Maryland Building Decarbonization Study

Updated Results

September 3, 2021

Energy+Environmental Economics

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Summary of Updates

+ **E3 has made the following three updates to the analysis based on feedback from the Buildings Subgroup and MWG participants**
  - Updated the **electric efficiency assumptions** in the High Decarb Methane scenario assuming **extension of EMPOWER**
  - Halved the **gas revenue requirement growth rate after 2035**, to be consistent with GGRA assumption that **STRIDE** will complete by then
  - Adjusted the **optimistic RNG scenario** to reflect **competition from liquid fuels**
+ **These updates did not change the key finding of the study that Electrification with Fuel Backup scenario shows lowest overall costs while also reducing reliance on technologies that have not yet been widely commercialized or that are uncertain in their scalability.**

Content

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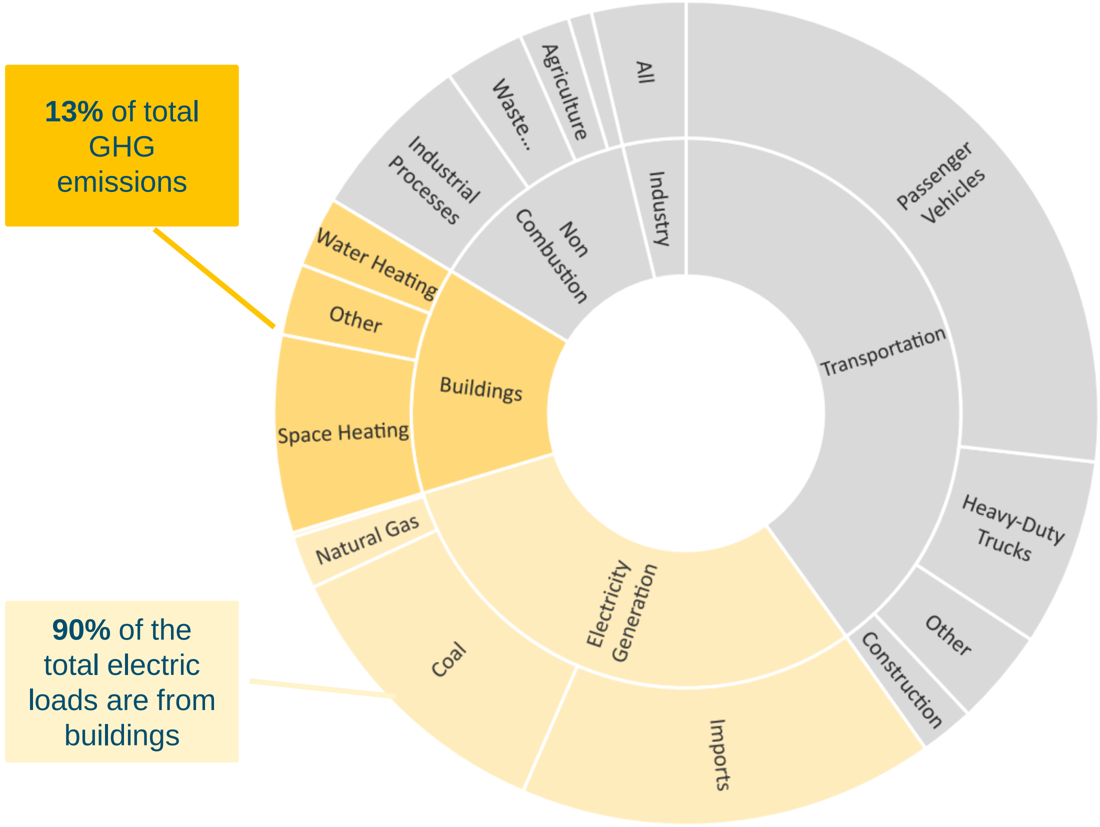
Background and Scenario Design

Project objective: a Maryland-specific pathway to achieve deep decarbonization of building end-uses by mid-century

- **Based on the most recent Maryland GHG Inventory for 2017, building direct-use emissions account for 13% of economywide GHG emissions in Maryland**
  - 80% of direct building emissions are from space heating and water heating
- **90% of the statewide electric load are from buildings, which contribute to upstream emissions in electricity generation**
  - Currently, electricity generation accounts for 30% of total GHG emissions, but will decrease as clean and renewable energy becomes a larger share
- **Key questions of this project:**
  - What are the potential pathways to achieve deep decarbonization of Maryland's building stock by mid-century?
  - What are the costs and benefits of each pathway from a total system cost perspective, as well as impacts on consumers?

MD 2017 Gross GHG Emissions by Sector and Subsector



This study investigates opportunities for building decarbonization through 3 scenarios

- E3 and MDE held a 4-hour workshop with the Buildings Ad-hoc Group, where we received feedback and input from stakeholders on scenario design that informed the selection of the following scenarios

Reference	High Electrification	Electrification with Fuel Backup	High Decarbonized Methane
+ Same as the Reference scenario in the GGRA analysis reflecting current policies + Buildings keep using existing devices with no electrification and little efficiency improvement + Building energy demand grows at 0.6%/yr, same as EIA's projected annual growth rate of Maryland households	+ Almost all buildings switch to ASHPs and GSHPs. Heating is supplied by electricity throughout the entire year + High efficiency through deep building retrofits	+ Existing buildings keep using fuels for heating and are supplied with a heat pump combined with existing furnace/boiler that serves as back up in the coldest hours of the year + All-electric for new construction	+ Buildings keep using fuels for heating while fossil fuels are gradually replaced by low-carbon renewable fuels. Some features: • RNG supplied by biomethane and synthetic natural gas • 7% hydrogen blend • High efficiency through deep building retrofits

3 steps to analyze the impacts of building decarbonization scenarios

3 selected scenarios

- **Scenario Specification**: Development of decarbonization scenarios, heating equipment costs and renewable fuel supply curve
- **Assess Energy System Impacts and Cost Implications**: Analysis of incremental equipment costs, electric system costs and fuel costs.
- **Electric and Gas Rate Impacts**: Development of electric and gas revenue requirement models to estimate rate impacts

Overview of technical and economic implications

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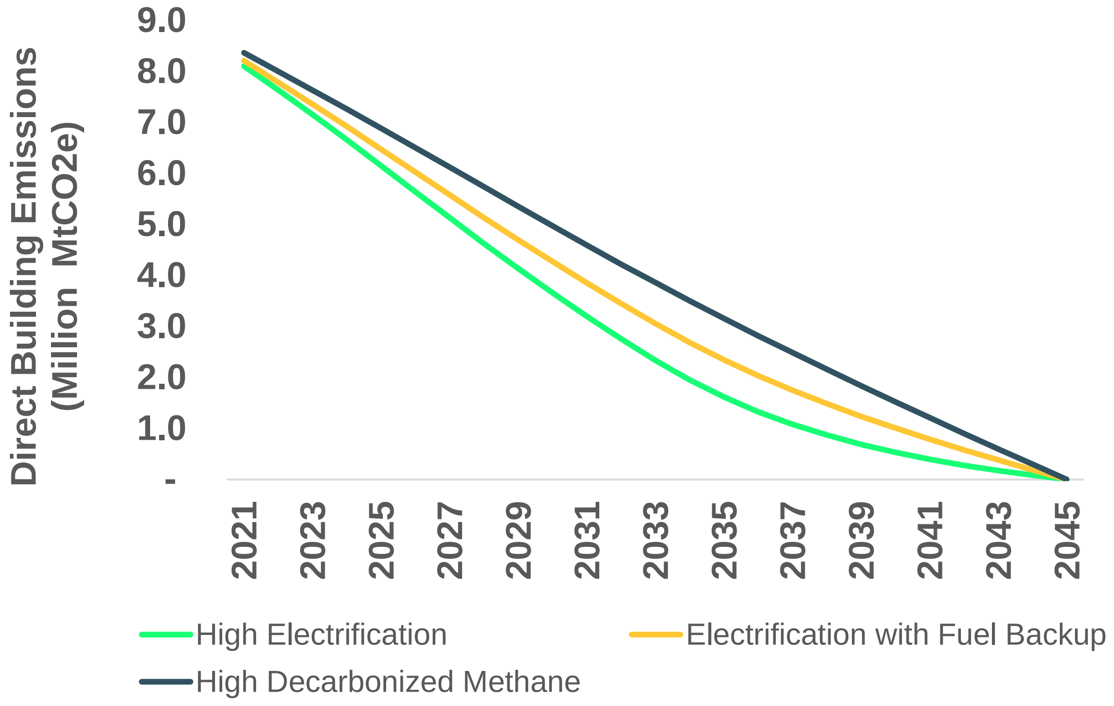
GHG Emissions and Energy Consumption

All scenarios achieve zero direct building emissions by 2045

Direct building GHG emissions trajectory (MMtCO2e per year)

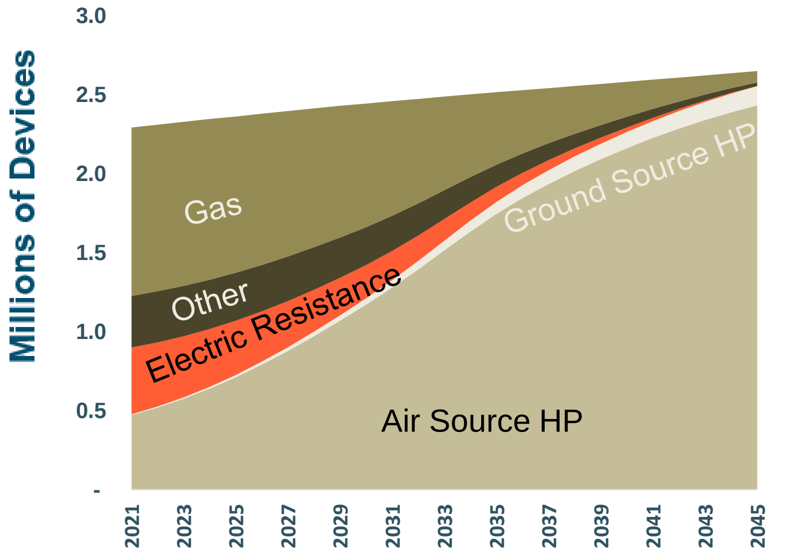


- **All scenarios achieve zero direct building emissions by 2045 through electrification, efficiency improvement and use of low-carbon fuels**
  - This is consistent with the MCCC-recommended economy-wide target of carbon neutrality by 2045

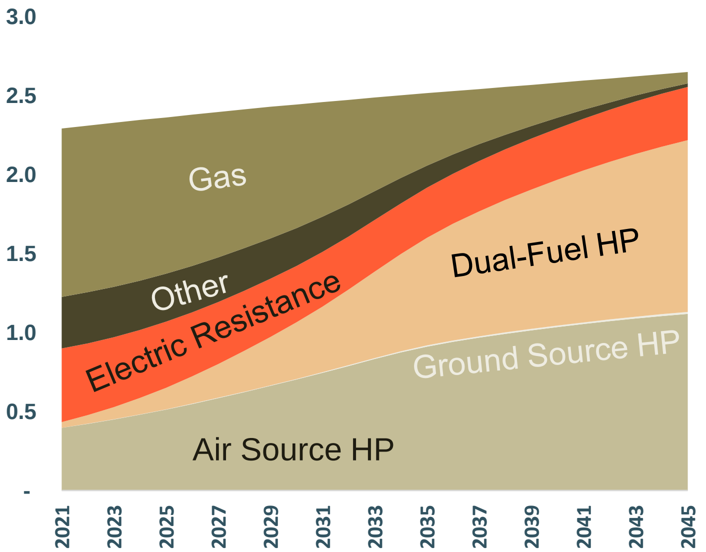
Space heating end-uses are mostly electrified by 2045 in the two electrification scenarios

- Heat pumps become the major space heating equipment in the High Electrification scenario
- Dual-fuel heat pumps are added to most retrofit buildings in the Electrification with Fuel Backup scenario, pairing with existing fuel-based systems
- Electric resistance currently accounts for about 20% of space heating devices

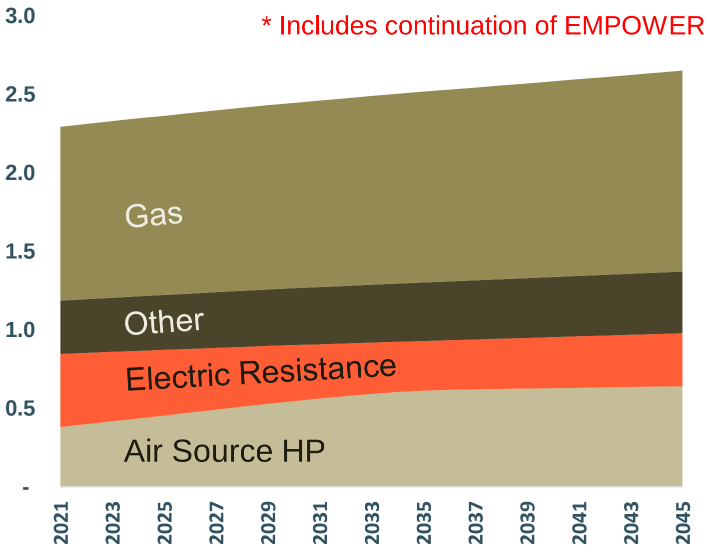
High Electrification



Electrification with Fuel Backup



High Decarbonized Methane



* "Other" space heating devices mainly include fuel oil and LPG-based furnaces and boilers

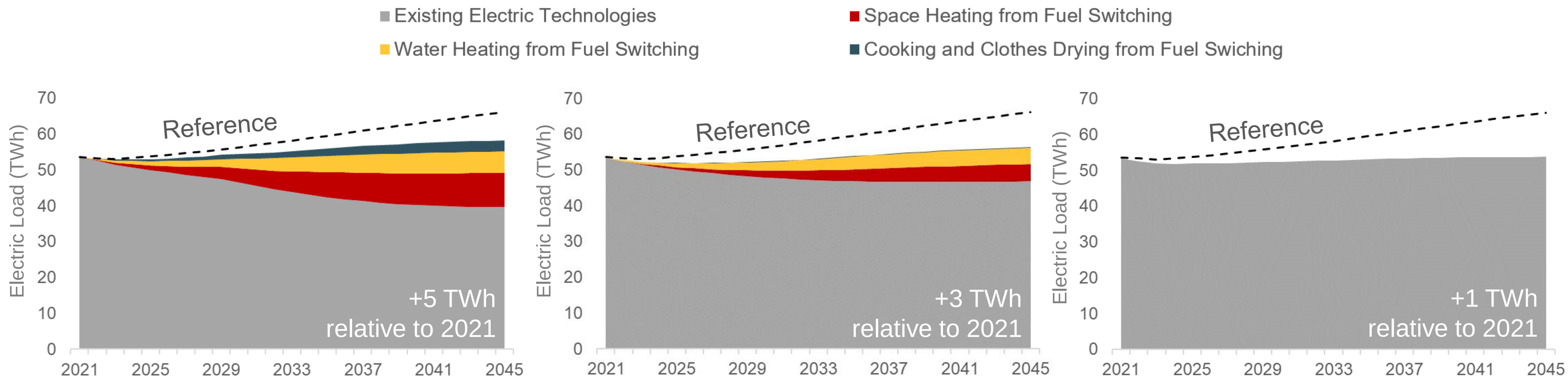
* Consistent with the 2030 GGRA Plan, the Electrification with Fuel Backup and High Decarbonized Methane scenarios assume continuation of EMPOWER program after 2023

* E3 is working with MDE to evaluate the impact of geothermal heating and cooling carve-out requirement in the RPS on GSHP adoption assumptions across the scenarios

Electricity demand in all scenarios are lower than Reference due to energy efficiency gains

- **Electricity demand increases in all scenarios due to growth in households**
  - **High Electrification** scenario has the highest load growth among the three scenarios due to new space heating, water heating and other loads as a result of fuel switching
- **Compared to Reference, all scenarios have lower electricity demand due to energy efficiency gains**
  - **High Electrification** scenario also has the largest reduction in existing loads due to higher levels of efficiency from building shell improvement and efficient electric device adoption

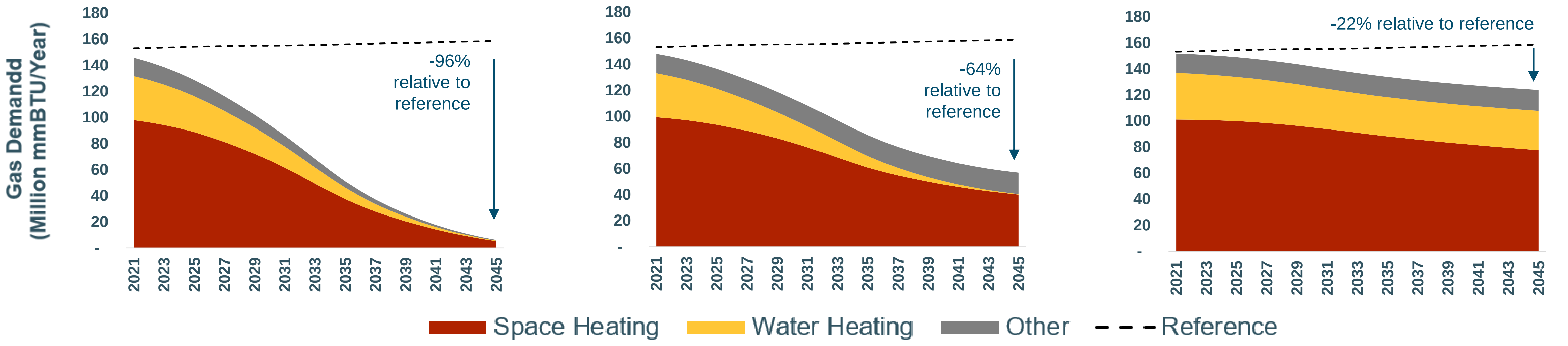
High Electrification	Electrification with Fuel Backup	High Decarbonized Methane



Natural gas demand declines in all scenarios due to energy efficiency gains and fuel switching offsetting growth

+ **Natural gas use in buildings is expected to decline in all scenarios due to energy efficiency gains offsetting growth in households, and this decline is accelerated in scenarios with significant building electrification**
  - **High Electrification** reduces gas demand by 96% by 2045 due to aggressive electrification of all building end-uses
  - **Electrification with Fuel Backup scenario** has lower reduction in gas demand by 2045 at 62%, as most customers adopt dual-fuel heat pumps that use gas with gas as a backup heating source during coldest hours of the year
  - **High Decarbonized Methane** scenario results in a 19% reduction in gas demand by 2045 due to efficient gas appliance adoption and building shell improvements

