BGE Integrated Decarbonization Strategy

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About this study

The transition to a deeply decarbonized economy is underway in Maryland, building upon over a decade of climate change mitigation efforts led by the State, utilities, and other key stakeholders. The Maryland Department of Environment (MDE) began to chart this path, supported by E3's analysis, by considering scenarios that meet the statewide Greenhouse Gas Reduction Act (GGRA) goals of 40% reductions in greenhouse gas (GHG) emissions below 2006 levels by 2030.[1] MDE then built on this work by engaging with E3 to develop more ambitious illustrative decarbonization pathways for the buildings sector, which confirmed that building electrification is critical to reducing emissions to net zero by 2045, and that pursuing a mix of technologies, including hybrid systems, helps to decrease costs.[2]

Expanding upon these recent statewide analyses, in late 2021, E3 began working with Baltimore Gas and Electric (BGE) to assess decarbonization options within BGE's service territory, focusing on impacts for BGE's gas and electric customers. With the subsequent introduction and April 2022 passage of the Climate Solutions Now Act of 2022 (CSNA), this latest E3 analysis represents the first decarbonization study developed since CSNA's enactment and shows the value of coordinated electric and gas infrastructure planning in meeting Maryland's new goals of 60% reductions by 2031 and net zero GHG emissions by 2045.

Reducing emissions from both Maryland's building and industrial sectors will be critical to achieve the State's climate targets. Direct fuel use in Maryland's building and industrial sectors accounts for 11% and 6% of State emissions respectively. As the largest utility in Maryland, serving approximately half of the state's residential, commercial, and industrial gas customers, BGE is a key partner in decarbonizing these sectors.

BGE currently delivers electricity to 1.3 million customers and natural gas to nearly 700,000 customers through its networks of electric and gas infrastructure. The decarbonization strategies that Maryland and BGE's customers pursue will materially impact the relative emphasis of the company's investment in its electric and gas infrastructure. Those changes will in turn affect BGE customers' costs to safely and reliably power and heat their homes and businesses, as well as their costs associated with transportation and mobility.

E3 developed an economy-wide Pathways model for BGE's service territory to evaluate plausible options that achieve the state's climate goals. E3's modeling approach includes an economy-wide treatment of energy demands across BGE's service territory, an assessment of impacts on both electric and fuel energy supply transformations that occur upstream of BGE's system, impacts on BGE's gas and electric infrastructure, and an assessment of implications of decarbonization for customer affordability.

E3 worked with BGE to develop three alternative decarbonization scenarios that vary the use of the Company's gas and electric infrastructure and the mix of technology solutions that customers adopt

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[1] https://mde.maryland.gov/programs/air/ClimateChange/Documents/2030%20GGRA%20Plan/Appendices/Appendix%20F%20-%20Docuementation%20of%20Maryland%20PATHWAYS%20Scenario%20Modeling.pdf

[2] https://mde.maryland.gov/programs/Air/ClimateChange/MCCC/MWG/Decarbonizing%20Buildings%20in%20Maryland.pdf

across sectors. The scenarios are summarized in Figure ES-1. Throughout this report, the Hybrid and Diverse scenarios are referred to as Integrated Energy System Scenarios, meaning that they rely on a combination of electric and gas infrastructure to achieve decarbonization. In contrast, the Limited Gas scenario shifts a larger share of energy demands to BGE's electric system.

Figure ES-1. Decarbonization scenario assumptions by sector

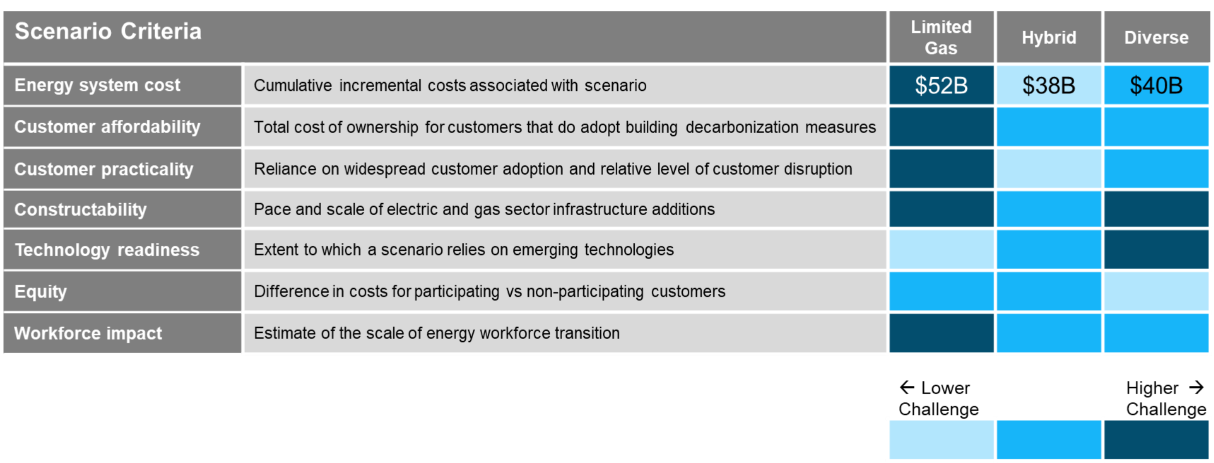
		Integrated Energy System Scenarios	
	1. Limited Gas	2. Hybrid	3. Diverse
Scenario narrative	High-electrification and shift away from delivered gas and other fuels	Leverages an increasingly clean electric system, high electrification, and the gas network	
Buildings	Efficiency and electrification	Efficiency, electrification, gas-electric hybrids, and a targeted role for alternative fuels	Efficiency, electrification, gas-electric hybrids, gas heat pumps, network geothermal, and alternative fuels
Industry	Efficiency and electrification	Efficiency, electrification, and alternative fuels	Efficiency, electrification and alternative fuels
Transportation	LDV electrification and alternative fuels for MDV & HDV		
Electricity	Zero-carbon electricity by 2045		
Other Sectors	66% reduction by 2045		

Key Findings

There are multiple viable paths to decarbonization, and any future that meets net zero will require significant transformations and investments across the economy and a role for electrification in buildings and transportation.

1. **Pathways that rely on an Integrated Energy System carry a lower overall cost and level of challenge relative to those that rely more exclusively on electrification or renewable gases.** Electrification is the core engine of decarbonization across all scenarios considered in this report because of its high level of commercialization, scalability, and complementarity to an increasingly decarbonized electricity system. However, scenario findings identify ongoing value for gas infrastructure that deliver an increasing blend of renewable gases[3] as a complement to electrification. Gas infrastructure serves as an existing, low-cost source of capacity that reduces the amount of electric generation, transmission and distribution capacity that will need to be added over the coming decades. Investments in gas infrastructure, including the STRIDE Program, help to modernize the system, reduce methane emissions and improve safety and reliability. Those investments could be balanced against future opportunities to pursue targeted electrification that enable gas infrastructure savings where such initiatives produce system and ratepayer cost savings. An integrated approach that leverages the advantages of both electric and gas infrastructure can help to reduce both total energy system and consumer costs, while also reducing challenges associated with large-scale electric infrastructure additions and customer retrofits, while still achieving decarbonization across all sectors.

Figure ES-2. Assessment of the level of challenge across evaluation criteria for decarbonization scenarios. "Level of challenge" denotes the extent to which the scenario is substantially different from current practices, policies, or technologies.

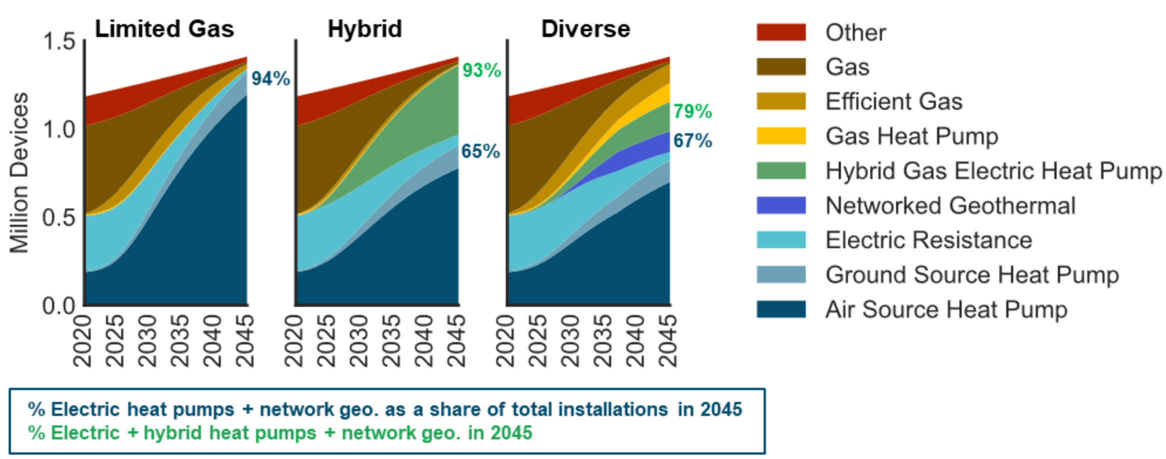


[3] Renewable gases considered in this study encompass renewable natural gas from biogenic sources produced via anaerobic digestion and gasification, hydrogen produced via electrolysis powered by renewable energy, and synthetic natural gas produced using hydrogen and a climate neutral source of CO2.

