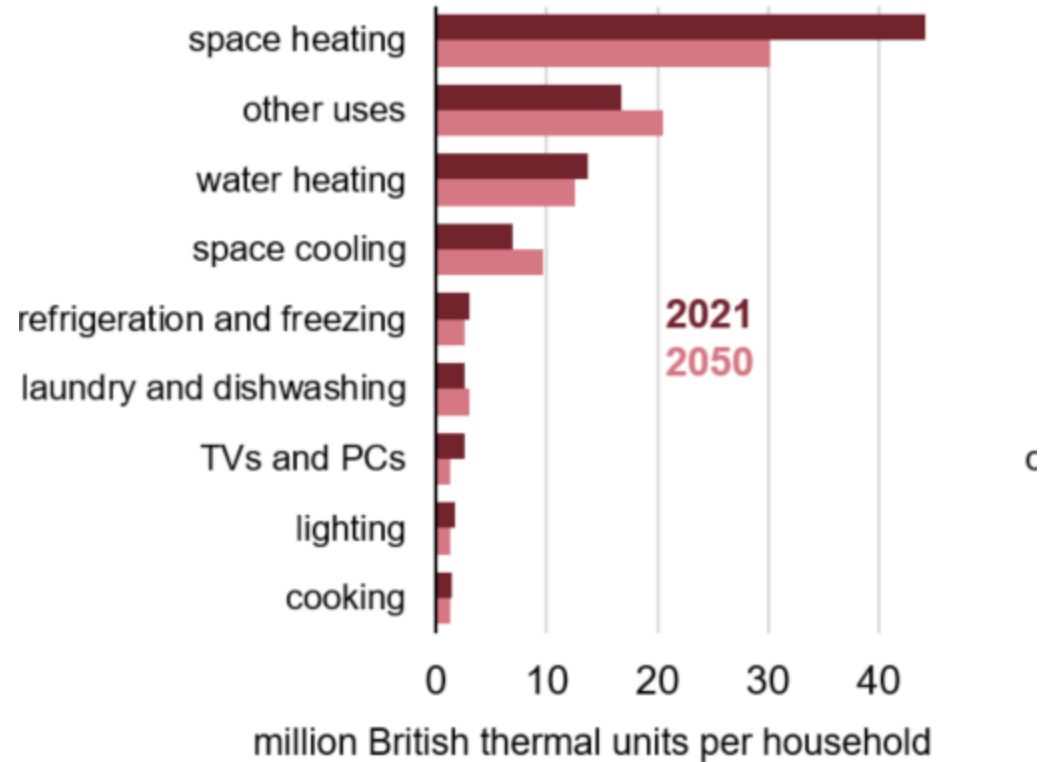


Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

www.eia.gov/aeo

Electricity and Natural Gas Prices

Residential energy intensity by end use AEO2022 Reference case



Note: Intensities reflect all energy sources consumed, including both purchased electricity and electricity produced onsite for own use.



Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

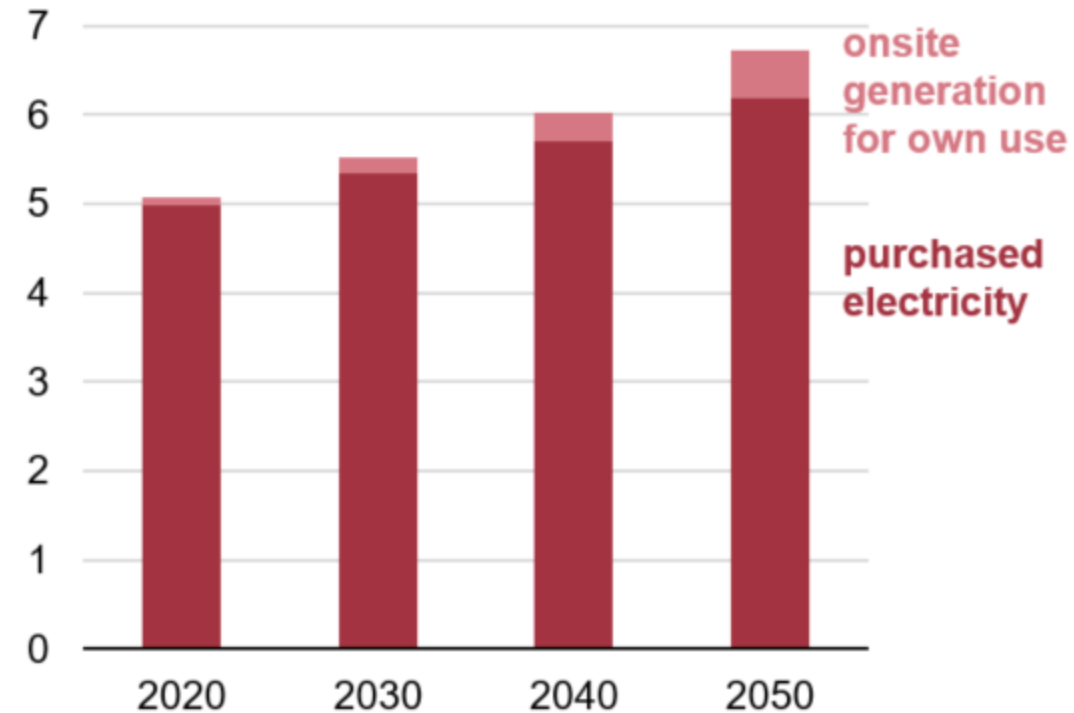
www.eia.gov/aeo

Energy Intensity by End Use

Residential sector electricity consumption

AEO2022 Reference case

quadrillion British thermal units



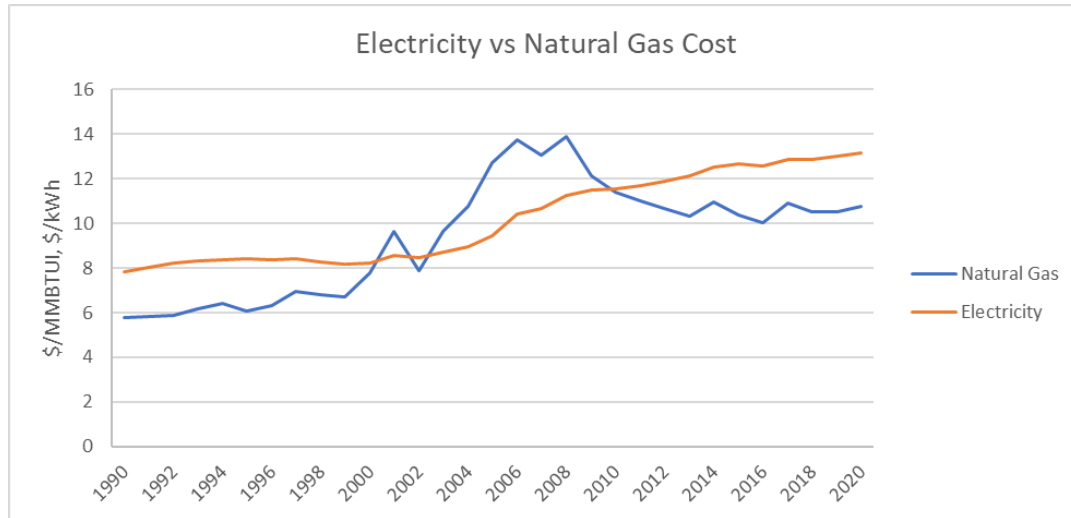
Source: U.S. Energy Information Administration, *Annual Energy Outlook 2022* (AEO2022)

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Electricity Consumption

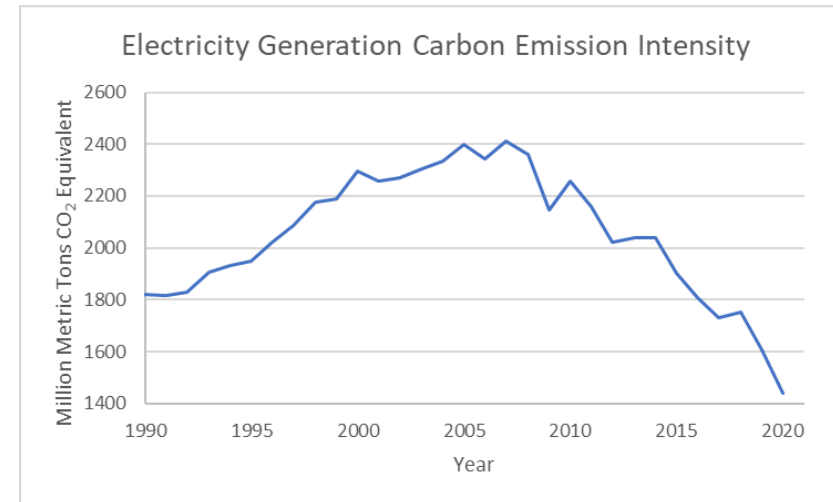
- <https://www.nature.com/articles/s41598-022-15628-2/figures/3>

Extras



<https://www.eia.gov/electricity/data/browser/#/topic/7?agg=0,1&geo=g&endsec=vg&linechart=~ELEC.PRICE.US-RES.A~~&columnchart=ELEC.PRICE.US-ALL.A~ELEC.PRICE.US-RES.A~ELEC.PRICE.US-COM.A~ELEC.PRICE.US-IND.A&map=ELEC.PRICE.US-ALL.A&freq=A&ctype=linechart<ype=pin&rtype=s&pin=&rs=e=0&maptype=0>

<https://www.eia.gov/dnav/ng/hist/n3010us3a.htm>



<https://cfpub.epa.gov/ghgdata/inventoryexplorer/>