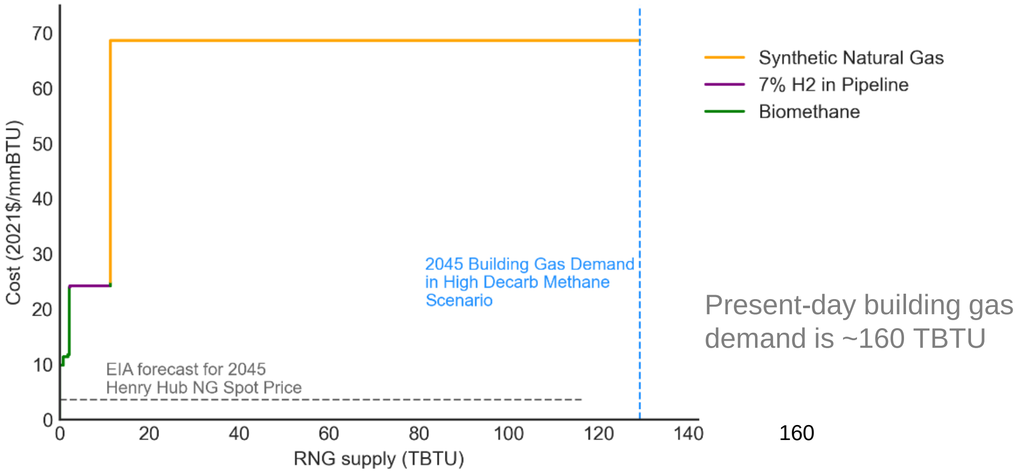
High Electrification | Electrification with Fuel Backup | High Decarbonized Methane



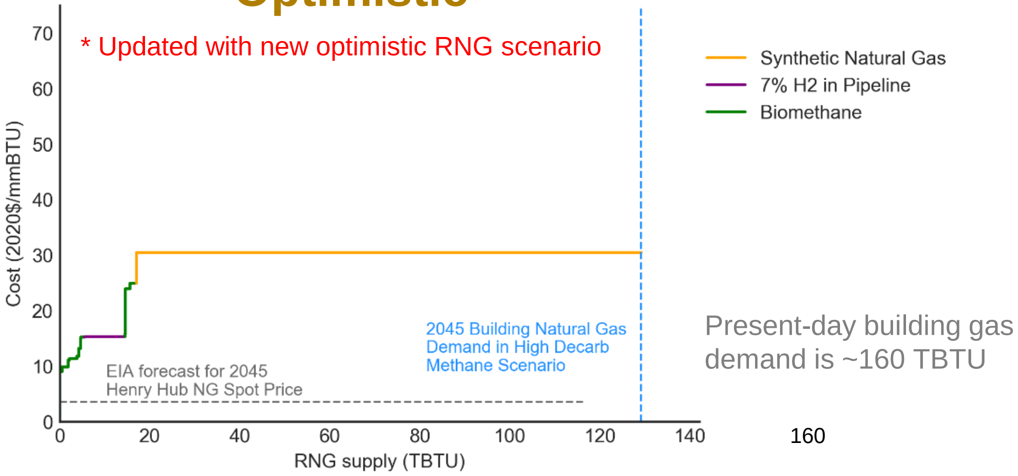
The E3 Biofuels Module models two bookends for RNG Supply

- RNG Supply Curve assumptions are developed using E3 biofuels optimization module, which determines the most cost-effective way to convert biomass into biofuel across all sectors.
- Conservative and Optimistic scenarios modeled here represent two bookends for the supply of RNG towards 2045 to reflect uncertainties with technology commercialization and scalability
  - Conservative scenario has heavy reliance on Synthetic Natural Gas (SNG); it assumes
    - MD only gets access in-state biomass feedstocks
    - Conservative projection of learning rate for electrolyzers, which is the main component of H2 production
  - Optimistic scenario has moderate reliance on SNG; it assumes
    - MD gets access to its population weighted-share of national feedstocks
    - Optimistic projection of learning rate for electrolyzers
  - Both scenarios assume that ALL cellulosic feedstocks would be more cost-effectively used to produce liquid fuels - such as renewable diesel or jet fuel (due to higher prices and carbon intensities for these fuels)

Conservative



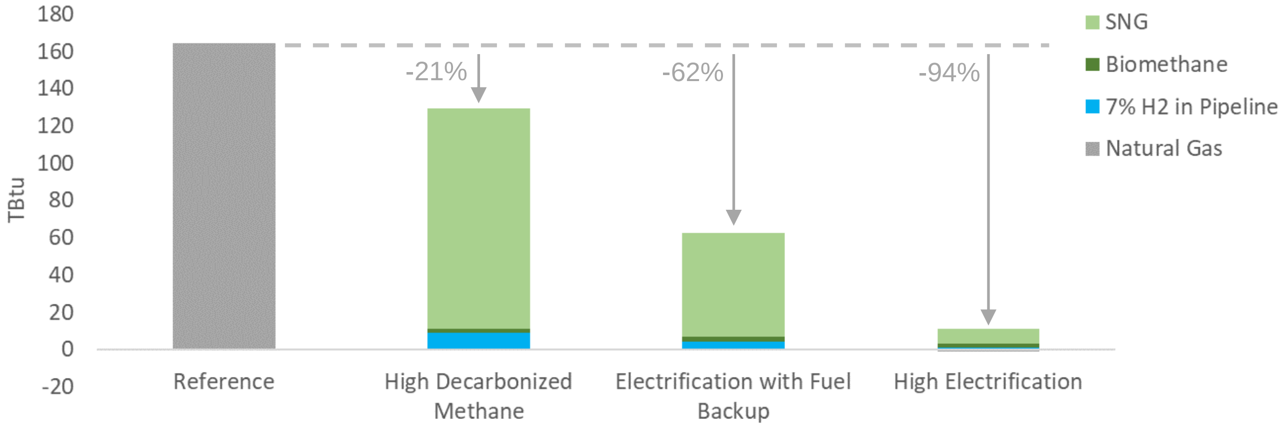
Optimistic



Sources & assumptions: Biomass supply assumptions are developed from the 2016 Billion Ton Report (DOE, 2016), with supplemental landfill gas assumptions from the Renewable Sources of Natural Gas report (American Gas Foundation, 2019). The conservative scenario assumes SNG is produced with CO_2 from Direct Air Capture (DAC), the optimistic scenario assumes SNG is produced using waste bio-CO2 from biofuels. The 7% hydrogen blend is as a percentage of energy content. More background on cost assumptions are included in the Appendix.

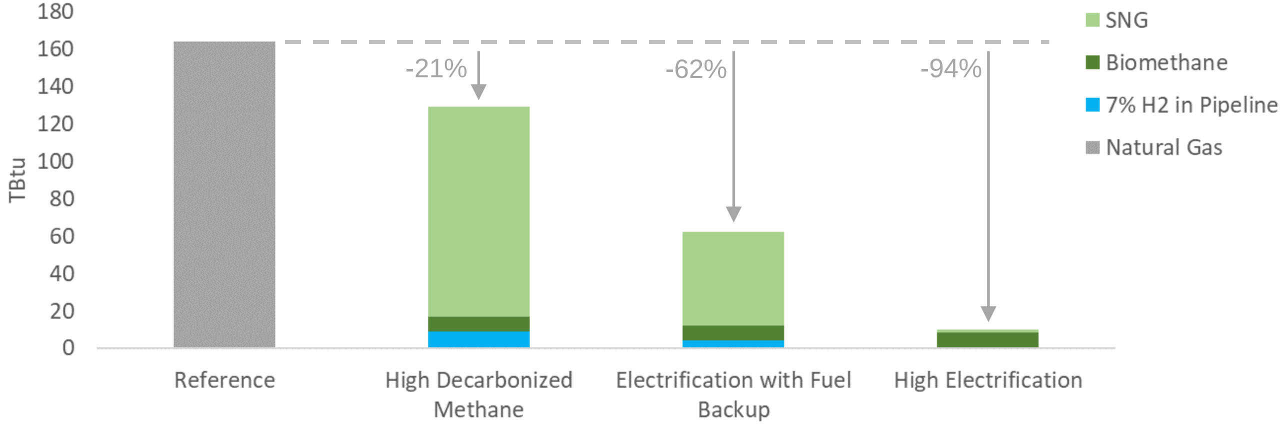
Gas composition transitions to RNG

Gas commodity blend in 2045 (Conservative)



Gas commodity blend in 2045 (Optimistic)

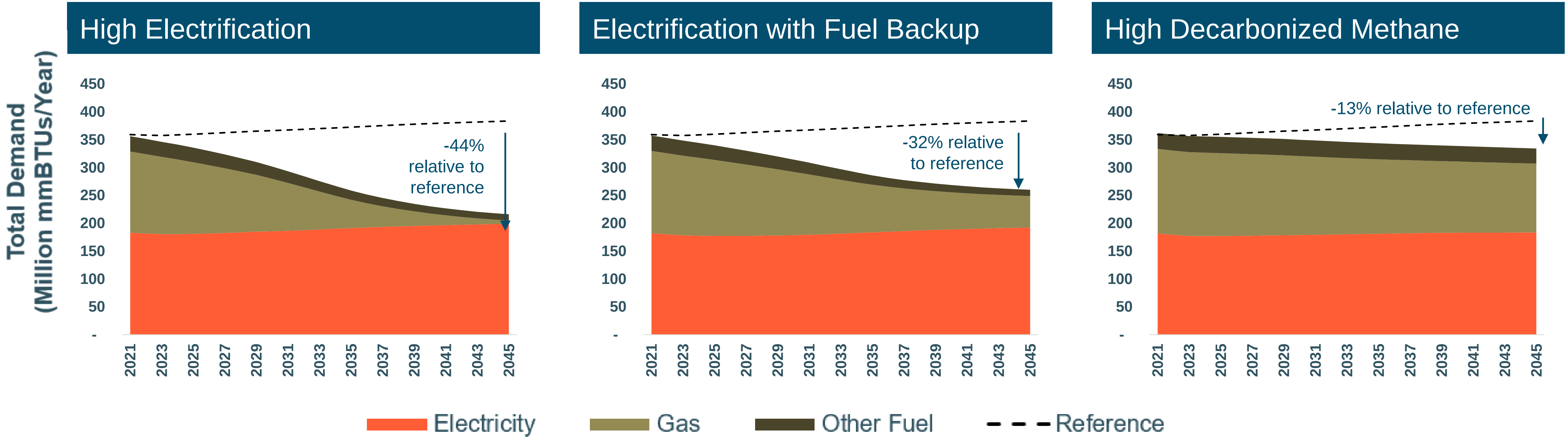
* Updated with new optimistic RNG scenario



+ **By 2045, all building scenarios have 100% blend of RNG in the remaining gas demand**
  - This helps all scenarios reach zero direct building emissions target by 2045
  - Hydrogen blend in pipeline is assumed in all scenarios where it makes economic sense, up to 7% in energy content (20% in volume) which is the maximum current natural gas pipelines can take without significant modification
+ **In a conservative RNG scenario where biomass supply is limited, SNG is the main source of low-carbon gas in all scenarios**
+ **In an optimistic RNG scenario, SNG is still needed across all scenarios due to the limit in biomass supply**

All scenarios reduce total energy demand

+ **Overall energy demand decreases through 2045 in all scenarios**
  - Deep electrification almost eliminates gas demand by 2045 under the High Electrification Scenario
  - Gas demand decreases ~62% in the fuel backup scenario due to adoption of dual-fuel heat pumps, while overall energy demand falls 32%
  - Efficiency gains from building shell improvements and efficient appliance adoption reduce overall demand by 13% in the High Decarbonized Methane Scenario



* Year 2021 will not perfectly match reference because electrification/efficiency adoption begins in model year 2017

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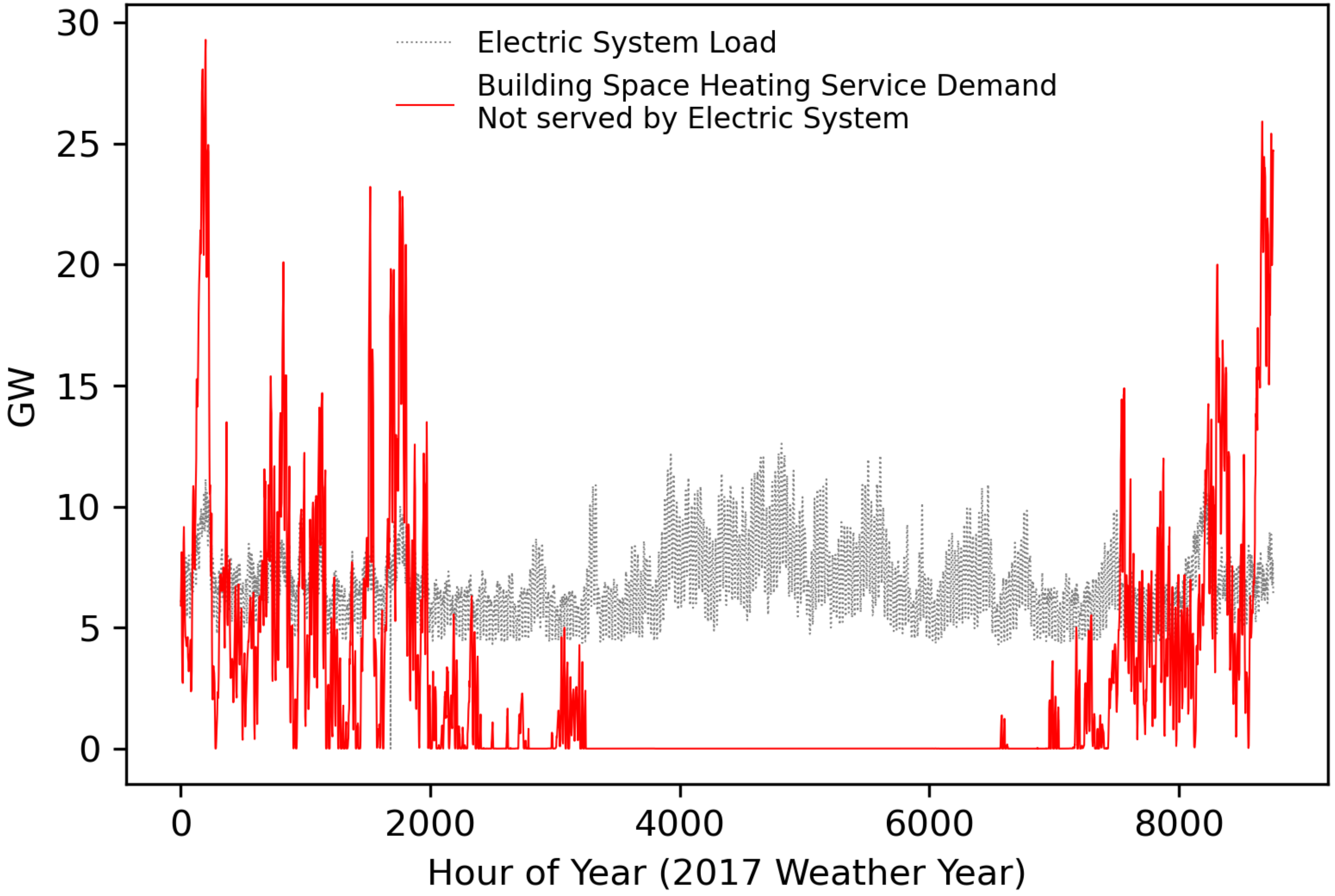
Electric system peak impacts

Maryland's current electric system peaks in summer



Electric system summer peak in 2017 was approximate 12.6 GW and the winter peak was approximately 11.1 GW.

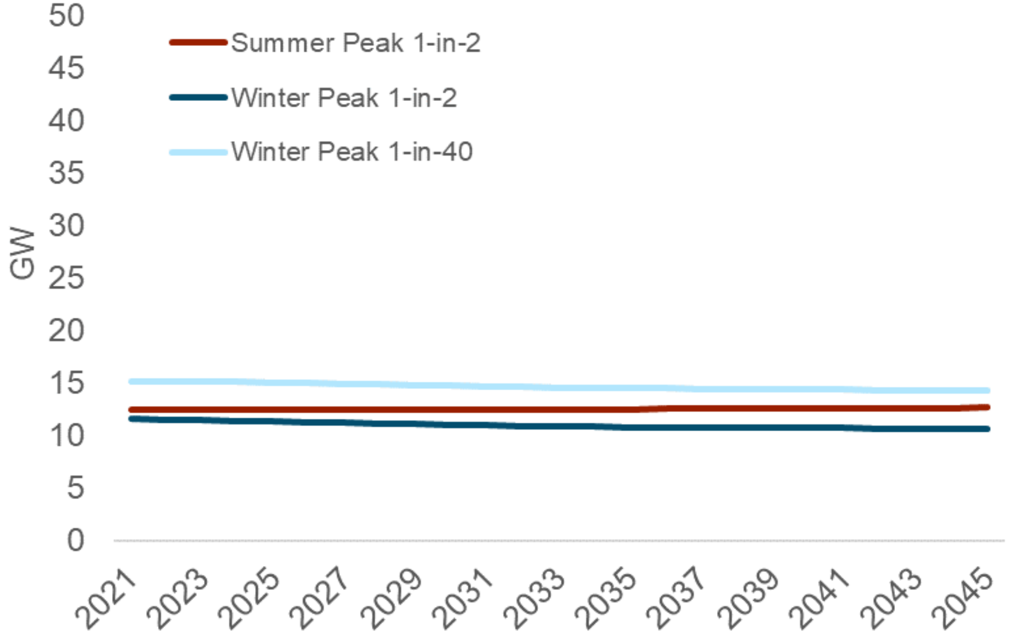
- **Currently, Maryland's electricity system experiences peak load in summer months**
  - Load peaks at around 13 GW, mainly as a result of residential and commercial air conditioning
- **Maryland's *building heat load,* however, currently mainly supplied by gas, shows a large peak in winter as a result of the state's cold winter climate**
  - Building heat loads represent *service demand* of both space and water heating, i.e. total heating load if all supplied by electric resistance
  - Moving the thermal load from gas to electric will result in a significant increase in electric peak in winter

Sources & assumptions: Building thermal load is based on PATHWAYS total space and water heating service. Shape of the thermal load is calculated using E3's RESHAPE model. Note that the chart shows imputed system load for November and December as a result of data gaps.

Maryland is expected to have little peak load growth in the High Decarbonized Methane scenario

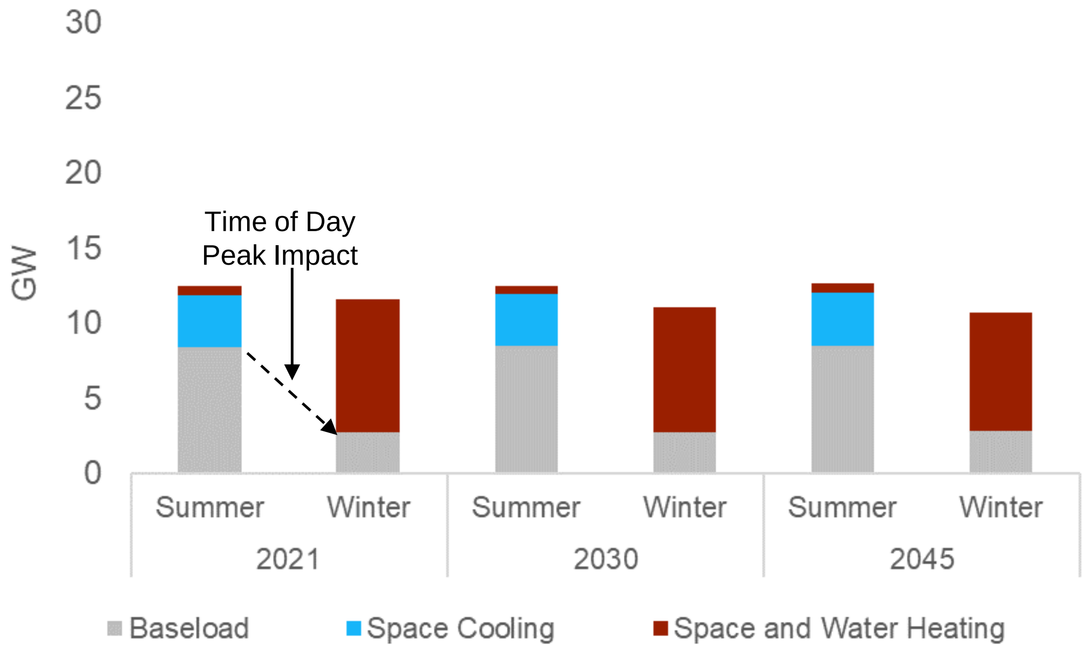
+ **In the High Decarbonized Methane scenario, the small peak load growth is due to growth of households and economy.**

Peak Load Projection 2021-2050
High Decarbonized Methane



*In 2045, the 1-in-10 and 1-in-40 summer peak is 0.6 and 0.7 GW higher than the 1-in-2 peak, respectively.