2. **All scenarios that achieve net-zero require significant investments in electric generation and delivery infrastructure, but those costs can be mitigated via an integrated approach**. Clean electric generation capacity will need to be sited, permitted, built and interconnected into the grid. BGE's electric delivery system will need to increase in capacity and modernize to accommodate new electrification loads while at the same time the energy it delivers via both gas and electricity will need to become cleaner. Relying on a dual energy approach reduces the overall scale of infrastructure additions required to achieve net-zero goals. As a result, pathways that rely on an integrated energy system are lower cost than all-electric or all-renewable gas based pathways [4] and have a lower level of challenge in terms of the constructability of new infrastructure, while providing more flexibility to navigate rapidly-changing technological and market developments to continue to allow the most appropriate choices for all customers throughout the energy transition. Those advantages are tempered by higher reliance on renewable fuels, which have a comparably lower level of technology readiness compared to all-electric measures.

3. **Consumers are central to the transformations required to achieve net-zero** and achieving the scale of adoption envisioned here will require developing solutions that are affordable and work for all customers, equitably. All-electric solutions can lead to higher retrofit costs for existing buildings, particularly older buildings, relative to alternatives. Decarbonization pathways that include a diverse set of heating technologies enable strategic application of all-electric solutions where they are most appropriate, while allowing for alternative strategies in cases where all-electric solutions are more challenging. Lower income customers are expected to face higher energy burdens, particularly in the Limited Gas scenario, so identifying strategies to mitigate those impacts will be critical to achieving a just transition to net-zero. Relative to Limited Gas, the Hybrid and Diverse scenarios offer potential pathways through which the energy burden of decarbonization can be managed.

Figure ES-3. Stock transition for residential space heating devices in BGE's territory



[4] This study does not directly consider an all renewable gas based pathway. Such a pathway was considered in the MD Buildings Report and was found to carry a high degree of challenge across several different considerations.

4. **As Maryland's largest utility, BGE will have an important role in supporting customer adoption of decarbonization options by introducing and scaling new products, programs, and services required to achieve net zero** through, for example, research and demonstration programs, incentives, and new types of infrastructure investments. Examples where BGE could have a role in facilitating and scaling decarbonization technologies include, but are not limited to, strategic electrification, networked geothermal, and green hydrogen production and delivery. BGE's role could also include working to ensure that all its customers are able to participate in and share the benefits of the decarbonization transition by, for example, ensuring equitable electric vehicle charging infrastructure in disadvantaged communities, supporting efficient heating technologies adoption for low-income customers, and finding additional ways to protect low-income customers from bearing undue burdens through the energy transition.

5. **Regulatory and policy support will be necessary to manage the challenges associated with decarbonization.** Regulatory and policy interventions are needed in several areas including, but not limited to, enabling BGE and its customers to support the state's decarbonization ambitions in order to manage the cost impacts of implementing decarbonization, supporting customer adoption of electrification technologies, and implementing non-pipe alternatives projects.

Key Recommendations

Based on the key findings of this study, E3 recommends the following strategies to BGE, its regulators, policymakers and other key stakeholders in Maryland:

1. **Increase funding for and scope energy efficiency programs and align measures to support decarbonization.** All scenarios include levels of energy efficiency savings that go beyond even Maryland's current ambitious targets and include both traditional efficiency measures and electrification. For that to happen, additional funding is likely needed and measures like weatherization of buildings will need to be emphasized even further.

2. **Develop incentives and other programs to support building decarbonization in new construction and in retrofits**. Customer incentives will be needed to support the adoption of building decarbonization technologies, including bringing down the up-front customer costs of retrofits and equitably supporting low-income customers with cleaner technologies choices.

3. **Support development of electric vehicle charging infrastructure and vehicle adoption**. Transportation electrification is a common feature of all the scenarios evaluated. For transportation electrification to scale to levels consistent with decarbonization goals, sufficient at-home, workplace, and public charging infrastructure is required, along with investments in electric grid infrastructure, management, and technology solutions to support such widespread transportation electrification.

In addition to those initiatives, E3 recommends that BGE, its regulators and policymakers in Maryland pursue the following types of research and development, demonstration, or pilot activities to support GHG reductions within BGE's gas delivery service:

1. **Pilot and develop hybrid electrification operations and control strategies.** E3 recommends that BGE pilot alternative hybrid heat pump operations to optimize the use of its combined electric and gas infrastructure. Supportive rate design structures, as well as the collection of real-world customer adoption and system performance data are needed to validate the potential benefits of hybrid electrification strategies in Maryland.

2. **Pilot and develop a networked geothermal pilot program.** Networked geothermal systems, which are renewably powered heating and cooling systems, hold the potential to provide commercial and home heating in a manner that substantially reduces electric system impacts, offers a possible transition path for BGE's gas workers, and could diversify BGE's business and operations to better support Maryland's energy transition. Networked geothermal systems are currently being piloted in Massachusetts and New York. Detailed engineering studies of networked geothermal potential in Maryland, followed by demonstrations, and supportive rate design structures, are needed to develop real-world cost data and experience with these systems in Maryland.

3. **Develop statutory support and a regulatory process to identify opportunities for non-pipeline alternatives to avoid or reduce conventional gas infrastructure investments. Define the utility incentives and cost-recovery mechanisms for non-pipeline alternatives to ensure the projects result in customer cost savings**. All-electric solutions like networked geothermal or air-source heat pumps are most likely to be cost effective in instances where gas infrastructure can be avoided and where the electric system has sufficient capacity. Developing a process to assess the technical feasibility, customer acceptance, and net-benefits or costs of non-pipeline programs would therefore help to identify where all-electric vs integrated gas-electric approaches are most warranted. Any non-pipeline alternative initiatives will need to be balanced against the safety, reliability and methane emissions reduction benefits of ongoing gas infrastructure replacement programs, including the Strategic Infrastructure Development and Enhancement (STRIDE) program.

4. **Support the emergence of renewable natural gas (RNG) supply sources and associated regulatory support and rate development**. RNG resources are leveraged in all scenarios though, given the modeled pace of electric sector decarbonization and electrification, these resources are not blended into the gas delivered by BGE until after 2030. In practice, BGE should consider procuring initial quantities of RNG before then to gain familiarity with the technology and support the development of regulatory standards through which these resources can be procured and developed.

5. **Pilot blends of hydrogen and dedicated hydrogen infrastructure.** The Hybrid and Diverse cases envision blends of hydrogen to reduce the GHG intensity of BGE's gas supply. Other studies[5]

[5] See for example: https://www.socalgas.com/sites/default/files/2021-10/Roles_Clean_Fuels_Full_Report.pdf and https://gasforclimate2050.eu/wp-content/uploads/2022/04/EHB-A-European-hydrogen-infrastructure-vision-covering-28-countries.pdf

have explored a role for dedicated hydrogen to decarbonize clusters of industrial activity. Similar to RNG, the use of hydrogen does not need scale until after 2030, so the remainder of this decade presents an opportunity to explore the technical and operational requirements of both dedicated hydrogen and hydrogen blends.

Introduction

Context and Previous Work

In 2022, the Maryland General Assembly enacted the CSNA, which calls for a 60% reduction in the state's GHG emissions by 2031 relative to 2006 levels and net-zero GHG emissions by 2045. These commitments established Maryland as a leading state in economy-wide climate policy ambition. While Maryland has already made meaningful progress towards a cleaner energy economy via policies like the Renewable Portfolio Standard and programs like EmPOWER Maryland, more action will be needed to realize the state's new targets.

The State of Maryland, supported by analysis by E3 conducted under the direction of the MDE, has done extensive analysis and research to evaluate pathways to decarbonize the state. In early 2021, MDE published the GGRA Plan, which described how the state would meet its previous goal of a 40% reduction in economy-wide emissions by 2030. The GGRA Plan identified strategies such as renewable and decarbonized electricity, energy efficiency and electrification as pivotal components of achieving the state's decarbonization targets. The final GGRA Plan scenario achieved a 48% reduction by 2030, exceeding the prior target but falling short of the new goal of 60% reductions by 2031. Though the focus of this work was the 2030 target, modeling extended through 2050, which allows for a comparison between those scenarios and the new targets under the CSNA. The GGRA Plan scenario achieved a 68% reduction by 2045 and an optimistic sensitivity achieved 81% reductions by 2045, highlighting a gap where new policies and actions will be needed to achieve the new CSNA goal of net zero by 2045.

The State followed its economy-wide work with a targeted sector analysis, the Maryland Building Decarbonization Study (MD Building Study), also supported by E3, which focused on options to reduce GHG emissions in the state's building sector by 86%-100%, going beyond the ambition in the GGRA. The MD Building Study further explored the role of energy efficiency in reducing building sector emissions and compared alternative pathways to decarbonize building heating loads. A key conclusion of the MD Building Study was that hybrid electrification, or electric heat pumps with fuel back-up, lower the total net incremental cost of achieving deep GHG emissions reductions in the building sector than scenarios that relied exclusively on electrification or renewable fuels.

Scope of this Study

As Maryland's largest energy utility, BGE delivers energy to approximately half the population of Maryland, including over 1.3 million electric and nearly 700,000 natural gas customers. BGE does not own electric generation infrastructure, nor does it produce natural gas. Instead, BGE owns networks of electric and gas infrastructure that deliver energy to its customers. In addition, BGE offers customer programs to support its customers in becoming more energy efficient or enabling them to adopt new technologies like electric vehicles. With that, BGE will play a key role in the transformation to a clean energy economy targeted by the State.

BGE originally retained E3 to explore potential strategies to achieving BGE's decarbonization targets for itself and its broader decarbonization goals for customers' own energy and sustainability choices. After initial engagement in 2021, upon introduction of early forms of the CSNA in 2022 and its passage in April 2022, BGE specifically asked E3 to build on its prior efforts in the State by evaluating the implications of decarbonization strategies that achieve the state's newly legislated net-zero targets with an intent to understand how BGE's electric and gas businesses and infrastructure could play a supporting role. Given the significant existing scenario analysis in Maryland, E3 was able to build on the foundation of core assumptions with scenarios specific to BGE's service territory and align with the new statewide emissions goals.