Contribution to 1-in-2 System Peak by Sector
High Decarbonized Methane

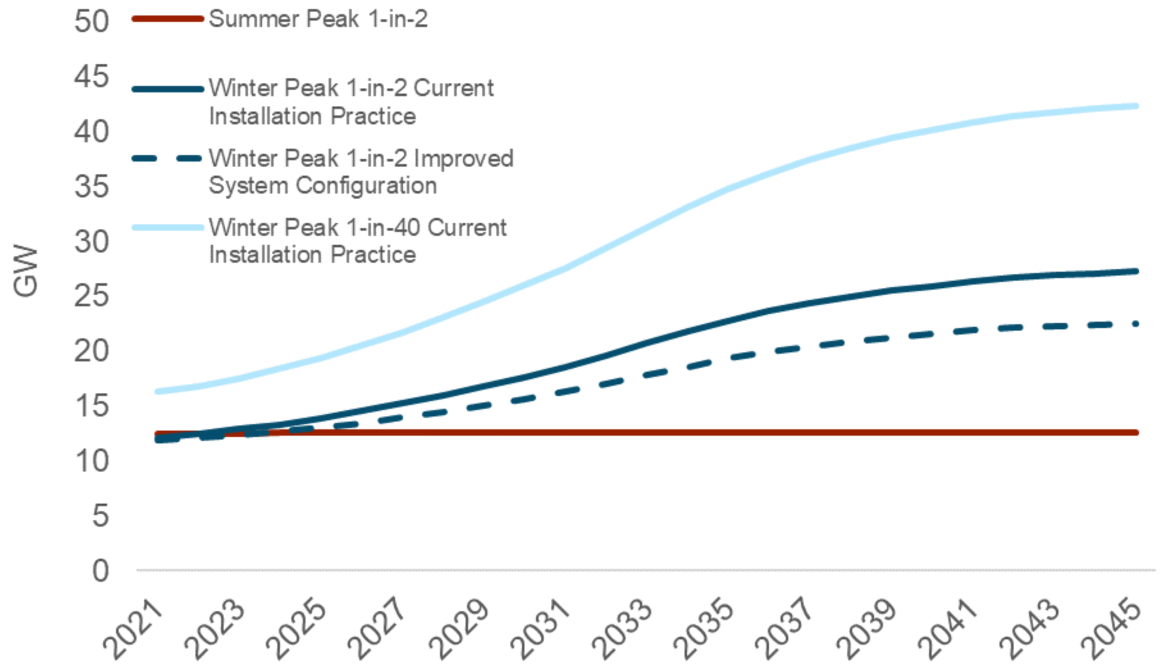


Sources & assumptions: Coincident peak load is based on a modeled hourly load for MD. The projected hourly load is calculated using incremental load in 2050 modeled from PATHWAYS and end-use shapes from RESHAPE based on 2017 weather added to the 2017 historical load.

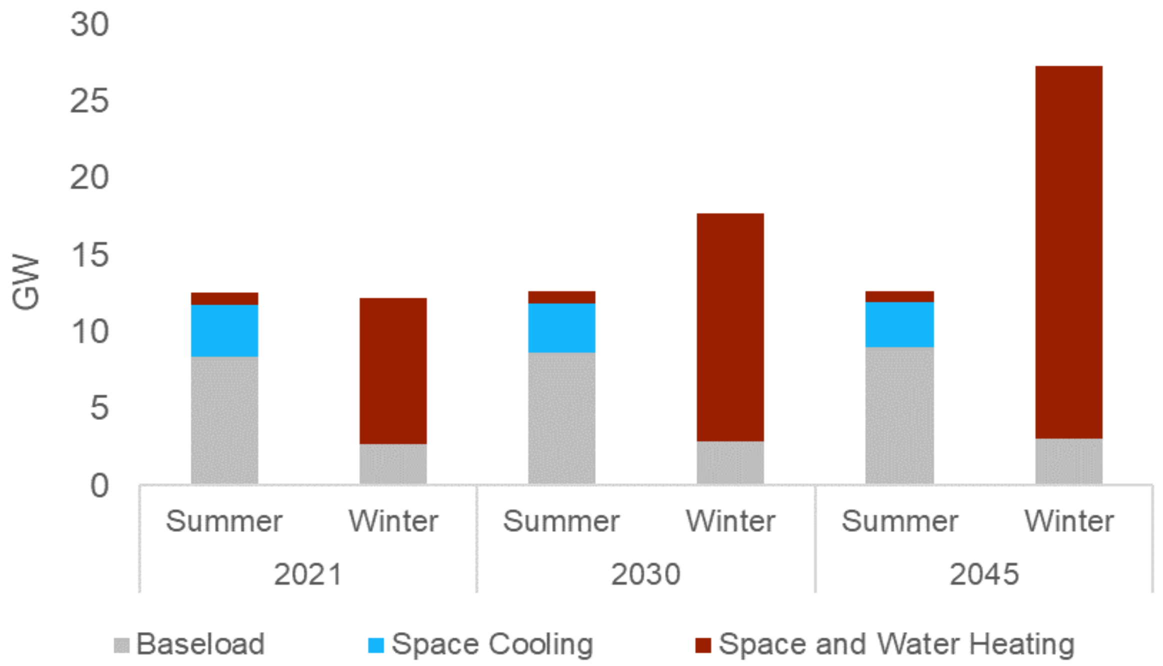
Winter peak load is expected to grow by 15 GW by 2045 in the High Electrification scenario

- **In the High Electrification scenario, Maryland's electricity system is expected to become winter peaking in the near future, and will more than double the current system peak by 2045**
  - Switching to heat pumps from electric resistance heating, which is currently used in about 25% of Maryland households, has a much smaller impact on <u>peak heating load</u> than on <u>annual total heating loads</u>

Peak Load Projection 2021-2045
High Electrification



Contribution to 1-in-2 System Peak by Sector
High Electrification – Current Installation Practice



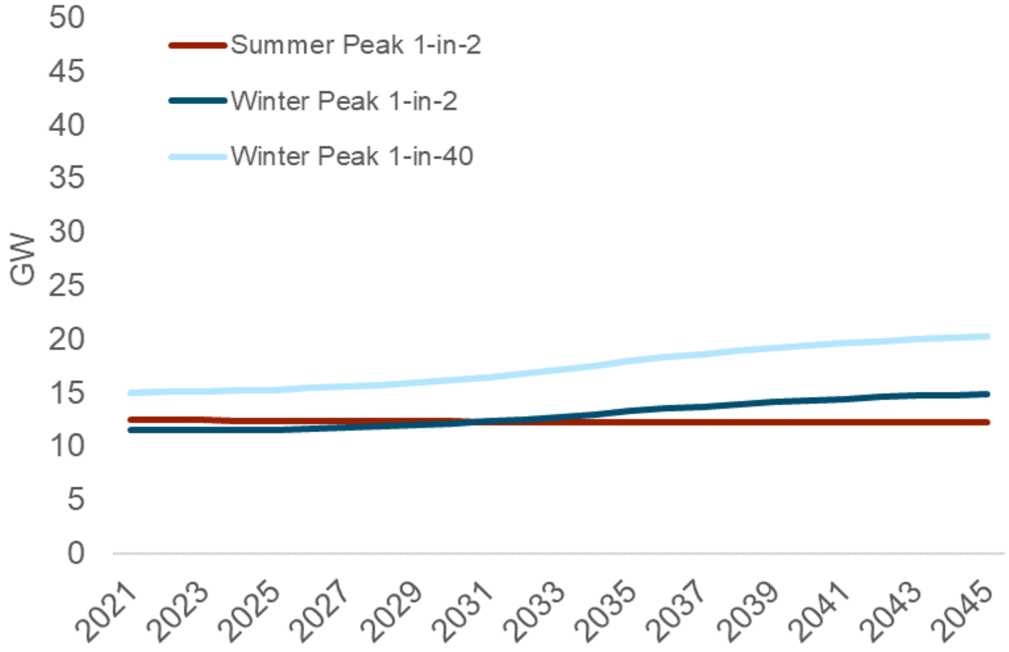
*In 2045, the 1-in-10 and 1-in-40 summer peak is 0.5 GW higher than the 1-in-2 peak

Sources & assumptions: Coincident peak load is based on a modeled hourly load for MD. The projected hourly load is calculated using incremental load in 2050 modeled from PATHWAYS and end-use shapes from RESHAPE based on 2017 weather added to the 2017 historical load.

Electrification with Fuel Backup scenario has much smaller winter peak load growth

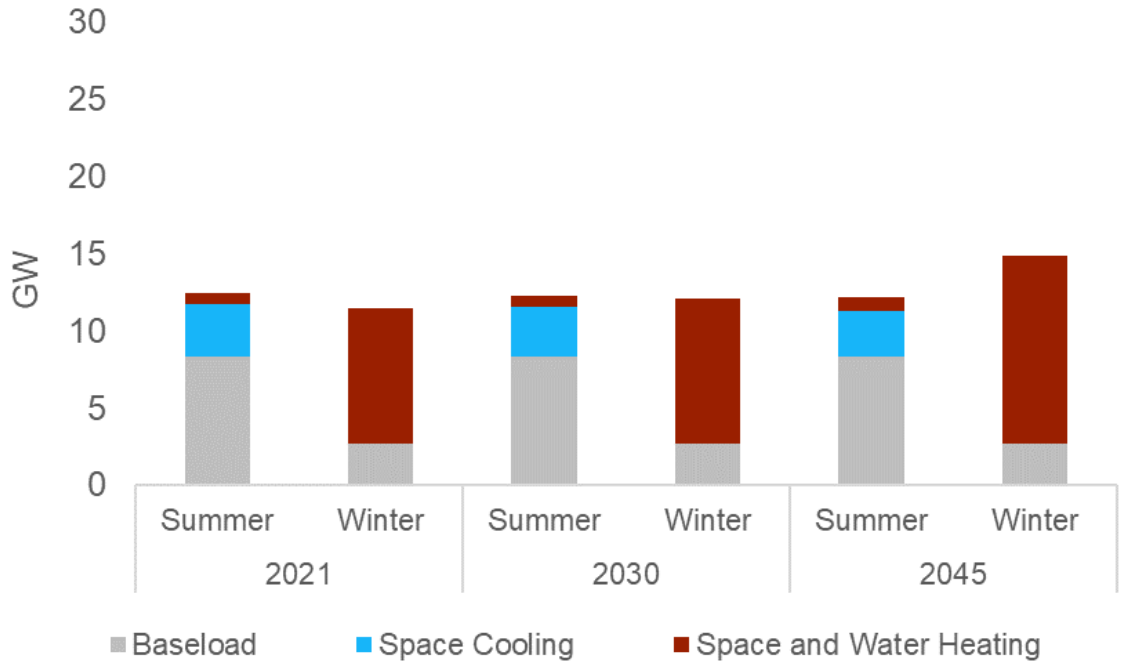
- Compared to the High Electrification scenario, Maryland's electricity system becomes winter peaking about a decade later
- Peak load growth is also significantly smaller, ~2 GW by 2045 compared to the current system peak

Peak Load Projection 2021-2045
Electrification with Fuel Backup



*In 2045, the 1-in-10 and 1-in-40 summer peak is 0.5 GW higher than the 1-in-2 peak

Contribution to 1-in-2 System Peak by Sector
Electrification with Fuel Backup



Sources & assumptions: Coincident peak load is based on a modeled hourly load for MD. The projected hourly load is calculated using incremental load in 2050 modeled from PATHWAYS and end-use shapes from RESHAPE based on 2017 weather added to the 2017 historical load.

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System Cost Impact

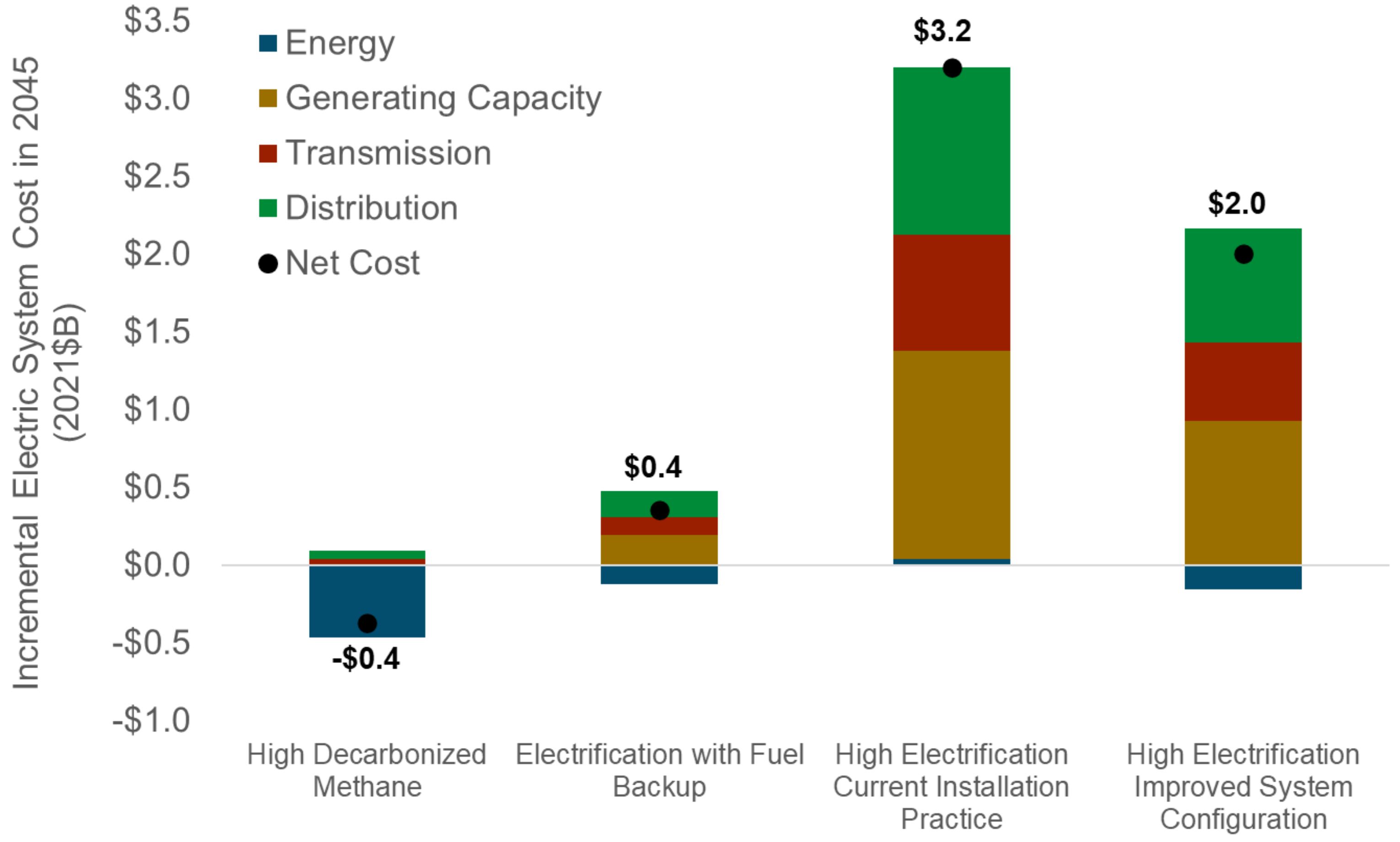
Approach for system cost impact analysis

- The following four cost components are considered in the system cost impact analysis
- System costs of the three main scenarios are calculated as incremental to Reference

Electric System	Gas System	Equipment	Other Fuels
❑ Investment in additional transmission and distribution infrastructure ❑ Investment in additional generating capacity to meet the peak electric demand ❑ Generation cost to meet the additional electricity demand	❑ Capital expenditure for reinvestment in the gas system ❑ Operating costs to maintain the gas system ❑ Gas commodity costs for RNG to replace natural gas	❑ Investment in efficient or electric appliances relative to a reference appliance ❑ Investment in building shell improvement	❑ Fuel commodity costs for bio-based liquid fuels to replace fossil fuels, mainly bio-diesel replacing fossil-based heating oil

Meeting electric loads in the High Electrification scenario requires around $2-3 billion of annual incremental system costs

Annual Incremental Electric System Costs relative to Reference in 2045 (2021$ Billions per year)

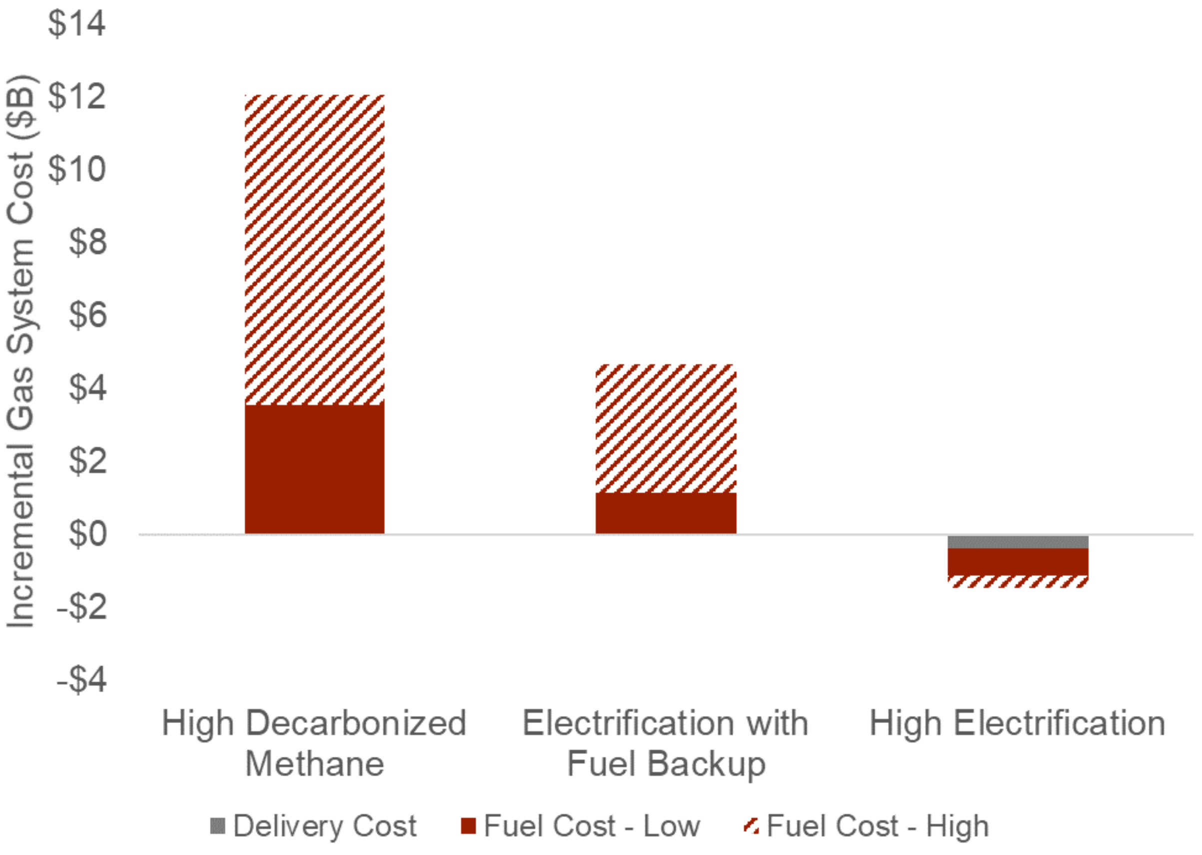


- **High levels of electrification significantly increase electricity system costs, mainly for meeting peak capacity needs.**
  - Improving system installation practices would result in less increase in electric system costs, only ~60% of that in the High Electrification scenario
- **Pairing ASHPs with fuel systems can save more than 80% of the incremental costs, mainly by avoiding T&D infrastructure and generating capacities**
  - System costs in the Electrification with Fuel Back Up scenario are $0.4 billion in 2045 compared to $3.2 billion for the High Electrification scenario

Sources & assumptions: Details of the electric sector cost assumptions are documented in the Appendix. T&D costs are high-level assumption reflecting new investment in lines. This captures the high-level investment requirement in the High Electrification Scenario given the magnitude of the peak impact from electrification. Further analysis is needed to explore near term opportunities for using headroom in existing T&D infrastructure and for expanding existing lines, which are likely going to be less expensive.