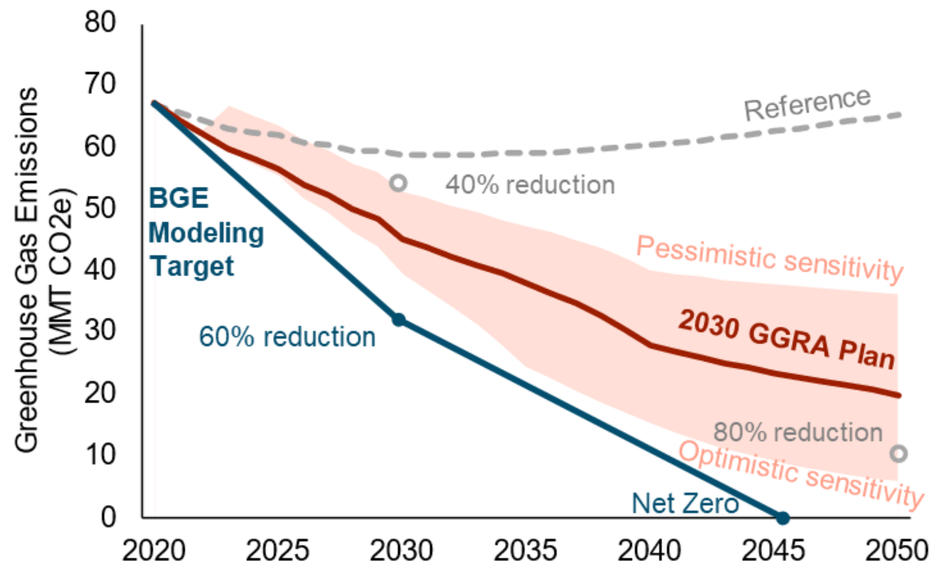
A key hypothesis of this study, based on findings from the MD Building Study, is that integrated approaches to decarbonization that leverage electric and gas infrastructure are more likely to be feasible and cost-effective relative to approaches that rely only on electrification or only on low-carbon fuels. With that hypothesis in mind this study considers several options to achieve decarbonization within BGE's service territory. Each strategy includes high levels of electrification, though the way electrification occurs, particularly in buildings, varies between all-electric, hybrid, and networked geothermal based strategies.

This study builds on past work developed by the State of Maryland in many respects, but differs in four key areas.

1. First, this study is focused on the energy transition specifically within BGE's service territory where E3's prior work has been statewide. This is significant given the difference between the population density and demographics, overall age of building stock and other industrial energy end-uses.
2. Second, this study considers a broader set of building heating decarbonization strategies than past work commissioned by the state, including emerging technologies like gas-powered heat pumps and networked geothermal systems reflective of rapid technology development occurring over the last decade and continuing today.
3. Third, the decarbonization scenarios modeled represent potential portfolios of decarbonization measures, rather than purely bookend solutions. The results are not meant to suggest a preferred portfolio, but rather to describe options that could be applied across a broad range of building types, gas and electric infrastructure needs, and sets of customer preferences.
4. Finally, consistent with the CSNA, this study considers a deeper and more rapid emissions reduction trajectory than past work developed by the state as highlighted in Figure 1.

A more detailed crosswalk of objectives and key assumptions between studies can be found in Appendix A.

Figure 1: GHG ambition in this study relative to past work

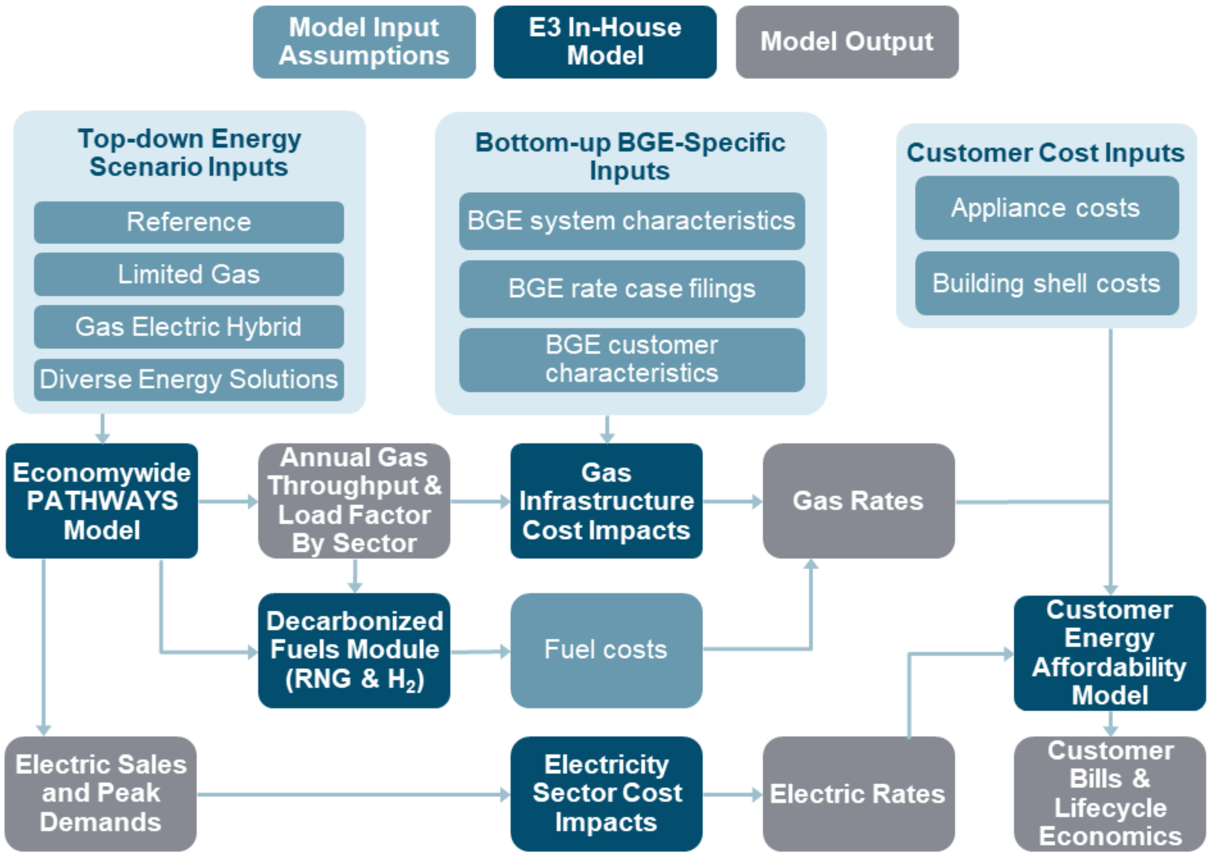


Approach

Modeling Framework

E3’s modeling approach includes an economy-wide treatment of energy demands across BGE’s service territory, an assessment of impacts on both electric and fuel energy supply transformations, impacts on BGE’s load and peak demands for gas and electric infrastructure, and an assessment of implications of decarbonization for customer affordability. These impacts are evaluated in an integrated modeling framework depicted in Figure 2.

Figure 2. E3 modeling framework



Key elements of the modeling framework include:

- **Economy-wide PATHWAYS Model**. This study explores BGE's role in the state's transition to net-zero GHG emissions. Given that, E3 developed a representation of energy and emissions within BGE's service territory in the PATHWAYS model, which includes an economy-wide representation of emissions and energy demands. This PATHWAYS model was also used in support of the state's GGRA Plan and the MD Building Study.
- **Electricity Module (Electric Sector Sales and Peak Demands and Electric Sector Cost Impacts).**
    - **Electricity Supply:** E3's representation of the electric sector is like that of the GGRA Plan, though it includes a refined treatment of the costs of decarbonizing out-of-state generation from the PJM Interconnection. That treatment builds on E3's 2020 study *Least Cost Carbon Reduction Policies in PJM*. This report includes no new modeling of electric supply decarbonization, instead treating BGE as a price-taker within the context of a broader state and regional electric sector transformation.
    - **Electric Delivery:** E3 assessed the likely investment needed to meet changes in BGE's electric delivery infrastructure by considering changes in the seasonal timing and magnitude of peak demands over time. This module includes a treatment of the

incremental costs associated with serving those peak demands and other transmission and distribution infrastructure upgrades associated with electrification.

- **Gas Infrastructure Module.**
    - **Gas Supply**: E3 modeled the cost and potential for decarbonized gas supply through E3's decarbonized fuels module that calculates a supply curve for renewable gases such as renewable natural gas from biogas and gasified biomass, green hydrogen from renewable-powered electrolysis, and synthetic natural gas with a biogenic carbon source.
    - **Gas Delivery:** E3 developed a treatment of BGE's gas revenue requirement, including costs associated with growth, routine reinvestments, and the Strategic Infrastructure Development and Enhancement (STRIDE) program. This module considers changes in gas system costs as utilization changes over time.
- **Customer Energy Affordability Module**. E3 assessed the impacts of decarbonization scenarios for representative residential customers in the Customer Affordability Module. The module calculates electric and gas bills for customers with traditional gas or new heating technologies. In addition, this module includes the upfront costs of building heating technologies, which is used to identify the total cost customers would incur to heat their homes in each scenario.

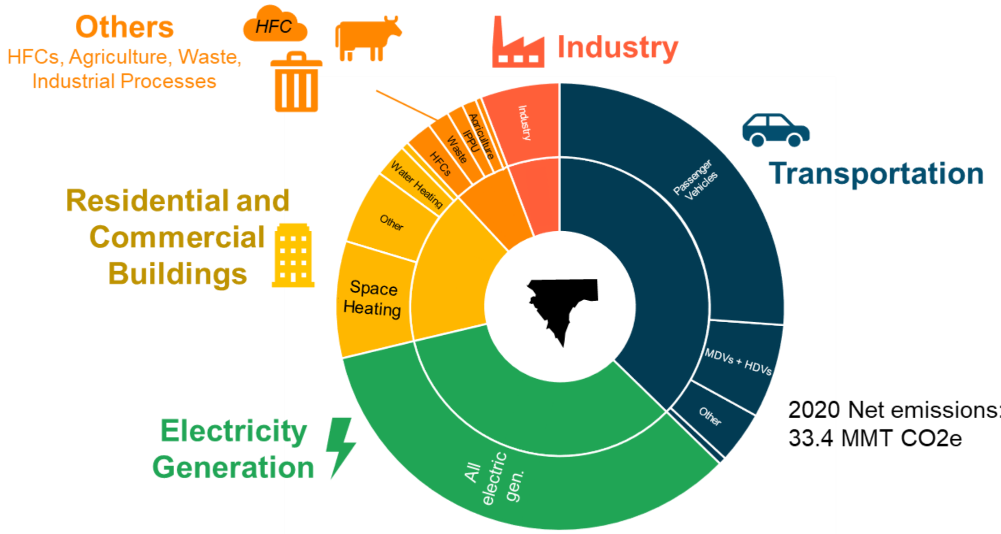
This modeling framework is similar to that used by E3 in past work in Maryland but includes additional detail relating to the current capacity of BGE's infrastructure and energy use requirements of their service territory, as well as a more detailed treatment of electric and gas rates and customer affordability. Similarly, most assumptions underlying this analysis were derived from past work conducted by the state, though this analysis reflects data specific to BGE's electric and gas systems and customers, and more up-to-date information on the costs and performance of emerging technologies, as well as more recent modeling of costs to decarbonize electric supply within PJM, by leveraging the 2020 study noted above that was not available at the time of the GGRA work. This study focuses on long-term technoeconomic scenarios; neither this study nor E3's prior work in Maryland presents a detailed analysis of electric generation capacity or transmission and distribution capacity needs under a net zero future, or detailed analysis of capacity siting challenges, capabilities and timelines. A comparison of differences in modeling assumptions and methodologies relative to past work can be found in Appendix A. A more detailed description of the technical approach and assumptions used for this analysis can be found in Appendix B.

Representation of BGE Geography

BGE's service territories cover many of the state's urbanized regions. As a result, approximately half of the state's population, energy usage and gas customers fall within BGE's service territory, highlighting BGE's critical role in meeting Maryland climate goals. This analysis represents all categories of GHG emissions within BGE's geography, which includes emissions associated with BGE's gas and electric business (both its own emissions and emissions associated with the supply and use of the energy they deliver) as well as all other categories of emissions that may occur within their territory and that are covered by the State's GHG inventory.

Notably, BGE only has direct control, subject to review by the Maryland Public Service Commission, over its electric and gas delivery infrastructure. Economy-wide decarbonization will require a broader set of actions by BGE's electric and gas suppliers, as well as its customers.

Figure 3. BGE GHG emissions scope



Buildings. The built environment within BGE's service territory materially impacts opportunities for electrification. Seventy-nine percent of homes within BGE's service territory currently have central air conditioning. These buildings are likely to represent lower-cost opportunities for electrification because the infrastructure for an air conditioner can, in many cases, be repurposed for a heat pump and these homes are likely to already have a sufficiently sized electrical panel. However, many homes, particularly those within the City of Baltimore, are older (just 36% were built after 1980) and are less likely to have either a central air conditioner or a high efficiency building envelope. Even homes with air conditioning may require some significant retrofits, including redoing ductwork to deliver sufficient heat to maintain occupant comfort. These and other physical characteristics of older buildings increase the complexity of electrification projects, making them harder to electrify from both technical and economic perspectives. In addition, lower-income customers are less likely to live in buildings with central air conditioning, so retrofitting these buildings carries additional challenges given those customers' limited access to credit and the higher likelihood that they are renters who do not have a direct choice in the equipment heating or cooling their homes.

BGE also provides gas to large commercial customers whose buildings tend to be heated via gas-fired boilers. Those boilers cannot be directly replaced by a heat pump system, so large commercial buildings would need to undergo a more extensive retrofit to accommodate a variant refrigerant flow system to be fully electrified. Such retrofits are technically complex, require substantial construction activities, and come at a larger incremental cost over conventional gas systems compared to projects in most residential or small commercial building types.

Transportation. The transportation sector within BGE's territory has similar characteristics to Maryland as a whole. Around 50% of total transportation energy consumption is assumed to occur within BGE's service territory, aligned with its share of the state's population.

Industry. Similar to Maryland as a whole, BGE's territory today has a relatively small amount of industry compared to other regions. Total industrial energy consumption is approximately 10% of energy consumption within BGE's territory. The largest industrial subsector by energy is the chemicals industry, which consumes approximately 30% of total industrial energy. Based on the industrial subsectors and end-uses present within the region, E3 assesses that approximately half of total energy consumption in the industrial sector within BGE's service territory could be electrified from a technical feasibility standpoint, though the economic feasibility of industrial electrification is far more uncertain and will be context-specific.

Electricity. Electricity generation in Maryland is served by in-state power plants and imports from neighbors in PJM, with imports making up nearly half of the electricity supply. As fossil plants within the state retire and demand grows with electrification, the percent of imported electricity could grow if not replaced and supplemented by clean in-state electric generation resources. As a delivery-only utility today, GHG emissions from the electric supply sector are largely outside of BGE's control but have been assumed to decline in line with the ambitions and associated costs from other net zero decarbonization studies for this work. Nonetheless, electric generation does represent a large share of both the emissions that must decarbonize, as well as the needed investments that drive costs to achieve decarbonization goals; generation supply is an important consideration for this study.

Non-Energy and Other GHGs. Remaining GHG emissions include categories such as agriculture, wastewater, and refrigerants, which have been downscaled to BGE territory by population. These emissions are also outside of BGE's control but represent a critical part of the story when modeling net zero emissions as they can be challenging to fully abate. Any net zero GHG future will need to consider these remaining emissions and pursue greater reductions in other sectors to compensate. Negative emissions from natural and working lands (e.g., carbon stored in Maryland's forests and soils) will need to offset any remaining positive emissions to achieve a net zero goal.

Decarbonization Scenarios

This analysis is scenario-based. Decarbonization scenarios reflect user-defined transformations of the energy system and economy-wide emissions. The scenarios are not forecasts, nor do they result in a single optimal or preferred solution. Instead, by examining multiple pathways, this analysis is used to identify and compare key features of different plausible futures and their relative costs, feasibility, and risks.

E3 worked with BGE to define three alternative scenarios that *all achieve* the state's 2031 and 2045 decarbonization targets. A key differentiator of these scenarios is the transition of the building heating sector, where E3 estimates that BGE's gas infrastructure delivers over two thirds of final energy today. Each scenario represents an alternative pathway for decarbonizing that sector, tracing through implications for BGE's infrastructure and resulting impacts on BGE's customers, while still including all sectors that will contribute to the state's GHG goals and have potential competing demands on BGE energy delivery systems. The scenarios include:

- **Limited Gas**. Emphasizes high levels of electrification and a shift away from delivered gas and other fuels in the buildings sector. This scenario also includes a relatively high level of electrification and a limited role for renewable fuels in the industrial sector. The primary technology driver of building thermal decarbonization in this scenario are all-electric air-source heat pumps.
- **Hybrid**. Emphasizes electrification, including high levels of electrification in the buildings sector, but some existing gas customers adopt a hybrid approach to electrification. A combination of electrification and renewable fuels reduces emissions in the industrial sector. The primary drivers of building thermal decarbonization in this scenario are air-source heat pumps, with the gas system and renewable gases used during cold conditions.
- **Diverse**. Emphasizes high levels of electrification but incorporates a mixture of strategies to decarbonize the building heating sector, including both all-electric buildings and hybrid electrification, as well as emerging strategies like gas powered heat pumps and networked geothermal systems. Gas powered heat pumps operate using similar principles to electric heat pumps and hold the potential to use gas to efficiently provide space- and water-heating services. Networked geothermal systems connect ground-source heat pumps for multiple buildings via a network of underground pipes that distribute heating and cooling energy between buildings. Networked geothermal systems could substantially mitigate the electric system impacts of electrification and repurpose BGE's expertise in maintaining and operating underground infrastructure.

In addition to achieving the same economy-wide reductions over time, each scenario also shares a consistent level of climate ambition in buildings to help make the customer gas and electric utility bill impacts comparable across scenarios.[6] This approach allows for a more direct comparison of the alternative strategies to decarbonize the buildings sector and the implications for BGE's systems and customers.

Outside of buildings and industry, the scenarios share many similar features. All scenarios include high levels of electrification in the transportation sector, a transition to zero-GHG electric supply by 2045 and strategies to mitigate emissions in non-energy sectors of the economy. The assumptions for electricity supply and other sectors (agriculture, waste, natural and working lands) were held constant across scenarios to help focus results on differences in the built environment. The key features of each scenario are shown in Table 1.