Gas system cost in all scenarios show wide ranges because of the large uncertainty associated with RNG commodity costs

Annual Incremental Gas System Costs relative to Reference in 2045 ($2021 Billions per year)

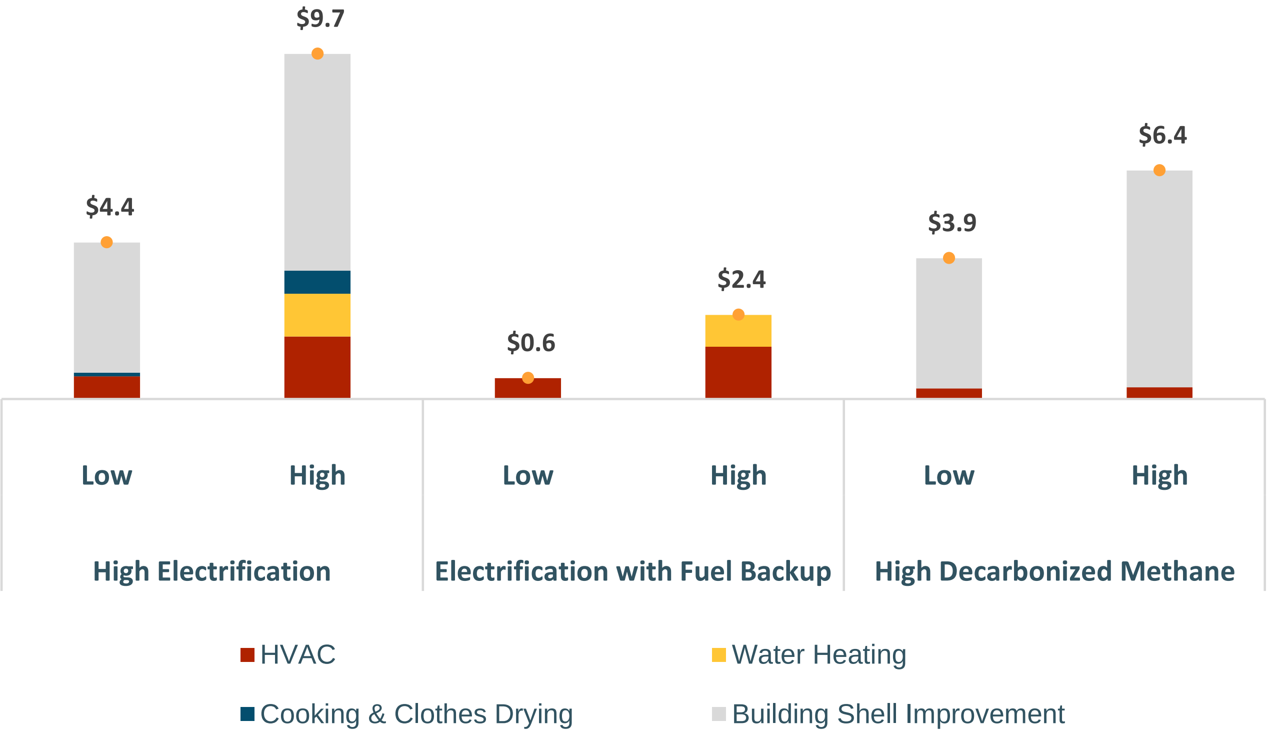


- **High Decarbonized Methane** scenario has the biggest range of incremental system costs due to its high gas demand
  - Meeting all gas demand with RNG in the High Decarb Methane scenario can increase the annual gas system cost by up to $12B
- Reduced throughput in the **Electrification with Fuel Backup** scenario results in much lower system costs and less wide cost ranges
  - The blend of RNG results in higher gas commodity costs and overall gas system costs relative to Reference even though throughput is less
- **High Electrification** scenario has lower gas system costs relative to Reference due to both lower gas demand and lower infrastructure costs
  - We assume that reduced peak gas throughput in this scenario would require less capital reinvestment and O&M to maintain the gas system

Sources & assumptions: Current gas revenue requirement projection assumes same growth rate as historical through 2045 in the High Decarbonized Gas scenario and the Electrification with Fuel Backup scenario. E3 will update growth rate assumptions based on recommendation by MDE to reflect STRIDE-related investment complete by 2035, same assumptions as in the 2030 GGRA Plan released by MDE.

The two book-end scenarios have relatively high incremental equipment costs due to building shell improvement

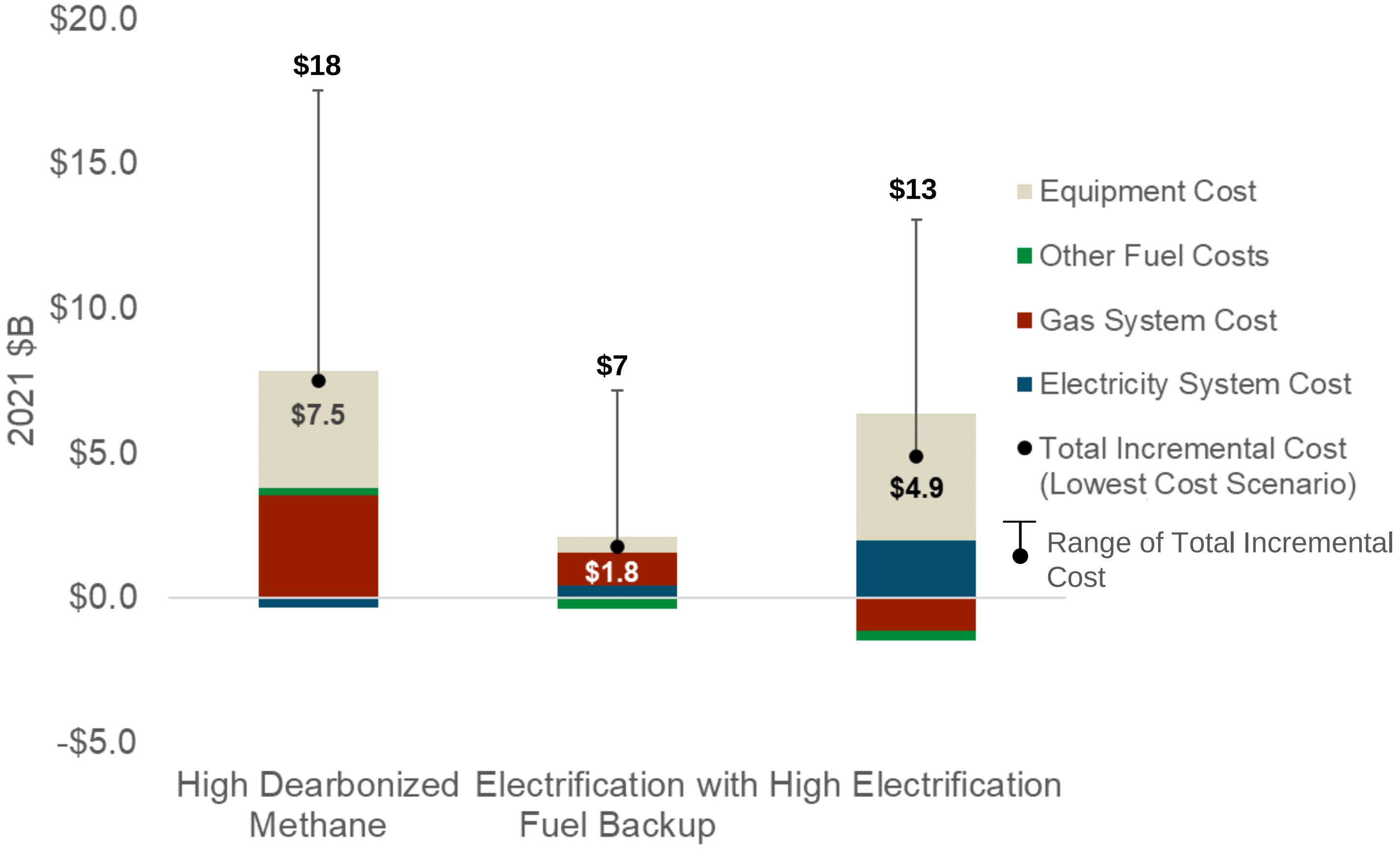
Levelized Total Incremental Equipment Costs in 2045 ($2021 Billions per year)



- **High and low equipment cost profiles creates uncertainty around future costs in the two book-end scenarios**
  - Building shell upgrades account for the majority of equipment costs
  - Current costs are based on deep shell retrofits that include energy efficiency and heat recovery, and are highly uncertain and location-specific
- **Electrification with Fuel Backup is the lowest-cost scenario because it does not include building shell improvement**

Electrification with Fuel Backup scenario is expected to be the relatively low-cost and low-risk path among the three scenarios

Incremental Total Resource Costs for Buildings (2045) ($2021 Billions per year)



Total cost range reflects assumptions regarding fuel costs, equipment cost, and heat pump installation practices

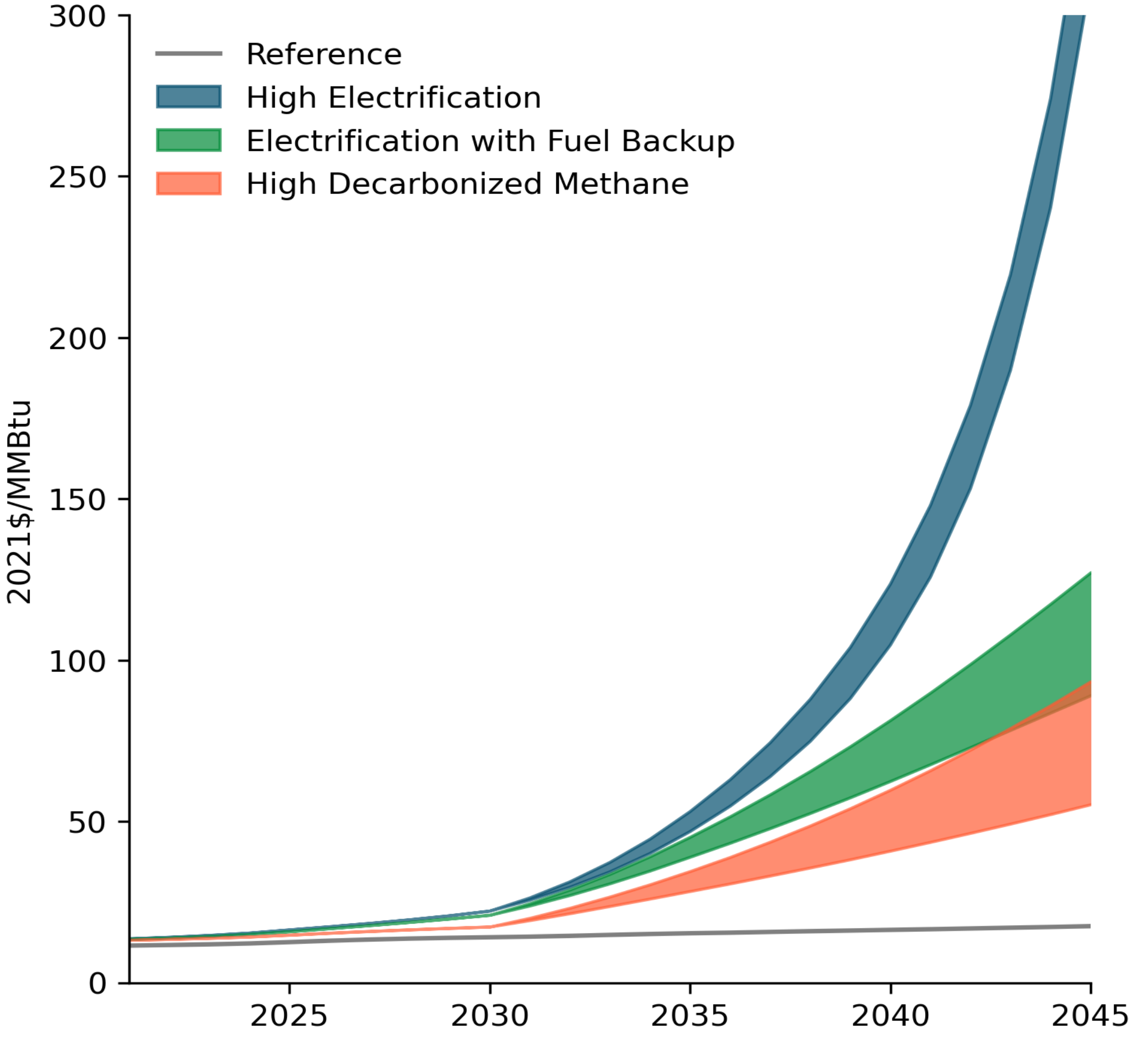
+ **Building sector costs show large variation across scenarios depending on:**
  - Gas fuel costs (optimistic/conservative supply curve)
  - Equipment costs (mainly building shell upgrade costs)
  - Installation practice for electric heating systems
+ **A hybrid scenario could potentially "hedge" for this uncertainty given its lower overall costs and narrow cost ranges**

Sources & assumptions: These charts show incremental resource costs of the scenarios compared to the reference scenario.

Gas and Electric Rate Impact

Gas rates increase significantly across all scenarios

Residential gas rates (2021$/MMBtu)



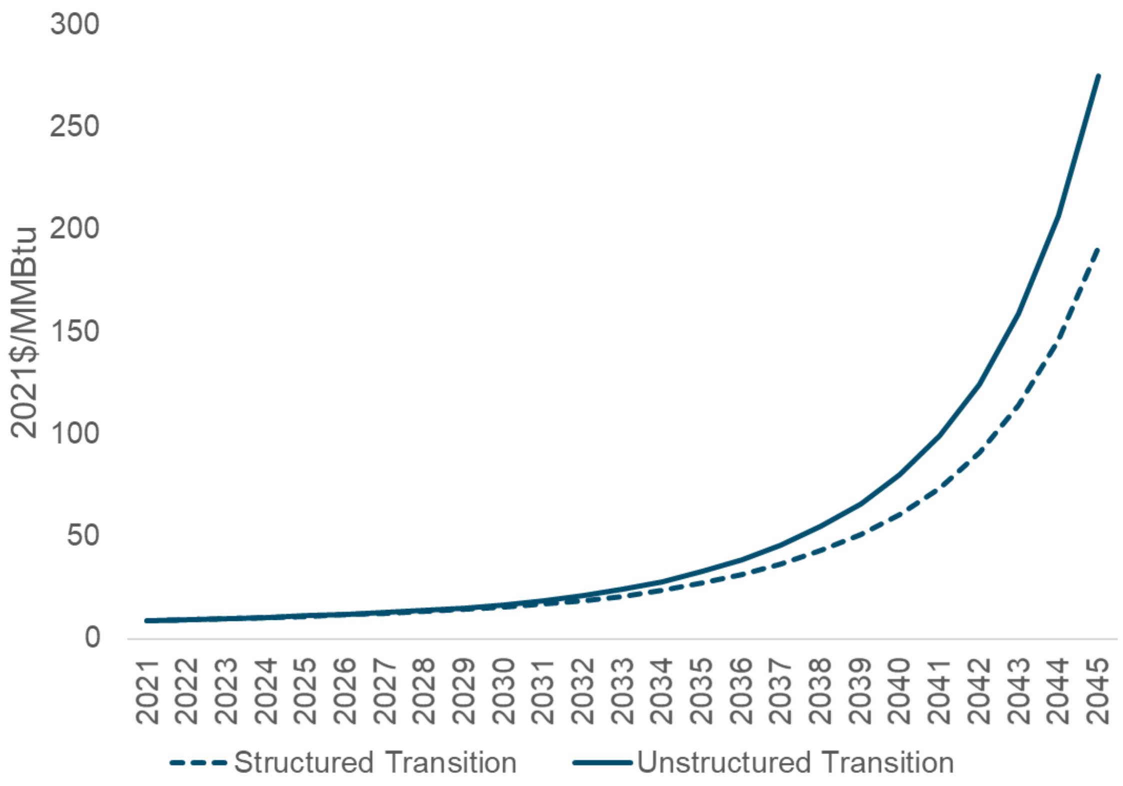
- **High Electrification scenario** experiences a rapid rate increase driven by declining throughput despite lower total delivery and commodity costs
- Rate increases in the **High Decarbonized Methane scenario** are driven primarily by the commodity cost for zero carbon fuel
- **Electrification with Fuel Backup scenario** has higher gas rates than the High Decarbonized Methane scenario, due to its lower throughput and the resulting higher per MMBtu delivery cost

*Range shown in figure reflects the commodity cost forecast uncertainty

Gas delivery rate under a structured gas transition may still remain high due to significantly reduced throughput

Residential gas delivery costs (2021$/MMBtu)

High Electrification with Structured Gas Transition



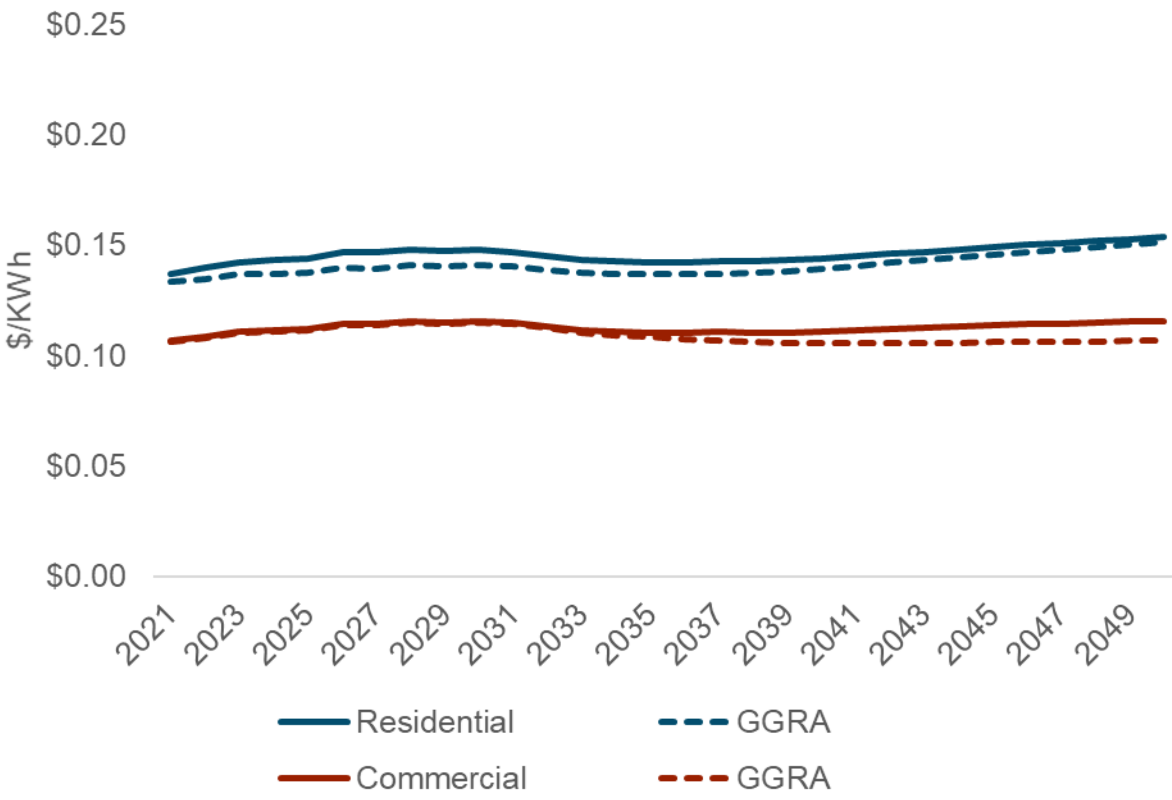
+ **E3 modeled an illustrative sensitivity scenario reflecting a high electrification future with structured gas transition, which would result in reduced level of revenue requirement compared to a base case**
  - Capital-related expenditure and pipeline maintenance costs become flat after 2030, which reflects half of the reinvestment level compared to today
    - Data source: E3 (2020), The Challenge of Retail Gas in California's Low Carbon Future
  - Administrative costs are reduced by 0.6% with every 1% reduction in customer base
    - Data source: Davis and Hausman (2021), Who Will Pay for Legacy Utility Costs?
+ **The structured transition reduces residential delivery rates by 30%, but the rates remain high**
+ **This sensitivity does not address the question of how utilities would reduce the revenue requirement or who would bear the cost gap between reduced revenue requirement and unavoidable costs for the remaining gas system**
+ **More legislative and regulatory efforts are needed to address the issues of stranded gas assets in a high electrification future**

High Electrification scenario shows a more rapid electric rate increase compared to Electrification with Gas Back Up

- **The Electrification + Gas Back-up scenario is projected to have a lower rate increase because it has a smaller load factor and manages to avoid the expensive peak capacity investment.**

Electric rates in the High Electrification Scenario (2021$/kWh)

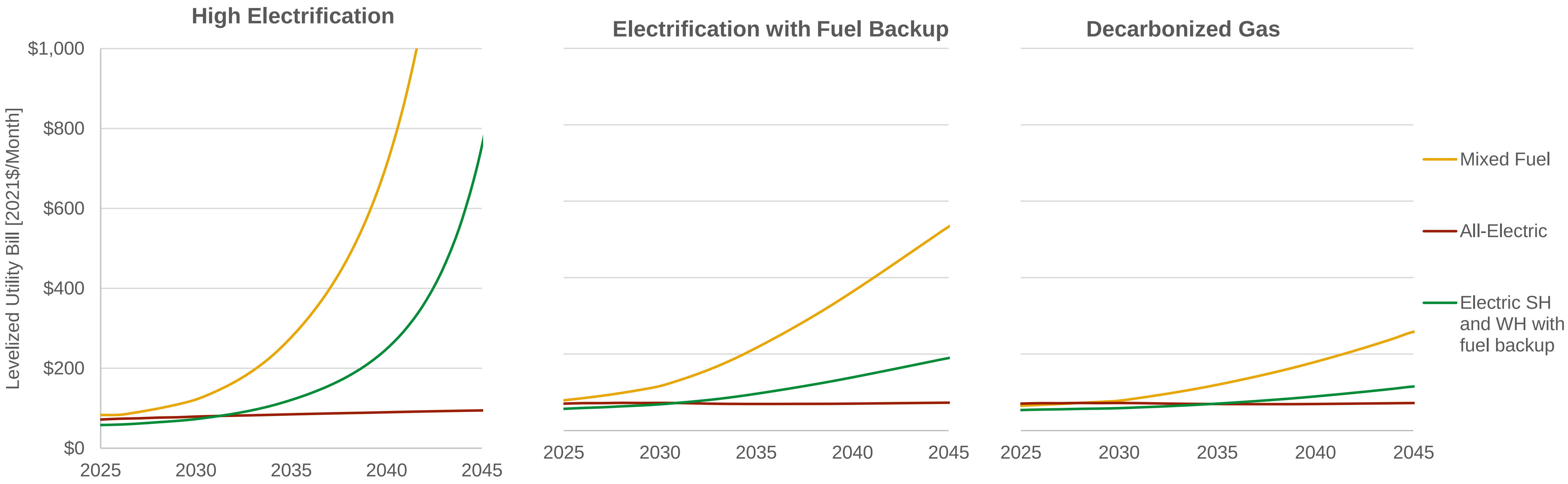
Electric rates in the Electrification + Gas Back-up Scenario (2021$/kWh)



Consumer Economics

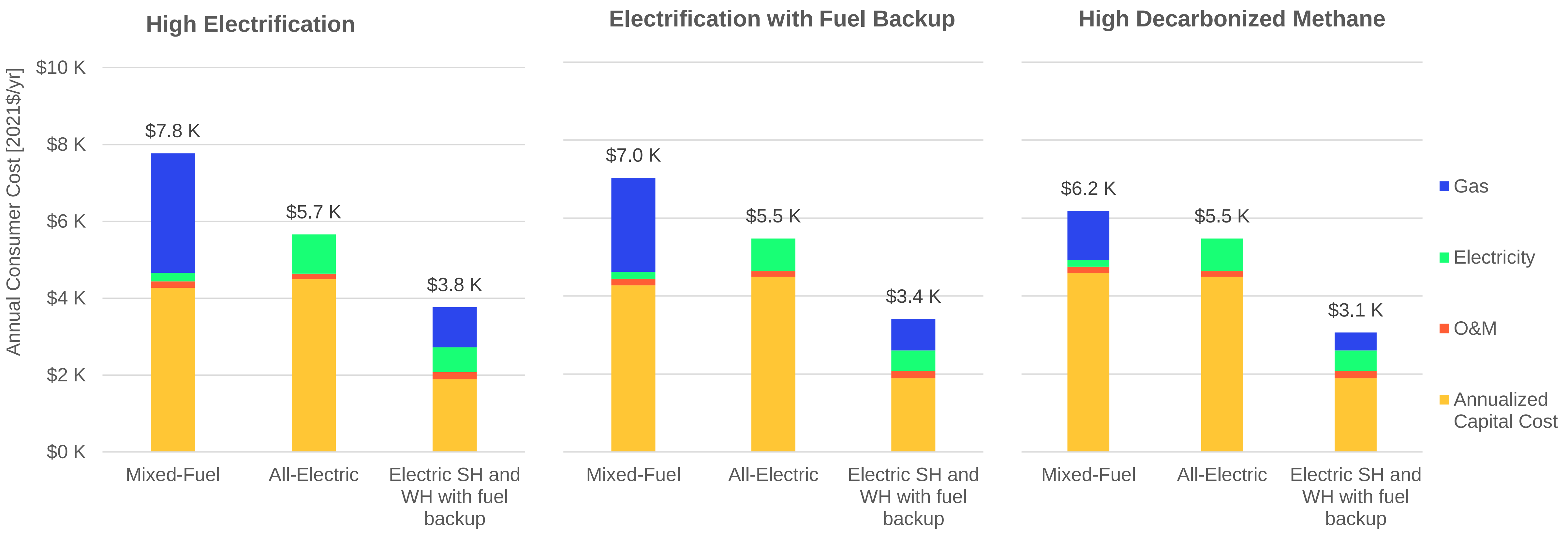
Illustrative customer bill impacts – residential single-family

- Across all scenarios, customers remaining on the gas system may experience a large increase in utility bills due to the blend of expensive RNG to decarbonize gas use
- CAVEAT: These are not predictions of customer bills, but a representation of the potential dynamics under the current ratemaking model. These results indicate the potential equity and affordability challenges that will require systemic changes to the current dynamics.



Electrifying heating with fuel backup is expected to be the least expensive option when both capital and operating costs are considered

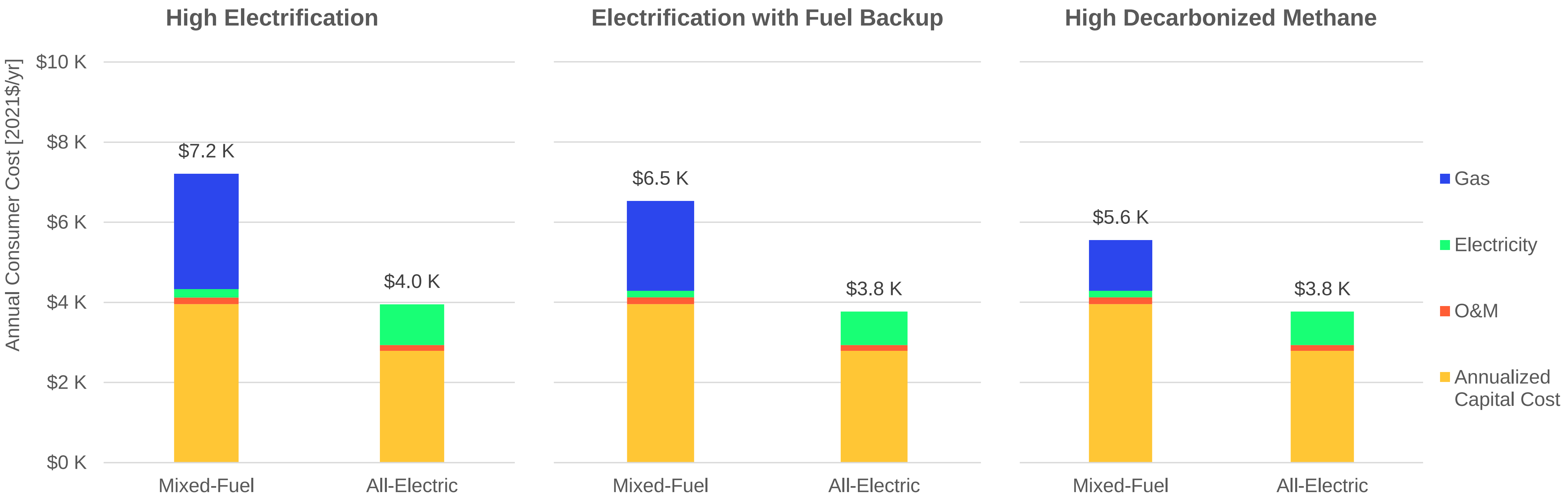
+ "Hybrid" customers can save money by utilizing their existing fuel-based heating equipment to provide backup heating during coldest hours of a year, and by not having to upgrade building shells



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent "optimistic" rate scenario

All-electric design is expected to be the less expensive option

+ **All-electric new construction is cheaper than mixed-fuel new construction for single-family residential homes across all decarbonization scenarios due to both lower capital (with avoided gas connection) and operating costs**



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent “optimistic” rate scenario

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Conclusions

Conclusions

+ **All scenarios** demonstrate technologically feasible pathways to achieve zero direct building emissions by 2045, but require extensive technology deployment and commercialization efforts.
+ The **Electrification with Fuel Backup** pathway shows lowest overall costs while also reducing reliance on technologies that have not yet been widely commercialized or that are uncertain in their scalability.
  - The **High Decarbonized Methane** pathway requires high demand for zero-carbon fuels, resulting in high incremental fuel costs with significant cost uncertainty
  - The **High Electrification** pathway results in a shift from a summer peak to a winter peak, mainly as a result of space heating loads in winter.
+ Consumers in **retrofit buildings** can save costs by employing a dual-fuel heating system with heat pumps providing majority of the heating need and fuel system providing backup during the coldest hours
  - **All-electric new construction** is found to be less expensive considering both equipment and fuel costs than those connecting to gas grid and using fuels for heating

Conclusions (cont’d)

+ **Achieving the Electrification with Fuel Backup pathway** would require careful policy design that incentivizes consumers to employ dual-fuel heating systems
    - For example, the current ratemaking model likely needs to be revisited, so that the right price signals are reflected in gas and electric rates and incentive consumers to switch to fuel backups during cold hours
+ **Each scenario** presents its own equity and affordability challenges
    - The average costs of the gas service are likely to increase in an electrification scenario as customers leave the system and infrastructure costs are spread over a smaller customer base.
    - Emphasis on mitigating the energy burden with customers ‘staying behind’ is important.
+ **Other factors** including but not limited to health impact, job impact and methane leakage, which are beyond the scope of this study, need further investigation to provide a more complete evaluation of impact of the different pathways

Appendix

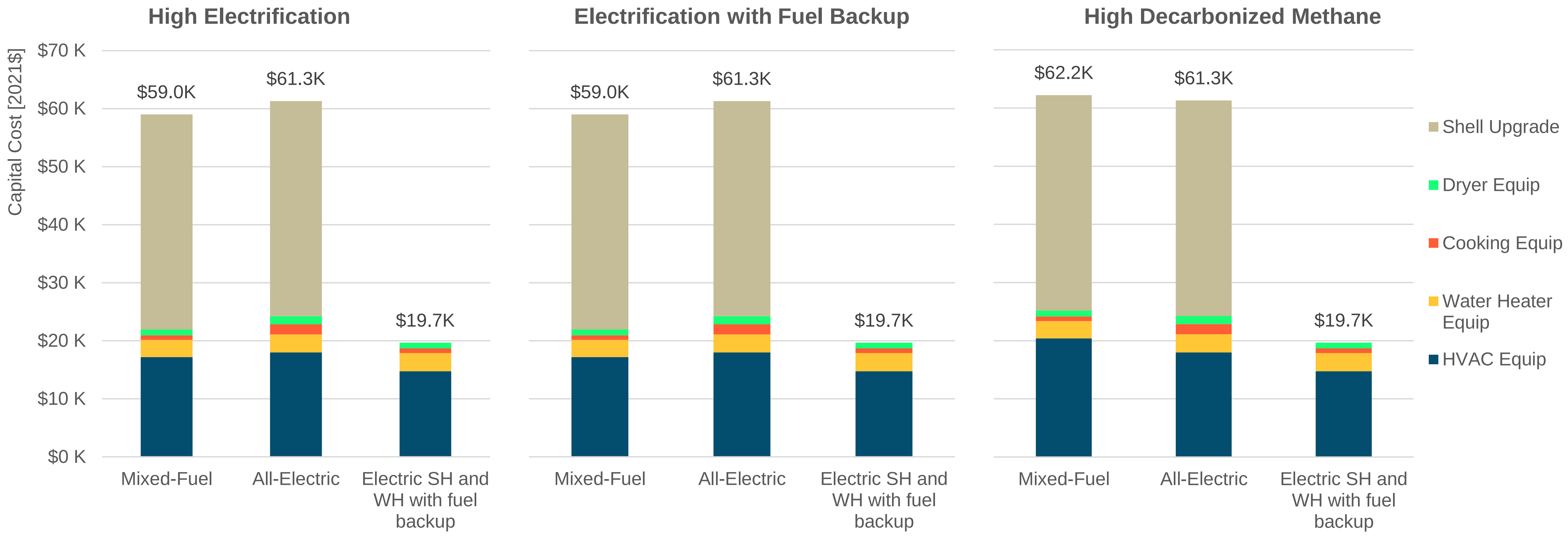
Energy+Environmental Economics

Energy+Environmental Economics

Additional Consumer Cost Results

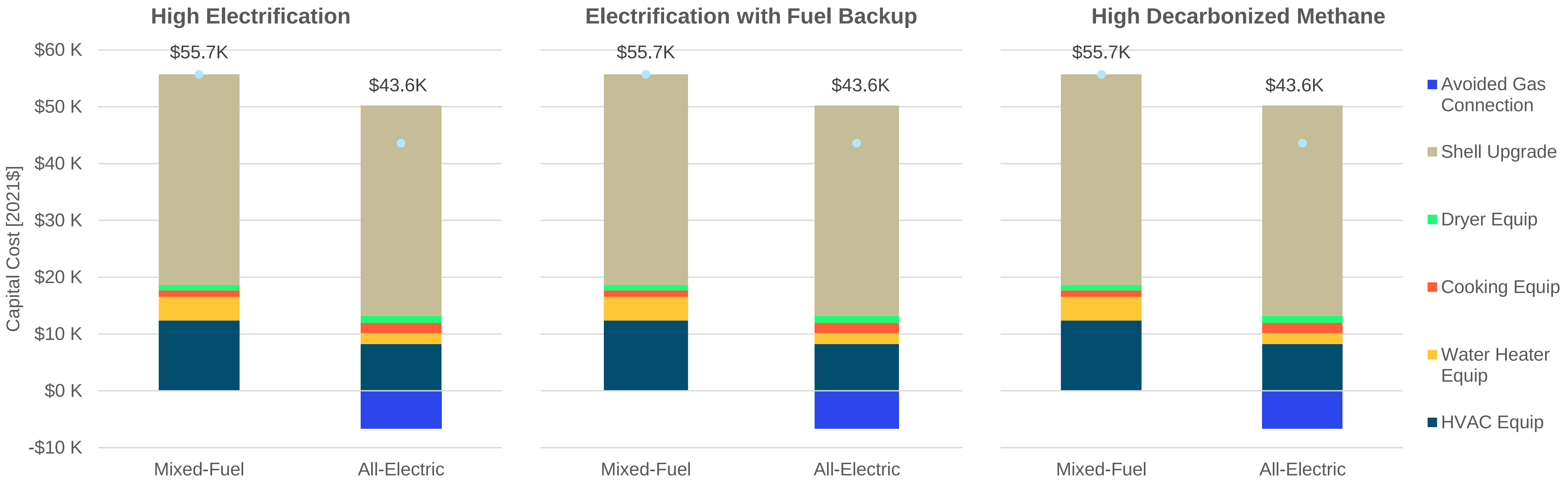
Switching to heat pumps saves costs for both retrofit and new construction residential single-family customers