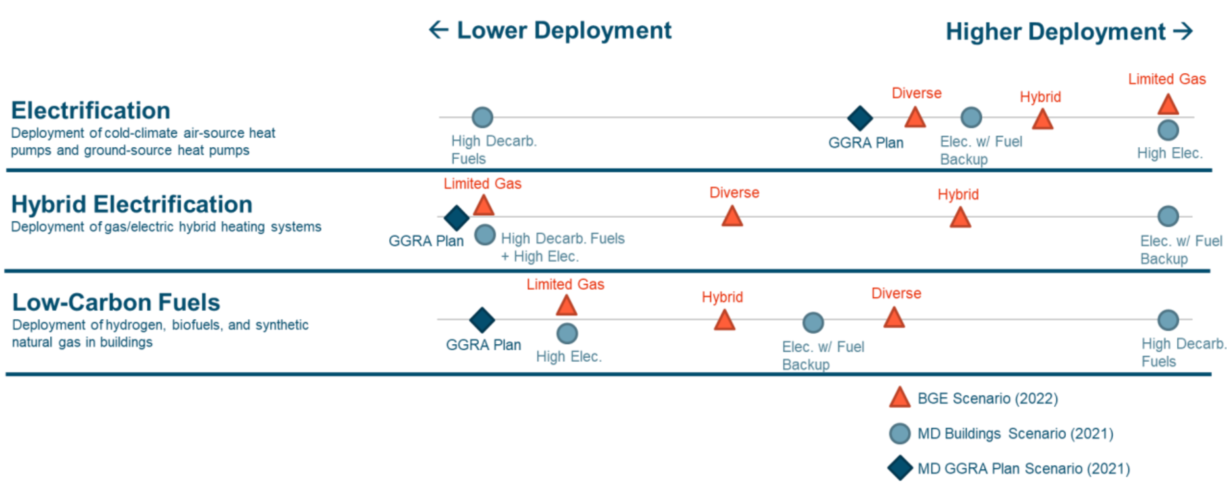
[6] The level of building decarbonization aligns to the MWG Policy Scenario from the Maryland Building Decarbonization work, which equates to an 86% direct reduction of GHGs in buildings relative to 2006 levels.

Table 1. Key scenario features by economic sector

		Integrated Energy System Scenarios	
	1. Limited Gas	**2. Hybrid**	**3. Diverse**
Scenario narrative	High-electrification and shift away from delivered gas and other fuels	Leverages an increasingly clean electric system, high electrification, and the gas network	
Buildings	Efficiency and electrification	Efficiency, electrification, gas-electric hybrids, and a targeted role for alternative fuels	Efficiency, electrification, gas-electric hybrids, gas heat pumps, network geothermal, and alternative fuels
Industry	Efficiency and electrification	Efficiency, electrification, and alternative fuels	Efficiency, electrification and alternative fuels
Transportation	LDV electrification and alternative fuels for MDV & HDV		
Electricity	Zero-carbon electricity by 2045		
Other Sectors	66% reduction by 2045		

Figure 4 compares the relative level of deployment of building decarbonization measures in each of the three BGE scenarios to the 2021 Maryland Building Decarbonization Study scenarios and the Maryland GGRA Plan Scenario. The figure illustrates that the BGE scenarios include high levels of building electrification and lower levels of hybrid electrification and low-carbon fuels compared to past scenarios evaluated for the state. The 2021 MD Buildings Study started with scenarios that explored more pure "bookends" related to high electrification or high decarbonized fuels, and learnings from that analysis and similar analyses in other jurisdictions have shown that those bookends often result in higher costs. The MD Buildings Study included a final scenario (the "MWG Policy Scenario") that combined elements of the High Electrification Scenario with a larger role for hybrid heating solutions.

Figure 4. Deployment of building decarbonization measures in BGE scenarios compared to recent MD scenario analysis



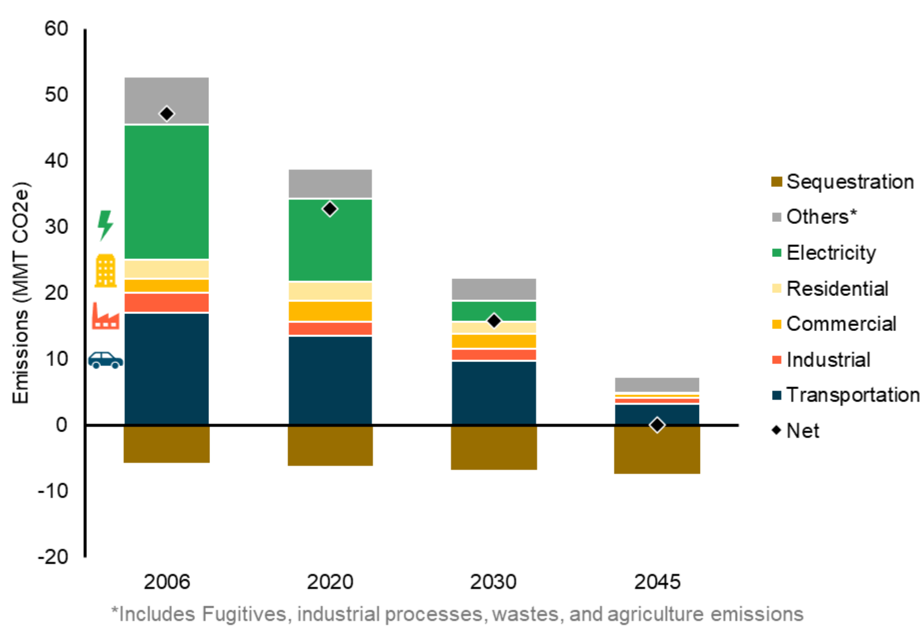
Decarbonization Pathways Key Results

Economy-wide results

GHG Emissions

All three scenarios achieve the state's 2031 60% GHG reduction and 2045 net-zero targets for BGE's geography, including deep reductions in all economic sectors as shown for the Diverse scenario in Figure 5. Achieving the state's decarbonization targets requires substantial reductions in emissions across all economic sectors. In buildings, industry, and transportation, we see a need for transformations in the equipment used (home appliances, vehicles), the type of energy that powers that equipment (renewable electricity, hydrogen, low-carbon fuels), and the infrastructure needed to support those transformations (vehicle charging infrastructure, hydrogen electrolysis). All pathways include a critical role for electric passenger and fleet vehicles, efficiency and electrification in buildings, and low-carbon fuels in sectors that are challenging to decarbonize. All pathways require significant investment in expanding zero carbon electric generation, transmission and distribution to fulfill energy use that is shifting from fossil fuels to electric. The differences in the scenarios incorporate varying levels of investment in clean fuel technologies to help pace those electric sector changes. In the 2030 timeframe, decarbonization of the electric sector is the largest single source of emissions reductions, while by 2045 deep emissions reductions are required in all economic sectors. Results indicate that how the transformation occurs affects the total cost of decarbonization, the costs that customers will pay, and the pace of technology deployment needed for customers. Given the significance of the transformation needed to meet the net zero GHG goal, all pathways require action and investments from all segments of the economy.

Figure 5. GHG emissions by sector in the Diverse Scenario



The range of emissions reductions across scenarios in this study by sector are shown in Table 2. The only sources of variation in sectoral emissions between scenarios are the transportation and industrial sectors. The level of climate ambition is held constant in buildings and electricity to make customer costs more comparable across scenarios, and small variations exist in the level of ambition in transportation and industry aligned with the mitigation actions included in each scenario. All scenarios achieve net-zero GHG emissions by 2045, which includes a reduction of total gross emissions of about 87% in 2045 (relative to 2006) and remaining emissions in that year are offset by negative emissions from natural and working lands. Maryland's natural and working lands (e.g. forests) in BGE territory currently store approximately 5 MMT CO2 per year, and with dedicated support we assume this will grow through 2045.

Table 2. 2045 GHG emissions reductions by sector relative to 2006 in BGE scenarios

All Sectors	Emissions Reduction by 2045
Buildings	86%
Transportation	81-85%
Industry	57-69%
Electricity	100%
Other Sectors	66%

It is important to note that the CSNA does not specify the level of GHG reductions required by sector, only the need to achieve economy-wide emissions reductions. We have modeled deeper reductions in buildings, transportation, and electricity generation where technology solutions are relatively mature. As this analysis will show, technology adoption is particularly significant in buildings and passenger vehicles. If new technologies mature and additional ambition is achievable in other sectors (e.g. trucks and off-road transportation, industry, agriculture, negative emissions technologies), a slower adoption trajectory in buildings and transportation could lessen the challenge for customers, which may lower costs and energy burdens.

Demand-Side Transformations

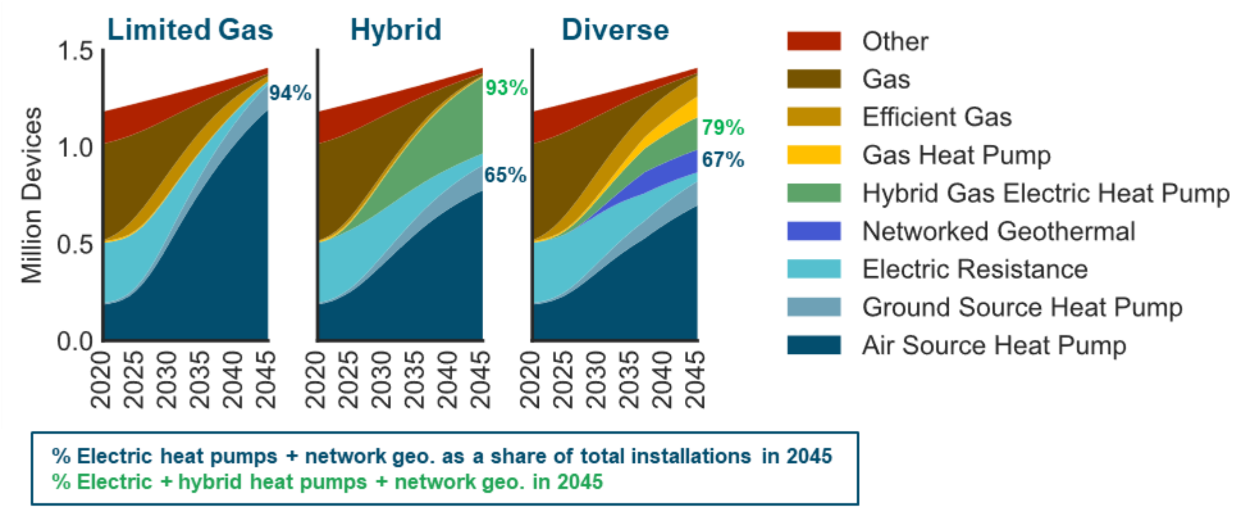
In order to achieve the sectoral emissions reductions targets described in Table 2, each of the three scenarios includes a transformation of how energy is both supplied and consumed.