+ **For single-family residential retrofit customers, installing a heat pump instead of a combined high-efficiency gas furnace + A/C system saves upfront cost**



Switching to heat pumps saves costs for both retrofit and new construction residential single-family customers

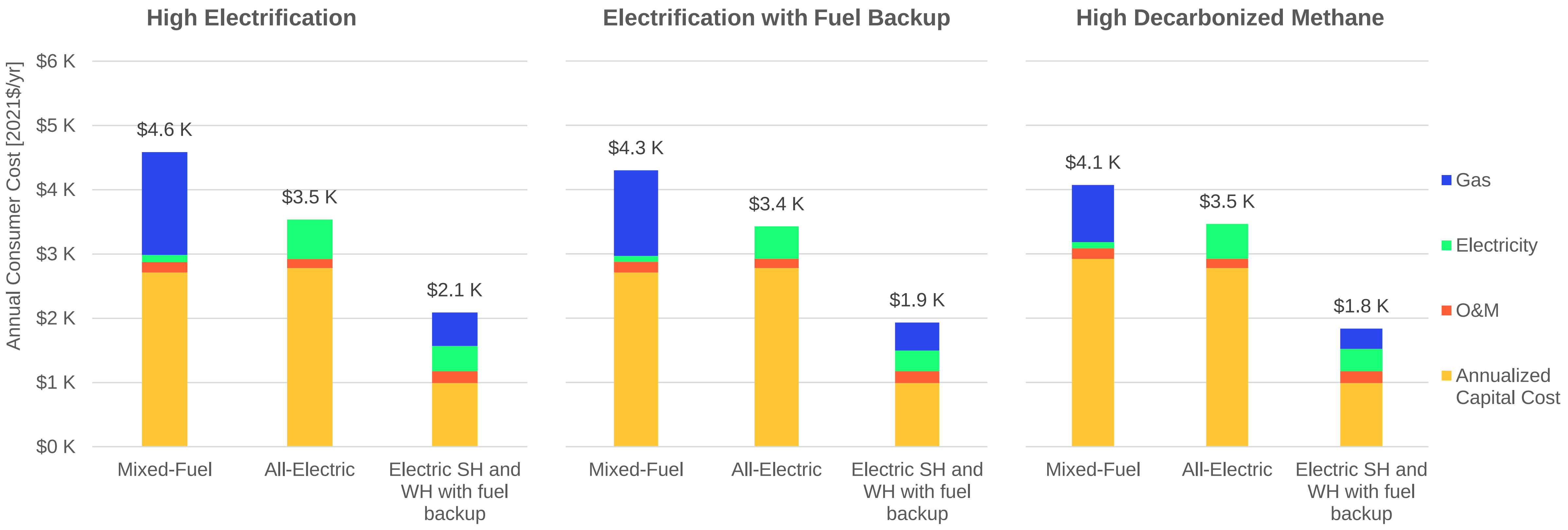
+ All-electric new construction buildings are less expensive than mixed-fuel buildings



Early Results and Preliminary

Multifamily residential retrofit consumer cost impact

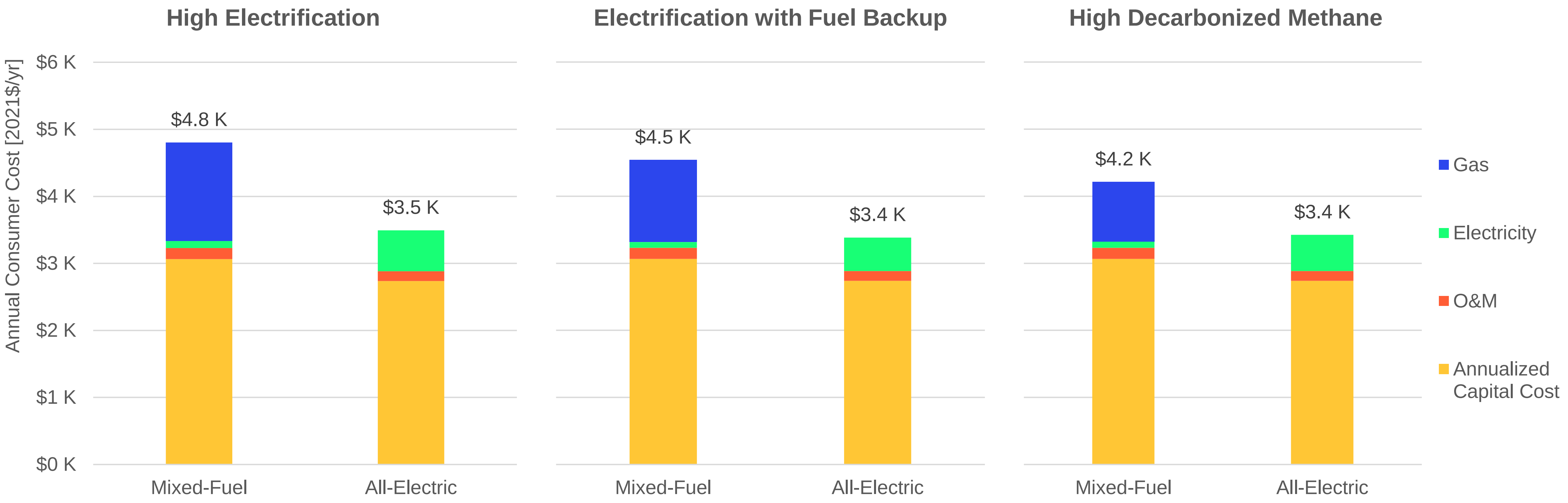
+ **"Hybrid" customers can save money by utilizing their existing fuel-based heating equipment to provide backup heating during coldest hours of a year, and by not having to upgrade building shells**



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent "optimistic" rate scenario ("conservative" gas scenario has 4% higher total cost for mixed-fuel)

Multifamily residential new construction consumer cost impact

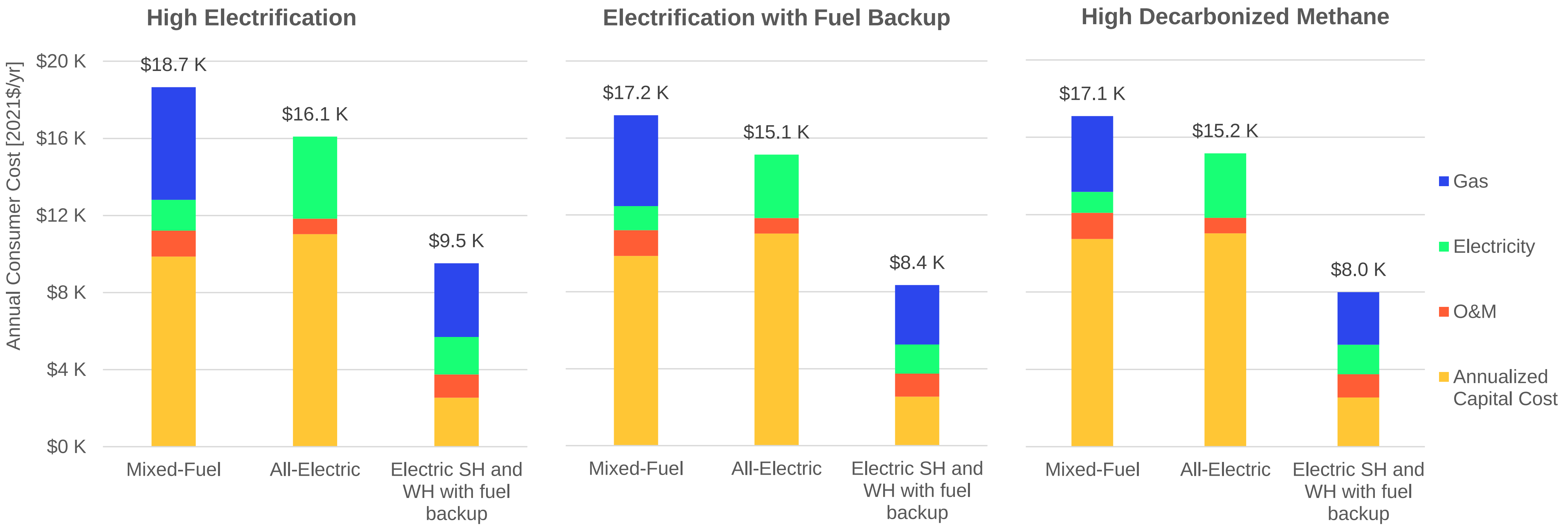
+ **All-electric new construction is cheaper than mixed-fuel new construction for multifamily residential homes across all decarbonization scenarios due to both lower capital (with avoided gas connection) and operating costs**



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent “optimistic” rate scenario (“conservative” gas scenario has 5% higher total cost for mixed-fuel)

Small commercial retrofit consumer cost impact

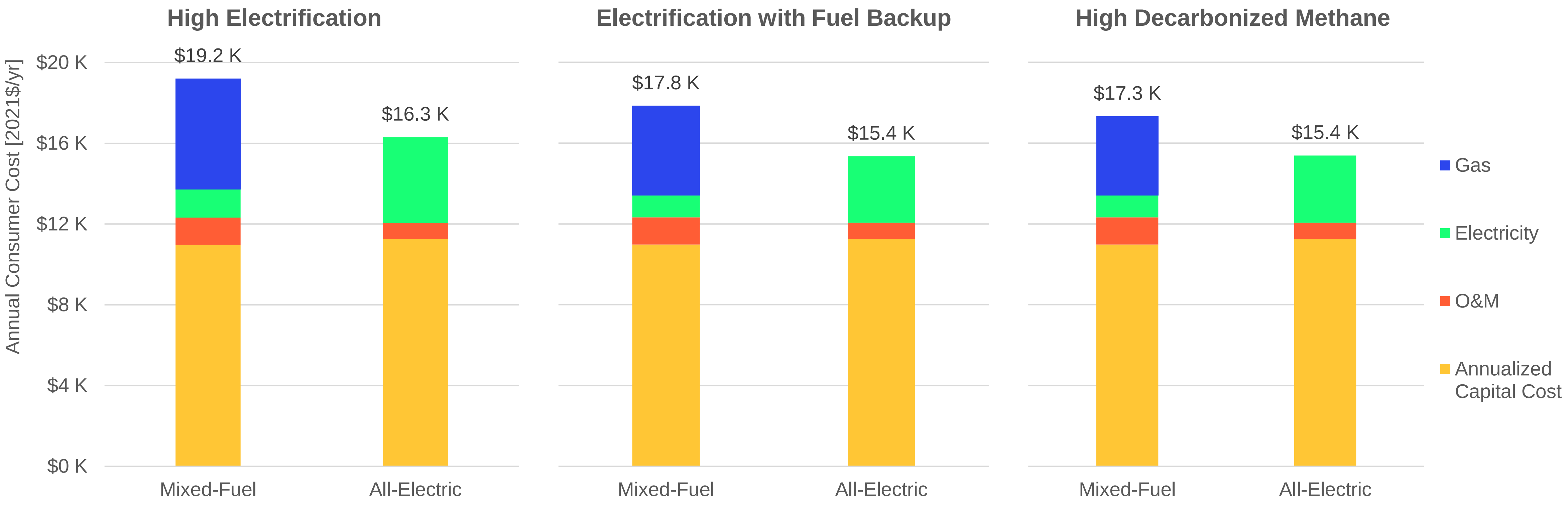
+ **"Hybrid" customers can save money by utilizing their existing fuel-based heating equipment to provide backup heating during coldest hours of a year, and by not having to upgrade building shells**



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent "optimistic" rate scenario ("conservative" gas scenario has 7% higher total cost for mixed-fuel)

Small commercial new construction consumer cost impact

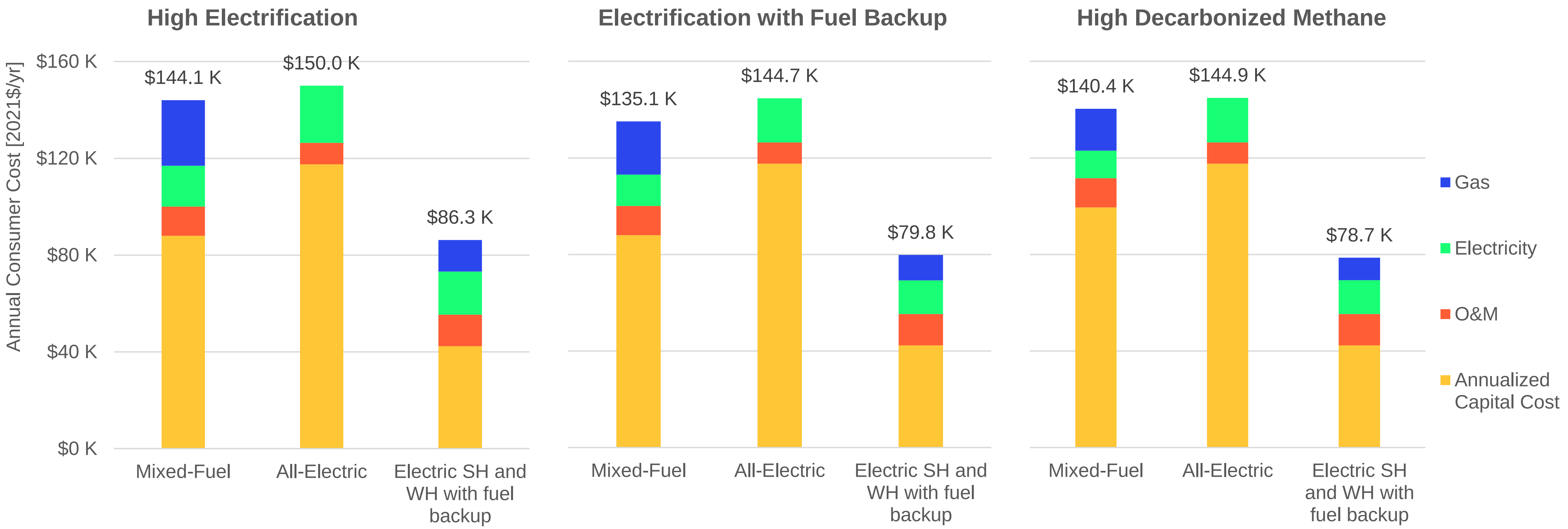
- All-electric new construction is cheaper than mixed-fuel new construction for small commercial buildings across all decarbonization scenarios due to both lower capital (with avoided gas connection) and operating costs



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent “optimistic” rate scenario (“conservative” gas scenario has 6% higher total cost for mixed-fuel)

Large commercial retrofit consumer cost impact

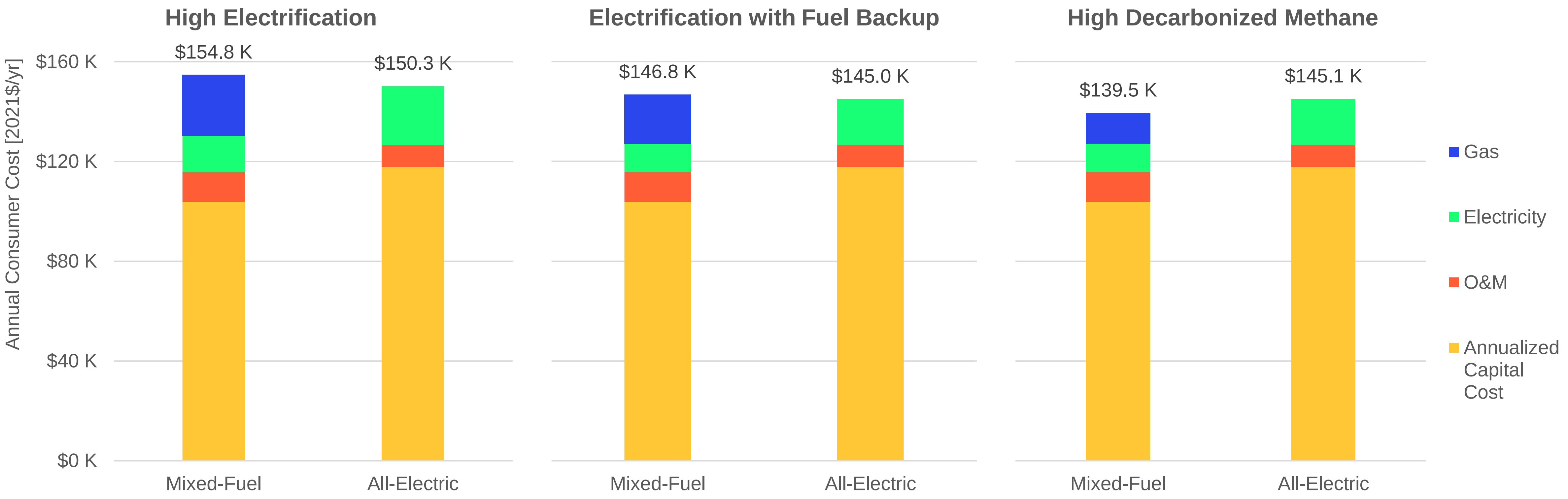
+ **"Hybrid" customers can save money by utilizing their existing fuel-based heating equipment to provide backup heating during coldest hours of a year, and by not having to upgrade building shells**



* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent "optimistic" rate scenario ("conservative" gas scenario has 6% higher total cost for mixed-fuel)

Large commercial new construction consumer cost impact

+ **All-electric new construction is cheaper than mixed-fuel new construction for large commercial buildings in a high electrification scenario and roughly cost neutral in all other decarbonization scenarios; By 2045, all-electric new construction is cheaper in every scenario**



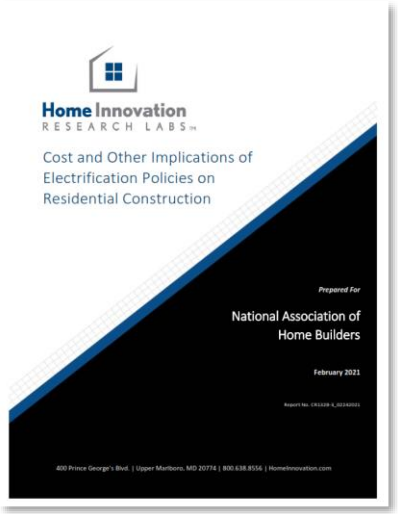
* Gas costs, electricity costs, and equipment costs are based on 2035 rates; Gas costs represent “optimistic” rate scenario (“conservative” gas scenario has 4% higher total cost for mixed-fuel)

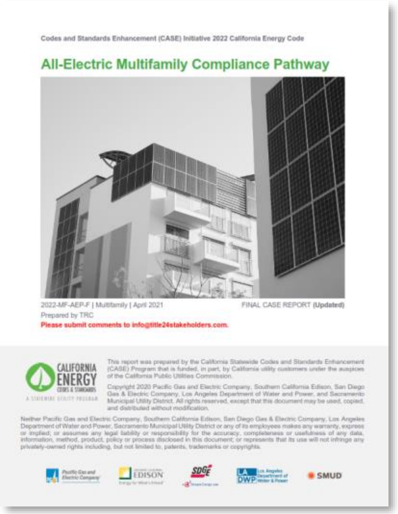
Energy+Environmental Economics

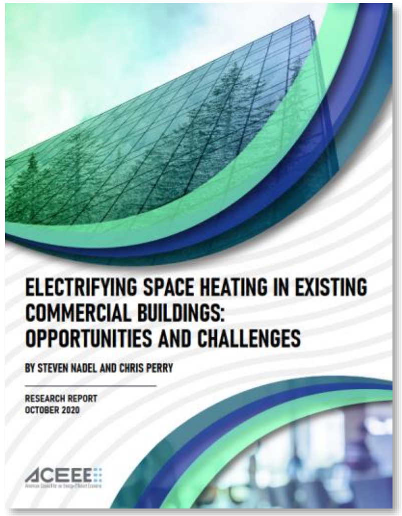
Equipment Cost Assumptions

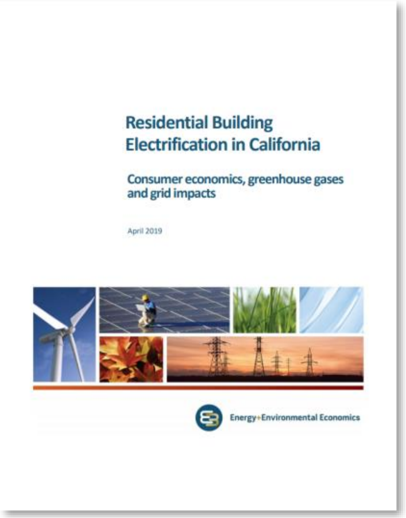
Equipment costs were identified for each electrification and efficiency measure considered for building decarbonization

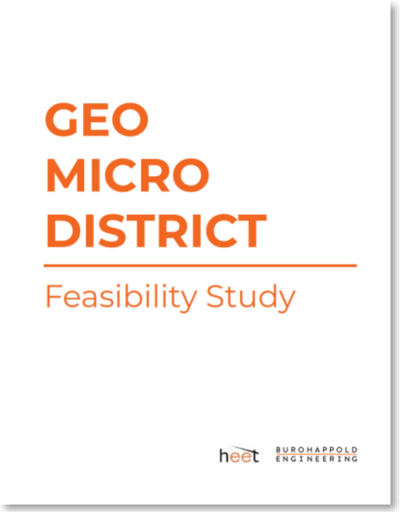
+ **Public data sources from national and statewide studies were used to identify equipment costs**
  - Cost and Other Implications of Electrification Policies on Residential Construction, National Association of Home Builders
  - All-Electric Multifamily Compliance Pathway, California Codes & Standards Enhancement (CASE)
  - Electrifying Space Heating in Existing Commercial Buildings: Opportunities & Challenges, ACEEE
  - Residential Building Electrification in California: Consumer Economics, Greenhouse Gases and Grid Impact, E3
  - Geo Micro District: Feasibility Study, HEET
  - Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study, Massachusetts Executive Office of Energy & Environmental Affairs
  - MassCEC Heat Pump Cost Database
  - National Energy Modeling System: An Overview 2018

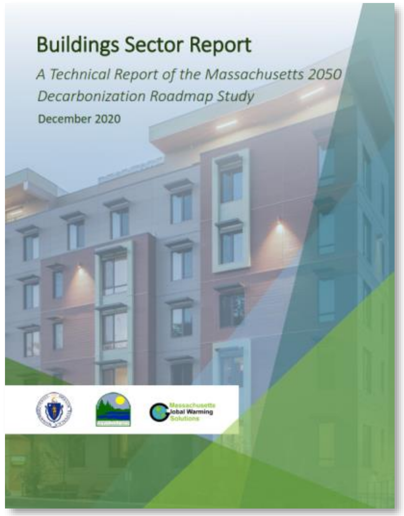












Equipment costs were identified for each electrification and efficiency measure considered for building decarbonization

+ Costs have been categorized by equipment typology

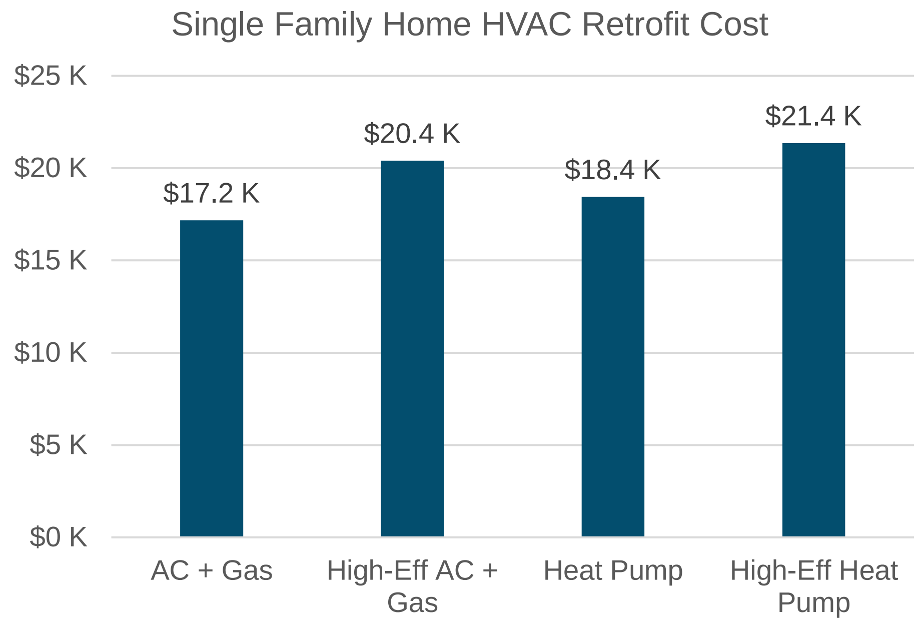
- For electrification, all-electric space heating, water heating, cooktops, and dryers were costed
- For efficiency, envelope and HVAC strategies were costed
- Geo Micro district heating and local GSHP were also included as an option for space heating
- Natural gas and fuel oil space heating, water heating, cooktops, and dryers were costed for comparison

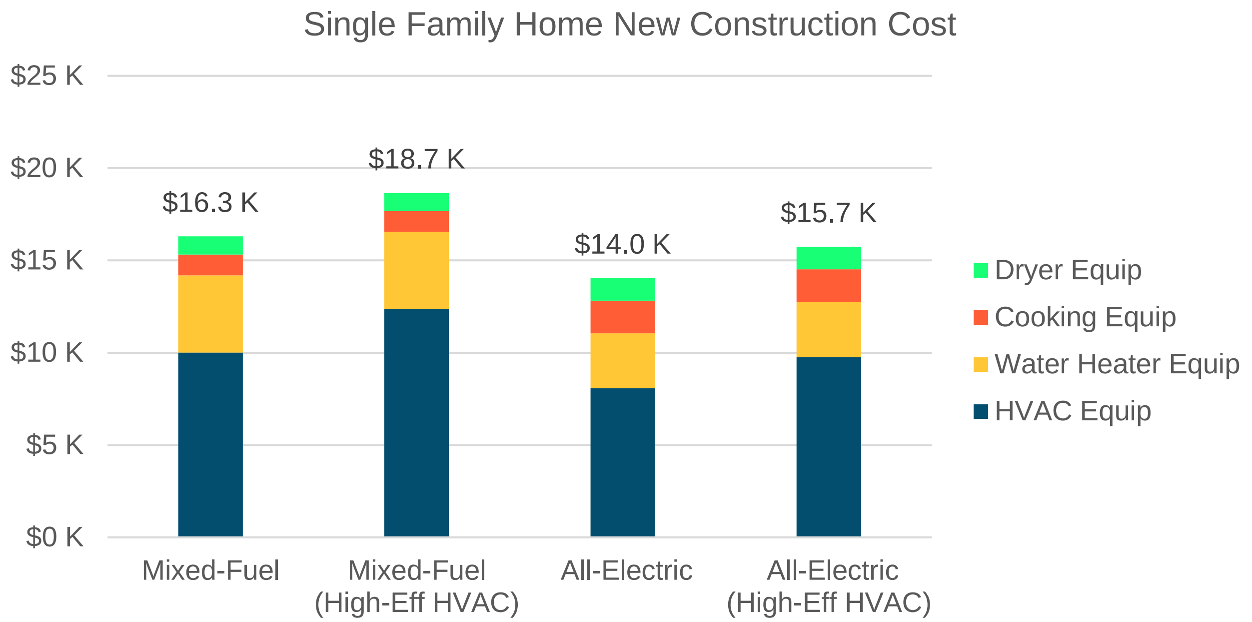
Equipment Category	Equipment Type
Air Conditioning	Air Conditioning Unit (Central & Zonal)
	High-Eff Air Conditioning Unit (Central & Zonal)
Space Heating	Gas Furnace (Central & Zonal)
	High-Eff Gas Furnace (Central & Zonal)
	Fuel Oil Furnace
	Air Source Heat Pump (Central & Zonal)
	High-Eff Air-Source Heat Pump (Central & Zonal)
	VRF
	Electric Resistance
	Ground Source Heat-Pump (Local & District)
Water Heating	Natural Gas
	Heat Pump
	Electric Resistance (Central & Zonal)
Envelope	Roof Insulation
	Wall Insulation
	Air-Tightness
	Glazing
HVAC	Heat Recovery Ventilation
	Demand Control Ventilation
Appliances	Electric Cooktop
	Gas Cooktop
	Electric Dryer
	Gas Dryer

Table 1. Equipment categorization

Equipment costs were aligned with building stock characterization and projected for average building sizes

- Single family res HVAC retrofit costs $17.2k-$20.4k for mixed-fuel and $18.4k-$21.4k for all-electric
- Single family res new construction costs $16.3k-$18.7k for mixed-fuel and $14.0k-$15.7k for all-electric





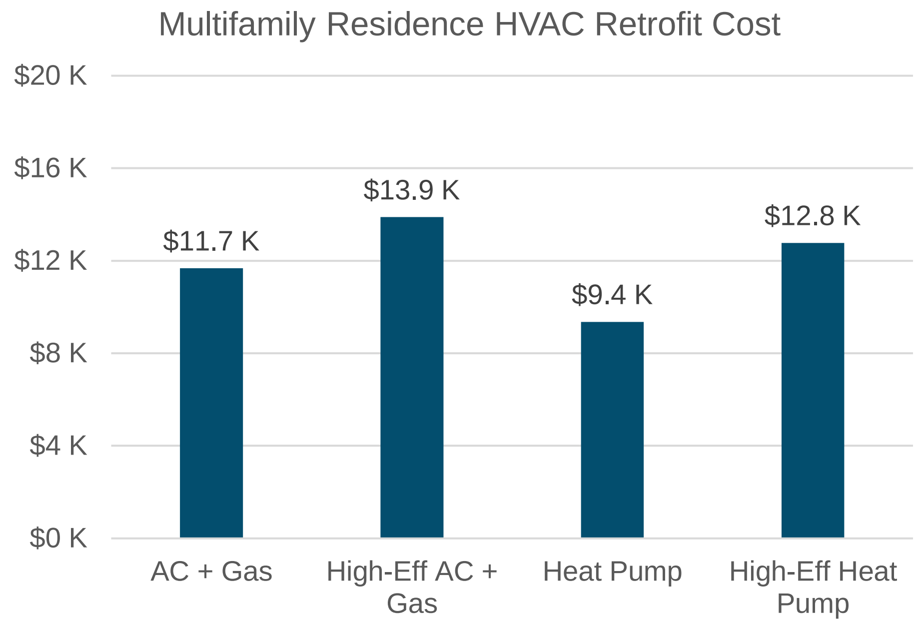
HVAC Equip Type	Ducted Attic Furnace, Split AC	Ducted Attic Furnace, Split AC	Ducted Split Heat Pump	Ducted Split Heat Pump	**HVAC Equip Type**	Ducted Attic Furnace, Split AC	Ducted Attic Furnace, Split AC	Ducted Split Heat Pump	Ducted Split Heat Pump
Data Source	Residential Building Electrification in California, National Energy Modeling System, Cost and Other Implications of Electrification Policies on Residential Construction				**Data Source**	Residential Building Electrification in California, National Energy Modeling System, Cost and Other Implications of Electrification Policies on Residential Construction			

Figure 1. HVAC Equipment retrofit costs for single family resi building sector

Figure 2. Total new construction equipment costs for single family resi building sector

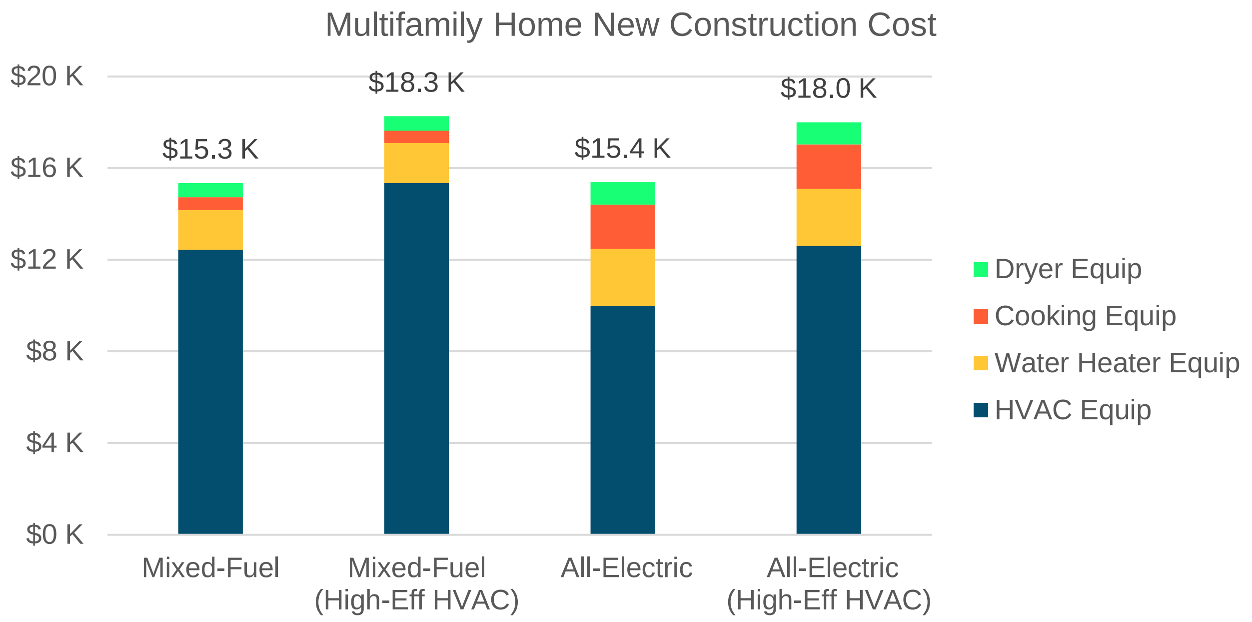
Equipment costs were aligned with building stock characterization and projected for average building sizes

- Multifamily res HVAC retrofit costs $11.7k-$13.9k for mixed-fuel and $9.4k-$12.8k for all-electric
- Multifamily res new construction costs $15.3k-$18.3k for mixed-fuel and $15.4k-$18.0k for all-electric
- Multifamily res HVAC new construction costs > retrofit costs due to higher efficiency equipment and new ductwork material costs



HVAC Equip Type	Hydronic AHU In-Unit, Split AC	Hydronic AHU In-Unit, Split AC	Package Terminal Heat Pump	Package Terminal Heat Pump
Data Source	Residential Building Electrification in California, National Energy Modeling System, Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study			

Figure 3. HVAC Equipment retrofit costs for multifamily resi building sector

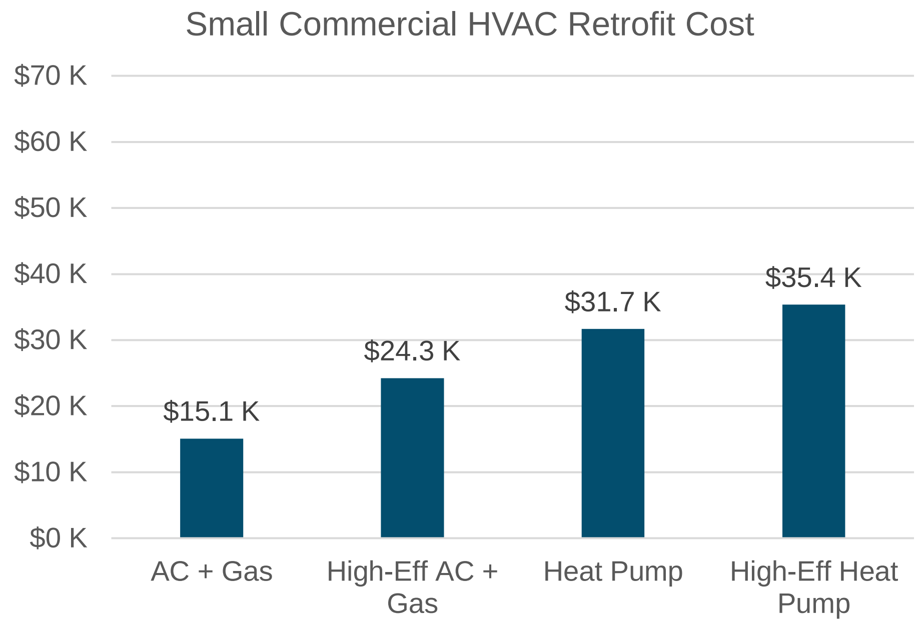


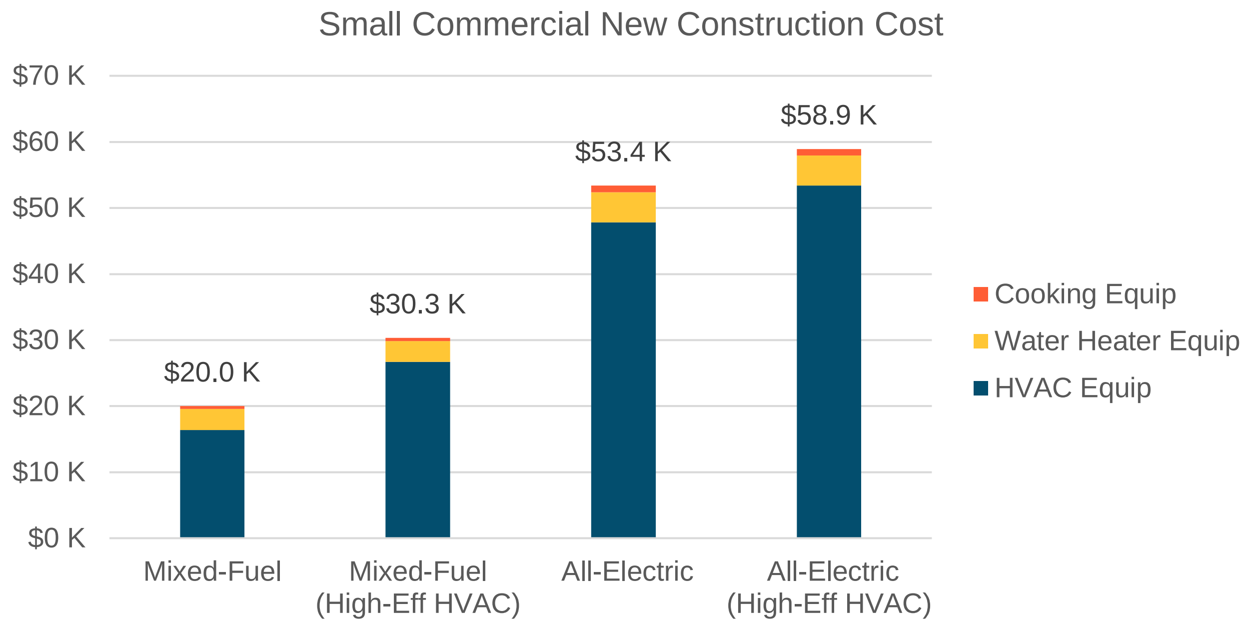
HVAC Equip Type	Ducted In-Unit Furnace, Split AC	Ducted In-Unit Furnace, Split AC	Ducted Mini-Split Heat Pump	Ducted Mini-Split Heat Pump
Data Source	Residential Building Electrification in California, National Energy Modeling System, Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study			