Buildings Sector

A key source of variation in the scenarios is the transition of the building heating sector. Based on the finding from the MD Building Study that all-electric new construction is lower-cost than alternatives, *all scenarios* assume all-electric new construction from 2027 onwards. With that, the key distinction between the scenarios are alternative strategies to decarbonize ***existing*** buildings.

Figure 6 shows the transition of residential building space-heating equipment for each scenario. The Limited Gas scenario has the largest growth in air-source heat pumps due to a near-complete conversion of natural gas heated buildings such that, by 2050, 94% of homes in BGE's service territory are electrically heated. The Hybrid scenario has a similar total number of electrically heated homes as Limited Gas, but gas furnaces and boilers are retained as back-up to air-source heat pumps in 28% of homes. The Diverse scenario has both the lowest overall level of electrified homes (79% of buildings are electrically heated) and the widest variety of technologies used, including condensing gas furnaces, gas heat pumps, and networked geothermal systems.

Figure 6. Stock transition for residential space heating devices in BGE's territory



Transportation Sector

A common feature of the scenarios are high levels of electrification in the transportation sector, including achieving 80-90% of new sales of zero-emission passenger vehicles by 2035, leading to nearly all zero-emission light-duty vehicles and a large number of zero-emission trucks by 2045. Cars and trucks are long-lived assets, so a rapid ramp-up of the market for these technologies is needed in the 2020s such that nearly all on-road vehicles sold in the 2030s are zero-emissions. By 2045, the vast majority of passenger vehicles in the state are battery electric, with roles for hydrogen fuel cell or biofuel powered vehicles in trucks and off-road vehicles. These necessary advances in all of the scenarios by 2045 may require adoption of policies to support continued and expanded education, programmatic and incentive offerings from BGE and the state now and in the future, along with increased availability, diversity and affordability of new and used electric vehicles.

Figure 7. Stock transitions of light-duty vehicles in BGE's territory

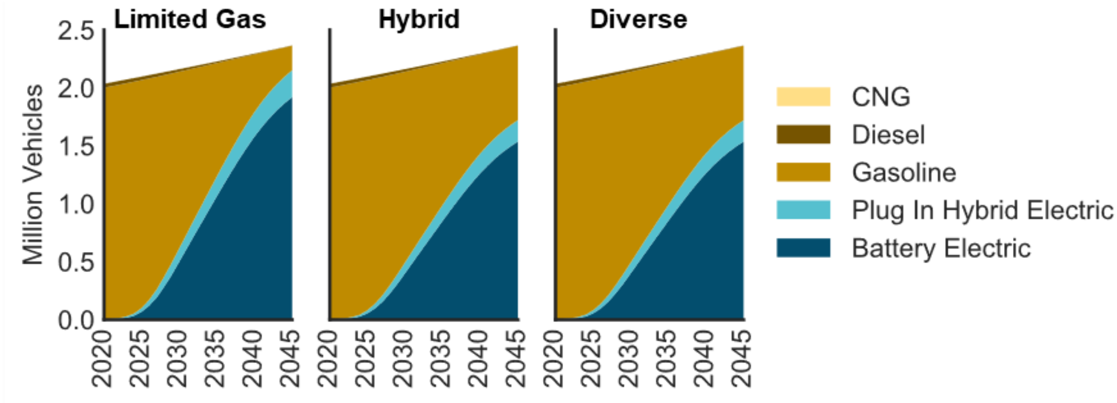
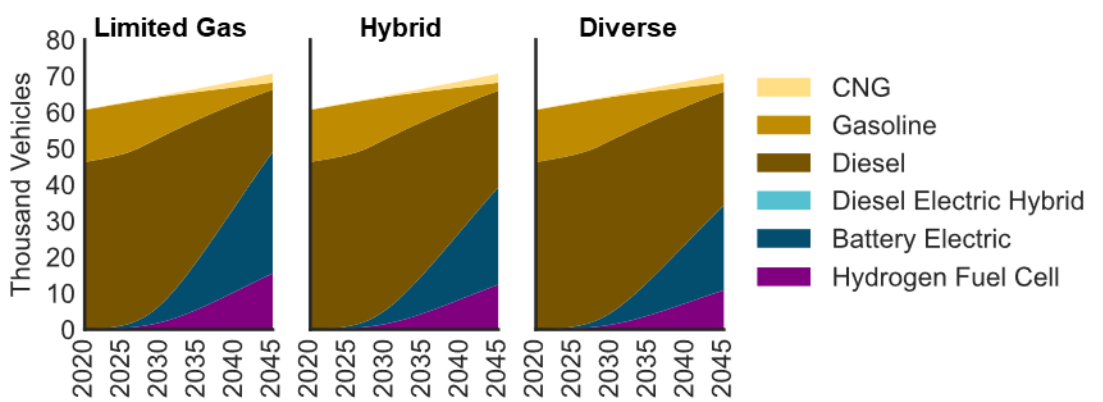


Figure 8. Stock transitions of medium- and heavy-duty trucks in BGE's territory



The levels of light-duty vehicle electrification in this study are most ambitious in the Limited Gas scenario, in line with goals in leading states of 100% zero-emission vehicle (ZEV) sales in light duty vehicles (LDVs) by 2035 and 100% sales in MHDVs by 2045. ZEV adoption is lower in the hybrid and diverse scenario, following from this study's scenario design approach, which was intended to align the emissions reductions achieved in the buildings sector.[7]

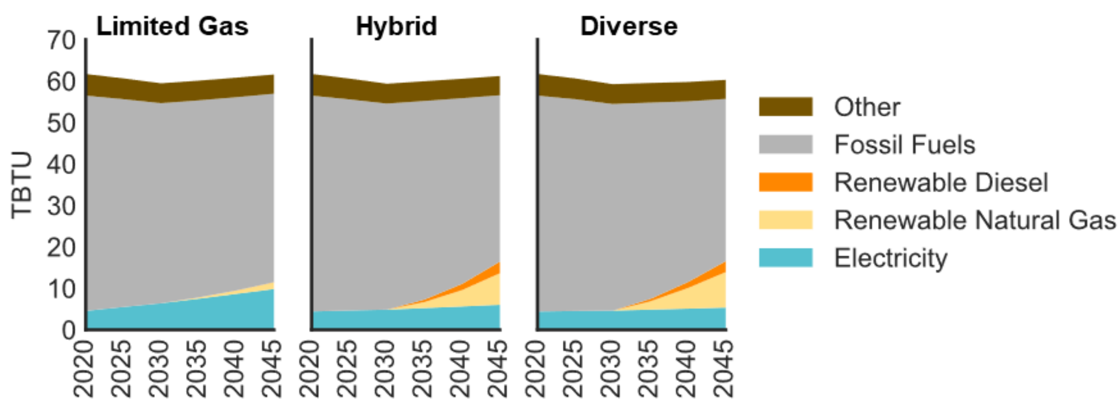
Industrial Sector

Energy usage in the industrial sector is approximately 13% of total energy consumption in BGE's service territory. Consistent with past state modeling efforts, the largest residual emissions allowed in each

[7] The scenarios were primarily defined based on different demand-side transformations in buildings (e.g. all-electric vs hybrid heat pumps, networked geothermal, etc.), which resulted in different levels of remaining gas and liquid fuel demands. As a result, the Hybrid and Diverse scenarios include higher levels of fuel demands, which impacts emissions across all sectors that use those fuels. Given those higher blends, and in order to meet the same economy-wide net-zero target, E3 applied a lower level of transportation electrification in the Hybrid and Diverse scenarios. In practice, higher levels of transportation electrification may be warranted given technology progress and the co-benefits of eliminating combustion of gasoline and diesel fuels.

scenario are in the industrial sector. E3 adopted this approach because, in general, industrial decarbonization options are less technologically mature and less cost effective than transportation and building decarbonization. In addition, many states such as Maryland have concerns about the economic development and jobs implications of imposing strict climate requirements on industry. The Limited Gas scenario emphasizes electrification where feasible, while the Hybrid and Diverse scenarios include a larger role for renewable fuels as replacements for natural gas. All scenarios share ambitious levels of energy efficiency, which is likely to be both more technologically mature and cost-effective than conversions of industrial processes to direct electrification or hydrogen combustion. The level of residual emissions in this sector does not represent an upper bound on decarbonization potential, but instead reflects a moderate and targeted approach to electrification and low-carbon fuels in industry. To the extent that cost effective emissions reductions can be achieved in industry through creative partnerships and commercialization of new technologies, additional decarbonization in this sector would help to relieve the burden of decarbonization required by other sectors.