Figure 4. Total new construction equipment costs for multifamily resi building sector

Equipment costs were aligned with building stock characterization and projected for average building sizes

- Small comm HVAC retrofit costs \$15.1k-\$24.3k for mixed-fuel and \$31.7k-\$35.4k for all-electric
- Small comm new construction costs \$20.0k-\$30.3k for mixed-fuel and \$53.4k-\$58.9k for all-electric
- Small comm HVAC new construction costs > retrofit costs due to higher efficiency equipment and new ductwork material costs





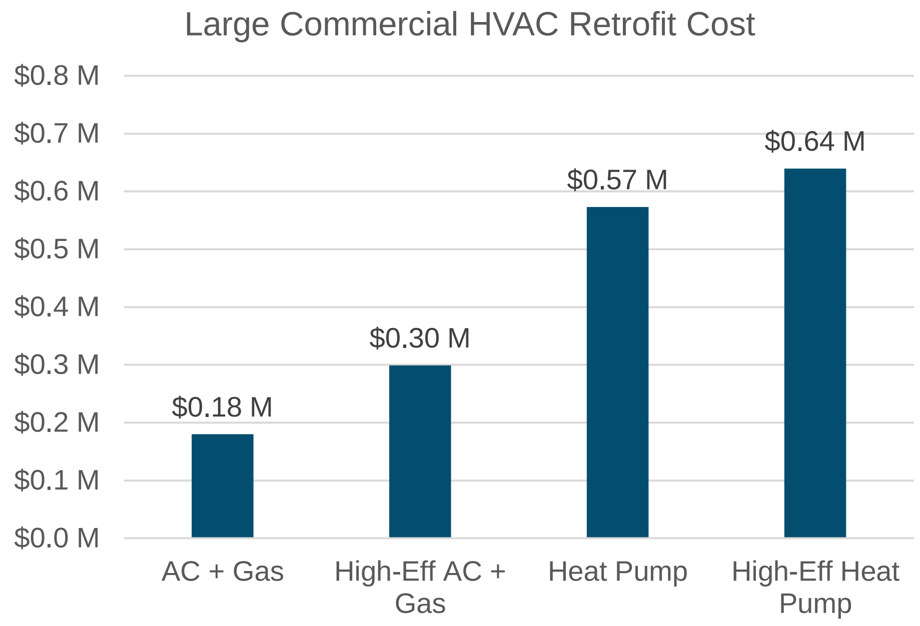
HVAC Equip Type	Central Boiler, Rooftop AC Unit	Central Boiler, Rooftop AC Unit	Ducted Mini-Split Heat Pump	Ducted Mini-Split Heat Pump	HVAC Equip Type	Central Boiler, Rooftop AC Unit	Central Boiler, Rooftop AC Unit	Ducted Mini-Split Heat Pump	Ducted Mini-Split Heat Pump
Data Source	National Energy Modeling System, Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study, MassCEC Heat Pump Cost Database				Data Source	National Energy Modeling System, Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study, MassCEC Heat Pump Cost Database			

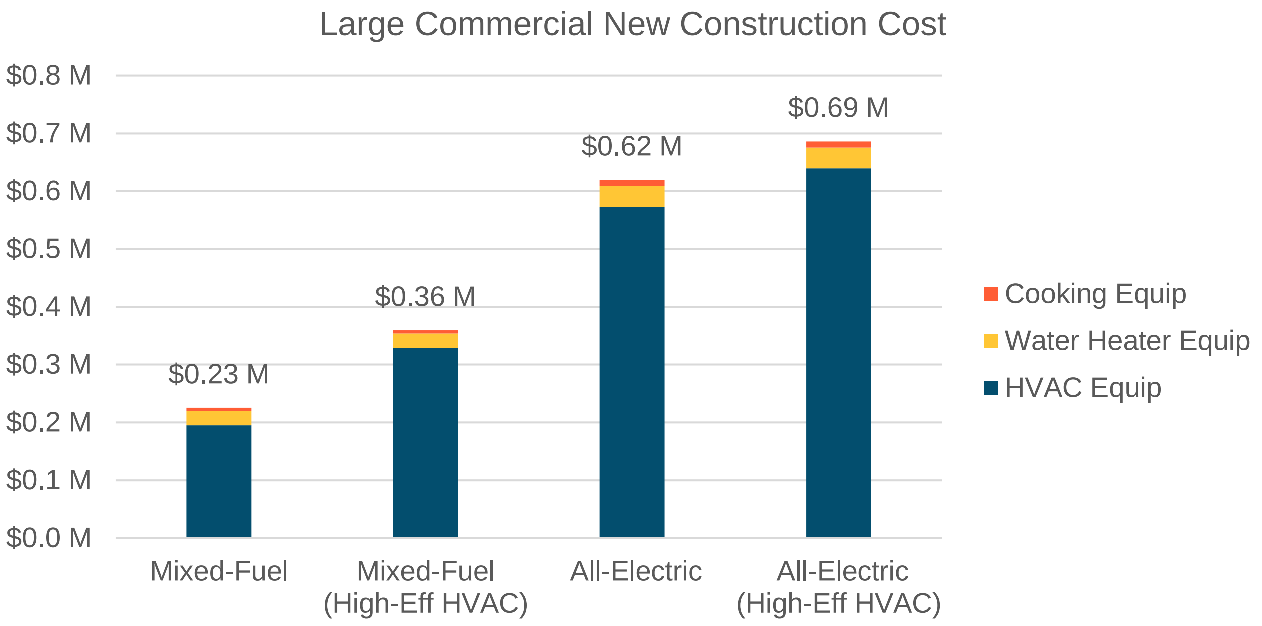
Figure 5. HVAC Equipment retrofit costs for small commercial building sector

Figure 6. Total new construction equipment costs for small commercial building sector

Equipment costs were aligned with building stock characterization and projected for average building sizes

+ **Large comm HVAC retrofit costs $0.18m-$0.30m for mixed-fuel and $0.57m-$0.64m for all-electric**
+ **Large comm new construction costs $0.23m-$0.36m for mixed-fuel and $0.62m-$0.69m for all-electric**
+ **Large commercial HVAC new construction costs are assumed to be equal to retrofit costs**





HVAC Equip Type	Central Boiler, Centrifugal Chiller	Central Boiler, Centrifugal Chiller	Central Air-Source Heat Pump	Central Air-Source Heat Pump	**HVAC Equip Type**	Central Boiler, Centrifugal Chiller	Central Boiler, Centrifugal Chiller	Central Air-Source Heat Pump	Central Air-Source Heat Pump
Data Source	National Energy Modeling System, Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study, MassCEC Heat Pump Cost Database				**Data Source**	National Energy Modeling System, Building Sector Report: A Technical Report of the Massachusetts 2050 Decarbonization Roadmap Study, MassCEC Heat Pump Cost Database			

Figure 7. HVAC Equipment retrofit costs for large commercial building sector

Figure 8. Total new construction equipment costs for large commercial building sector

Equipment costs trajectories were calculated up to 2050

- Residential retrofit heat pump costs are projected to decrease by 28% by 2050
- Commercial retrofit heat pump costs are projected to decrease by 37% by 2050

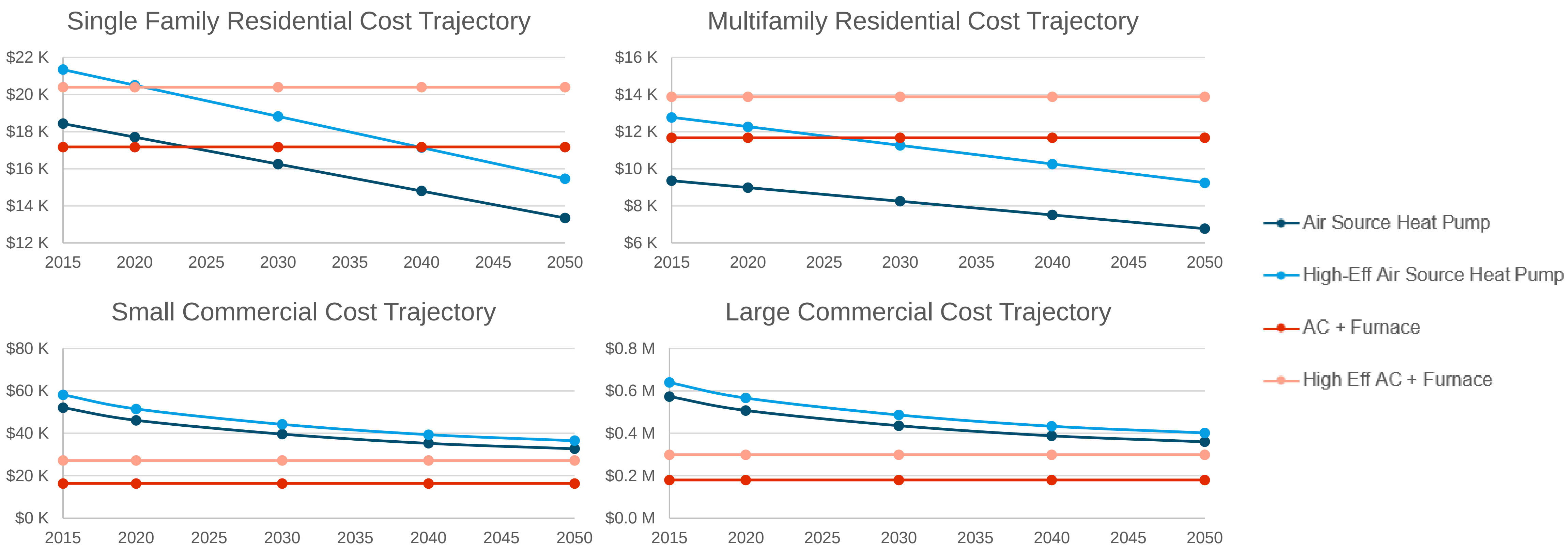


Figure 9. HVAC Equipment retrofit cost trajectories for each building sector

Detailed Equipment Cost A

Building Stock Characterization Segment	Single Family Residential Retrofit Costs ($/sq ft)																
Space Heating Equipment	AC	AC (high-eff)	Gas Furnace	Gas Furnace (high-eff)	ASHP	ASHP (high-eff)	Hybrid ASHP/ Furnace	Elec Res Heating	Gas Water Heater	HP Water Heater	Elec Res Water Heater	HR Vent	Shell Upgrade	Gas Cooktop	Electric Cooktop	Gas Dryer	Electric Dryer
Electric Resistance	$4.08	$5.14	-	-	$8.47	$9.81	-	$1.89	$1.37	$2.18	$3.04	$2.00	$15.02	$0.37	$0.80	$0.45	$0.64
Natural Gas	$4.08	$5.14	$3.81	$4.23	$8.47	$9.81	$8.05	-	$1.37	$2.18	$3.04	$2.00	$15.02	$0.37	$0.80	$0.45	$0.64
Fuel Oil	$4.08	$5.14	$3.81	$4.23	$8.47	$9.81	$8.05	-	$1.37	$2.18	$3.04	$2.00	$15.02	$0.37	$0.80	$0.45	$0.64
Heat Pump	-	-	-	-	$8.47	$9.81	-	-	$1.37	$2.18	$3.04	$2.00	$15.02	$0.37	$0.80	$0.45	$0.64
Other	$4.08	$5.14	$3.81	$4.23	$8.47	$9.81	$8.05	-	$1.37	$2.18	$3.04	$2.00	$15.02	$0.37	$0.80	$0.45	$0.64

Table 2. Equipment retrofit costs for single family residential building sector

Building Stock Characterization Segment	Single Family Residential New Construction Costs ($/sq ft)													
Space Heating Equipment	AC	AC (high-eff)	Gas Furnace	Gas Furnace (high-eff)	ASHP	ASHP (high-eff)	GSHP	Gas Water Heater	HP Water Heater	HR Vent	High-Perf Shell	Gas Cooktop	Electric Cooktop	Gas Dryer	Electric Dryer
All	$2.54	$3.20	$2.06	$2.48	$3.71	$4.49	$7.88	$1.92	$1.37	$2.00	$15.02	$0.52	$0.82	$0.45	$0.56

Table 3. Equipment new construction costs for single family residential building sector

Detailed Equipment Cost B

Building Stock Characterization Segment	Multifamily Residential Retrofit Costs ($/sq ft)																
Space Heating Equipment	**AC**	**AC (high-eff)**	**Gas Furnace**	**Gas Furnace (high-eff)**	**ASHP**	**ASHP (high-eff)**	**Hybrid ASHP/ Furnace**	**Elec Res Heating**	**Gas Water Heater**	**HP Water Heater**	**Elec Res Water Heater**	**HR Vent**	**Shell Upgrade**	**Gas Cooktop**	**Electric Cooktop**	**Gas Dryer**	**Electric Dryer**
Electric Resistance	$6.69	$8.43	-	-	$10.15	$13.86	-	$1.89	$1.89	$2.71	$3.04	$1.22	$23.08	$0.60	$2.10	$0.67	$1.05
Natural Gas	$6.69	$8.43	$5.97	$6.63	$10.15	$13.86	$9.64	-	$1.89	$2.71	$3.04	$1.22	$23.08	$0.60	$2.10	$0.67	$1.05
Fuel Oil	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Heat Pump	-	-	-	-	$10.15	$13.86	-	-	$1.89	$2.71	$3.04	$1.22	$23.08	$0.60	$2.10	$0.67	$1.05
Other	$6.69	$8.43	$5.97	$6.63	$10.15	$13.86	$9.64	-	$1.89	$2.71	$3.04	$1.22	$23.08	$0.60	$2.10	$0.67	$1.05

Table 4. Equipment retrofit costs for multifamily residential building sector

Building Stock Characterization Segment	Multifamily Residential New Construction Costs ($/sq ft)														
Space Heating Equipment	**AC**	**AC (high-eff)**	**Gas Furnace**	**Gas Furnace (high-eff)**	**ASHP**	**ASHP (high-eff)**	**GSHP**	**Gas Water Heater**	**HP Water Heater**	**HR Vent**	**High-Perf Shell**	**Gas Cooktop**	**Electric Cooktop**	**Gas Dryer**	**Electric Dryer**
All	$7.34	$9.25	$6.14	$7.39	$10.82	$13.66	$9.29	$1.89	$2.71	$1.22	$23.08	$0.60	$2.10	$0.67	$1.05

Table 5. Equipment new construction costs for multifamily residential building sector

Appendix A

Building Stock Characterization Segment	Small Commercial Retrofit Costs ($/sq ft)																
Space Cooling Equipment	**AC**	**AC (high-eff)**	**Gas Furnace**	**Gas Furnace (high-eff)**	**ASHP**	**ASHP (high-eff)**	**Hybrid ASHP/ Furnace**	**Elec Res Heating**	**Gas Water Heater**	**HP Water Heater**	**Elec Res Water Heater**	**HR Vent**	**Shell Upgrade**	**Gas Cooktop**	**Electric Cooktop**	**Gas Dryer**	**Electric Dryer**
Central AC	$2.73	$4.48	$0.54	$0.96	$10.42	$11.63	$9.90	$1.33	$0.64	$0.92	$0.47	$0.44	$27.22	$0.09	$0.20	$0.09	$0.14
Packaged AC	$2.48	$3.89	$0.54	$0.96	$6.34	$7.07	$6.02	$1.33	$0.64	$0.92	$0.47	$0.44	$27.22	$0.09	$0.20	$0.09	$0.14
Heat Pump	-	-	-	-	$10.42	$11.63	-	-	$0.64	$0.92	$0.47	$0.44	$27.22	$0.09	$0.20	$0.09	$0.14
No AC	-	-	-	-	$6.34	$7.07	$6.02	$1.33	$0.64	$0.92	$0.47	$0.44	$27.22	$0.09	$0.20	$0.09	$0.14

Table 6. Equipment retrofit costs for small commercial building sector

Building Stock Characterization Segment	Small Commercial New Construction Costs ($/sq ft)														
Space Cooling Equipment	**AC**	**AC (high-eff)**	**Gas Furnace**	**Gas Furnace (high-eff)**	**ASHP**	**ASHP (high-eff)**	**GSHP**	**Gas Water Heater**	**HP Water Heater**	**HR Vent**	**High-Perf Shell**	**Gas Cooktop**	**Electric Cooktop**	**Gas Dryer**	**Electric Dryer**
All	$2.99	$4.91	$0.56	$1.07	$9.56	$10.68	$9.04	$0.64	$0.92	$0.44	$27.22	$0.09	$0.20	$0.09	$0.14

Table 7. Equipment new construction costs for small commercial building sector

Building Stock Characterization Segment	Large Commercial Retrofit Costs ($/sq ft)																
Space Cooling Equipment	**AC**	**AC (high-eff)**	**Gas Furnace**	**Gas Furnace (high-eff)**	**ASHP**	**ASHP (high-eff)**	**Hybrid ASHP/ Furnace**	**Elec Res Heating**	**Gas Water Heater**	**HP Water Heater**	**Elec Res Water Heater**	**HR Vent**	**Shell Upgrade**	**Gas Cooktop**	**Electric Cooktop**	**Gas Dryer**	**Electric Dryer**
Central AC	$2.73	$4.48	$0.54	$0.96	$10.42	$11.63	$9.90	$1.33	$0.45	$0.65	$0.38	$0.55	$21.51	$0.09	$0.20	$0.09	$0.14
Packaged AC	$2.48	$3.89	$0.54	$0.96	$7.44	$8.31	$7.07	$1.33	$0.45	$0.65	$0.38	$0.55	$21.51	$0.09	$0.20	$0.09	$0.14
Heat Pump	-	-	-	-	$10.42	$11.63	-	-	$0.45	$0.65	$0.38	$0.55	$21.51	$0.09	$0.20	$0.09	$0.14
No AC	-	-	-	-	$7.44	$8.31	$7.07	$1.33	$0.45	$0.65	$0.38	$0.55	$21.51	$0.09	$0.20	$0.09	$0.14

Table 8. Equipment retrofit costs for large commercial building sector

Building Stock Characterization Segment	Large Commercial New Construction Costs ($/sq ft)														
Space Cooling Equipment	**AC**	**AC (high-eff)**	**Gas Furnace**	**Gas Furnace (high-eff)**	**ASHP**	**ASHP (high-eff)**	**GSHP**	**Gas Water Heater**	**HP Water Heater**	**HR Vent**	**High-Perf Shell**	**Gas Cooktop**	**Electric Cooktop**	**Gas Dryer**	**Electric Dryer**
All	$2.99	$4.91	$0.56	$1.07	$10.42	$11.63	$11.66	$0.45	$0.92	$0.44	$21.51	$0.09	$0.20	$0.09	$0.14

Table 9. Equipment new construction costs for large commercial building sector