Figure 9. Final energy demand by fuel in BGE's industrial sectors



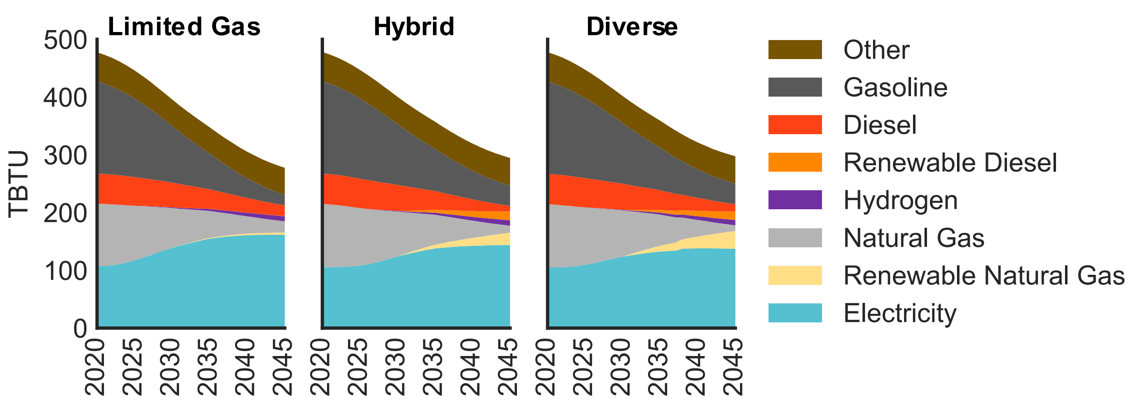
"Other" includes wood and waste.

Final Energy Demands

Final economy-wide energy demands within each scenario fall over time due to the high levels of electrification incorporated by E3 across all scenarios. Electrification reduces final energy demands because technologies like electric motors and electric heat pumps are substantially more efficient than combustion-based technologies they replace. Indeed, taking the transformations across each sector as an economy-wide whole, the pivotal role of electrification in achieving net-zero in Maryland becomes clear. The share of final energy demands that are served by electricity increases from 22% today to 46-58% by 2045. When paired with 100% clean electric supply, electrification is also the largest driver of GHG emissions reductions across all scenarios. The use of other fossil liquid, gaseous and solid fuels falls precipitously in all scenarios (60-73% in 2045 relative to 2020), with remaining demands being served by increasing blends of renewable fuels.

While overall energy use may decrease, notably, across all scenarios, the share of final energy delivered via BGE's electric and natural gas infrastructure increases as it takes on more electric load from what is now energy supplied by GHG-intensive transportation fuels. Today, electricity and natural gas are 45% of the final energy consumed in BGE's service territory, while in 2045 that combined value rises to between 61 and 67%.

Figure 10. Economy-wide final energy demands by scenario



"Other" includes jet kerosene, asphalt and road oil, coal, kerosene, LPG, miscellaneous petroleum, residual fuel oil, waste, wood, biomass, feedstocks, and still gas.

Other Sectors

The focus of this analysis is on the distinct impacts to buildings, industry, transportation, and fuel supply, but to reach a net zero GHG economy, action will be needed in other sectors as well – including, for instance, in agriculture, waste, and natural and working lands. Modeled actions in these sectors are in line with past work in Maryland and are consistent across scenarios. One key interconnection with building decarbonization is the role of refrigerants with a high global warming potential (GWP), which are used in heat pump systems. It will be critical to pursue climate-friendly refrigerant policies in any scenario, but especially in scenarios that rely more on heat pump adoption. Key measures are reflected in Table 3.

Table 3. Key mitigation actions in agriculture, waste, industrial processes, fossil fuel industry and natural and working land sectors

Sector	Subsectors Represented	Key Mitigation Actions Modeled
Agriculture	Methane from animal manure and enteric fermentation, soil management	Methane management, soil carbon programs
Waste	Wastewater treatment, landfills	Methane capture from wastewater and landfill facilities, organic material management in landfills
Industrial Processes	Refrigerants (e.g. Hydrofluorocarbons or HFCs), process emissions	Refrigerant management policies

	from cement, iron and steel, and other facilities	
Fossil Fuel Industry	Coal mining, natural gas industry	Methane emissions reduction from natural gas transmission and distribution
Natural and Working Lands	Forests, urban trees	15% growth in Maryland's natural carbon sink

Impacts to BGE's Gas and Electric Systems

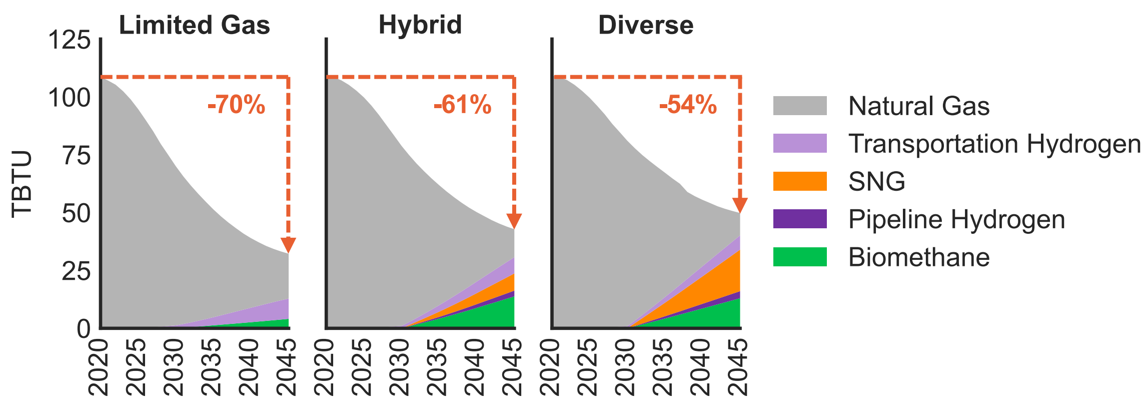
Electrification is a key driver of decarbonization across all three scenarios considered. Between scenarios, differences in electrification, particularly building heating electrification, implicate the pace and scale of electric generation, transmission, and distribution infrastructure additions that will be needed to support the state's decarbonization goals. Conversely, the way building heating loads are electrified impacts the utilization and long-term transition pathways for the State's gas infrastructure. Indeed, the transition of the State's gas and electric systems are, to a significant extent, linked. Less reliance on existing gas infrastructure necessarily requires more investment in the electricity system, and the role of the remaining gas infrastructure will depend on the needs of remaining gas customers. Within that state context, BGE's role is primarily in the maintenance and transformation of the electric transmission and distribution system and gas system within its service territory. BGE does not own or operate electricity generation or upstream gas supply assets, but identifying the necessary transformations of energy supplied through BGE's infrastructure is critical to understanding potential paths to decarbonization and affordability impacts on customers.

Gas System

BGE's gas system has been primarily built to provide heating services to buildings. As a result, approximately 74% of the company's gas revenues are from residential customers and a further 11% from small commercial customers. All the decarbonization scenarios evaluated by E3 in this study envision a transformation in the way buildings are heated in BGE's service territory, including an emphasis on electrification as the core engine of building heating decarbonization. As a result, BGE's gas sales fall in all scenarios, with reductions ranging between 54% and 70% in 2045 relative to 2020, which also includes potential supply of hydrogen for medium- and heavy-duty vehicle fueling (Figure 11). Focusing just on all gas delivered via BGE's pipelines, gas throughput declines 60%-78% in 2045 relative to today. The drastic reduction of natural gas – through a combination of electrification, efficiency, and displacement by cleaner fuels – is a critical factor in how emissions reductions are accomplished in the building and industrial sectors. These reductions reflect the fact that in all scenarios electric heat pumps are the primary source of heating energy for most of the year. The remaining gas delivered by BGE in 2045 is primarily used by the industrial sector, to provide heating to buildings during very cold days via hybrid heat pumps, and potentially for use in a limited number of buildings with high efficiency gas equipment. Taking an economy-wide approach to reaching net-zero GHG emissions can allow a small amount of natural gas to remain in industry and buildings and those remaining emissions can be offset with Maryland's natural carbon sinks.

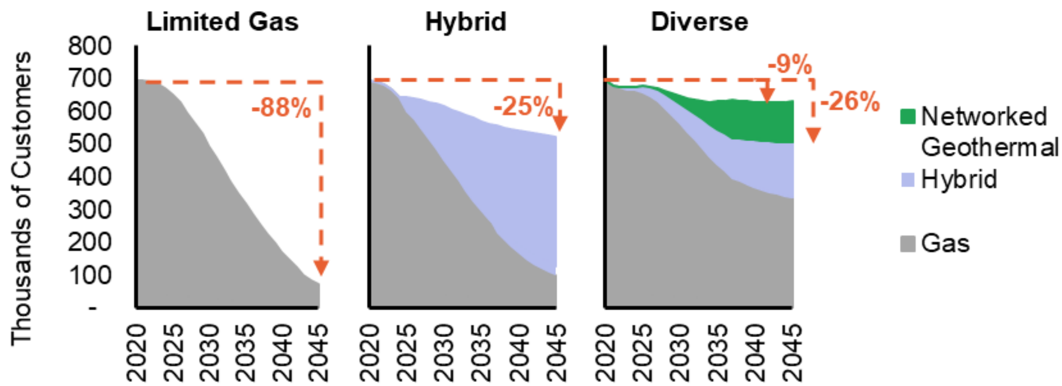
At the same time as BGE's gas throughput falls, the composition of the gas it delivers changes in each scenario. From 2030 onwards, BGE's gas supply shifts from entirely natural gas to a blend that includes increasing quantities of renewable fuels. Because each scenario is designed to achieve the same 86% reduction in building sector emissions, scenarios with lower levels of building electrification and higher gas throughput leverage higher levels of renewable fuels. For example, as shown on Figure 11, the Diverse scenario has the lowest level of electrification and therefore relies to the greatest extent on renewable fuels to meet emission reductions goals. Conversely, the Limited Gas scenario uses a lower amount of renewable fuels because nearly all buildings are fully electrified. Potential availability and an increasing cost curve for renewable fuels (especially green hydrogen, biomethane from gasified feedstocks, and synthetic natural gas (SNG)) are considerations that were used when determining amounts of renewable fuels used in each scenario.

Figure 11. Change in BGE's gas sales and composition of gas supply by scenario



Like gas sales, all scenarios see declining numbers of BGE gas customers as they electrify or convert to geothermal heat sources. The Limited Gas scenario has the largest number of departures, with 90% of BGE's existing customers converting to all-electric service by 2045. The Hybrid and Diverse scenarios see more gradual rates of customer attrition. In both cases, the number of customers with a gas meter falls by approximately one quarter relative to today. In the Hybrid scenario, most of the remaining customers use the gas system primarily as back-up, while in the Diverse scenario approximately 42% of remaining customers have not adopted electrification measures and instead rely on efficient gas appliances. The Diverse scenario is also unique given that it includes the transition of customers from gas to networked geothermal service. Depending on regulatory treatment, discussed below, those networked geothermal customers could be considered part of BGE's gas or electric customer base.

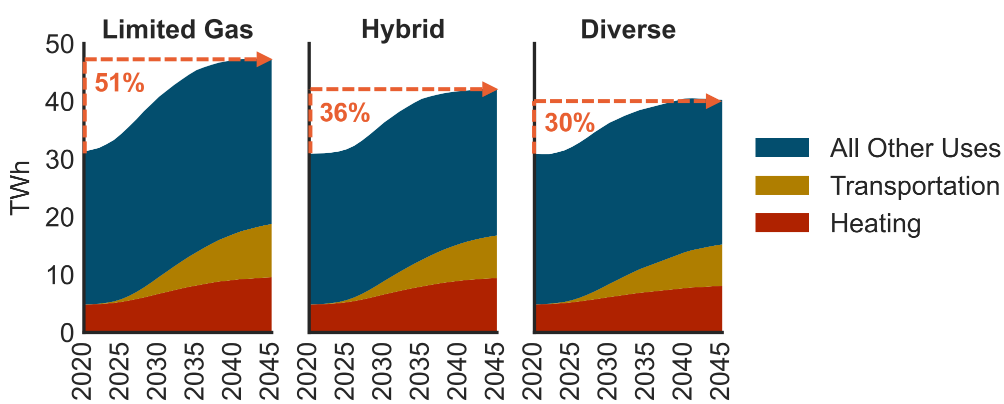
Figure 12. Transition of BGE's residential and commercial gas customers by scenario



Electric System

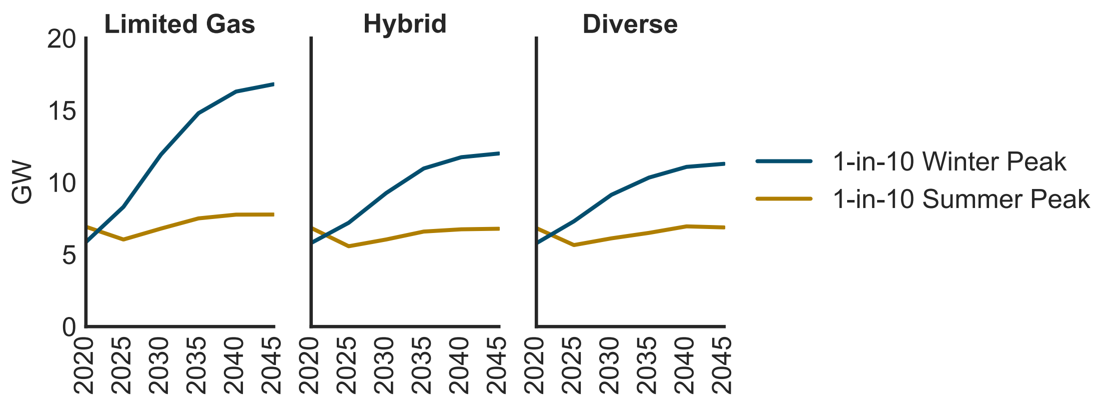
All scenarios include high levels of electrification in the transportation and buildings sectors, leading to increased sales of electricity of between 30% and 51% on BGE's system by 2045. The largest single source of electric sales growth is the transportation sector, where energy demands that are currently served by gasoline and diesel are converted to electricity. The Limited Gas scenario has the largest load growth because it includes the highest overall amount of electrified heating loads and because it includes the highest levels of direct electrification in the transportation and industrial sectors. The Diverse scenario has the lowest overall level of electric load growth because it has the lowest levels of direct electrification and because networked geothermal systems are more energy efficient than the air-source heat pumps leveraged in Limited Gas and Hybrid.

Figure 13. Electric load growth by scenario



An electric system must be designed to operate reliably not only for average annual operations but also for extreme weather events, regardless of frequency. Thus, the system peak is a key system design parameter and overall cost driver of electric capacity and the transmission and distribution system. Today, the primary electric generation technology to provide that reliability service is natural gas-fired generation (e.g. combustion turbines). In the long-run, clean firm resources like long-duration energy storage, natural gas-fired turbines with carbon capture or hydrogen, or advanced nuclear – along with significant demand management technology deployment and control, as well as substantial physical distribution system upgrades – will be needed for systems with 100% decarbonized electricity, any of which come at higher cost and many of which involve siting challenges.

Figure 14. Electric peak demand by scenario, before flexibility



Peak electric demands (inclusive of all categories of electricity demand such as building appliances and electric vehicles) increase more quickly relative to annual sales in all scenarios due to conversions of current fossil space-heating loads to electric heat pumps. As shown in Figure 14 system peak electricity demands increase by 66-150% by 2045 relative to 2020. Space-heating loads primarily occur during the winter, with particularly large peak requirements occurring during multi-day cold-snaps. A challenge for all-electric approaches is that during very cold weather the efficiency of air-source heat pumps, including cold-climate models, falls just as heating loads are at their highest. Those periods can also coincide with low levels of wind and solar production across a large geographic extent, and therefore require significant amounts of firm generation capacity to be served reliably.

BGE currently plans their distribution system to a 1-in-10 year reliability standard. This standard reflects that a reliable electric system must be designed to meet unusually high periods of load, rather than simply planning to typical conditions. Such conservatism will be particularly important as a larger share of final energy demands are moved to the electricity system. In particular, customer power outages during a cold-snap would present significant safety and human health challenges. Given BGE's imperative to maintain a reliable system, the 1-in-10 year levels of peak demands are used to assess the incremental infrastructure required in each scenario.

The Limited Gas scenario has the largest electric system impacts because it primarily relies on air-source heat pumps. The Hybrid scenario substantially reduces those peak demands and associated infrastructure impacts by leaving a role for gas backup in a subset of existing buildings. The gas backup utilizes the existing firm capacity of BGE's gas infrastructure rather than requiring new electric infrastructure. Finally, the Diverse scenario has the lowest peak demand impacts because it has the lowest overall level of electrification. The electrification that does occur in the Diverse scenario includes peak mitigation strategies like hybrid electrification and the use of networked geothermal systems, whose efficiencies are not affected by outdoor air temperature.

The Limited Gas scenario includes both higher overall levels of peak demand impacts during a typical cold snap and higher overall sensitivity of load to extreme conditions. Thus, maintaining reliability requires the addition of more electric infrastructure, including transmission and distribution, than for the Hybrid and Diverse scenarios. Those latter two scenarios require less new electric infrastructure because a substantial share of customers continue to use the existing capacity of BGE's gas system.

Some peak impacts can be mitigated through demand-side load management programs, including treating space heating and electric vehicle charging as flexible loads. Without load management programs, transportation electrification would have a significant impact on peak loads, but the impact can be limited by implementing rate structures and programs that encourage customers to charge vehicles during off-peak hours. For light-duty vehicles, approximately 50% of load is assumed to be shiftable to avoid peak hours. For heating loads, by preheating spaces ahead of the coldest hours of a cold snap, space heating impacts to peak load can be reduced between 2-6%, reflecting a smoothing of demand over the coldest hours of the morning. However, a key challenge from a peak demand perspective are sustained, multi-day day cold-snaps, which load shift strategies are not well suited to address. In addition, customer acceptance of load-flexibility and other demand management approaches warrants further investigation. Still, load flexibility reduces infrastructure investments are across all scenarios, with the largest benefit in the Limited Gas scenario.

Scenario Comparison and Discussion

This study examines three alternative and distinct decarbonization scenarios that all achieve the same climate goal of net zero GHG emissions by 2045. The purpose of this approach is not to pick a preferred pathway for BGE or the state of Maryland, but rather to identify key commonalities and trends to better inform the eventual development of a portfolio of decarbonization solutions; while not the purpose of this study, E3 does, however, offer recommendations for the State's and BGE's consideration. As illustrated in Figure 15, each scenario faces challenges when considered across different evaluation criteria. For example, scenarios that rely to a greater extent on air source heat pumps may have a lower level of risk with respect to technology readiness, but carry high infrastructure requirements and costs due to the peak design dynamics previously discussed. Conversely, the Hybrid and Diverse scenarios could reduce economy-wide cost but rely to a greater extent on technologies with lower levels of commercialization. **However, on balance, the findings of this work support the hypothesis that decarbonization strategies that leverage the advantages of both electrification measures and gas infrastructure carry a lower overall level of challenge relative to an all-electric approach**.

Figure 15. Assessment of the level of challenge across evaluation criteria for decarbonization scenarios. "Level of challenge" denotes the extent to which the scenario is substantially different from current practices, policies, or technologies.

Scenario Criteria		Limited Gas	Hybrid	Diverse
Energy system cost	Cumulative incremental costs associated with scenario	$52B	$38B	$40B
Customer affordability	Total cost of ownership for customers that do adopt building decarbonization measures			
Customer practicality	Reliance on widespread customer adoption and relative level of customer disruption			
Constructability	Pace and scale of electric and gas sector infrastructure additions			
Technology readiness	Extent to which a scenario relies on emerging technologies			
Equity	Difference in costs for participating vs non-participating customers			
Workforce impact	Estimate of the scale of energy workforce transition			

← Lower Challenge — Higher → Challenge

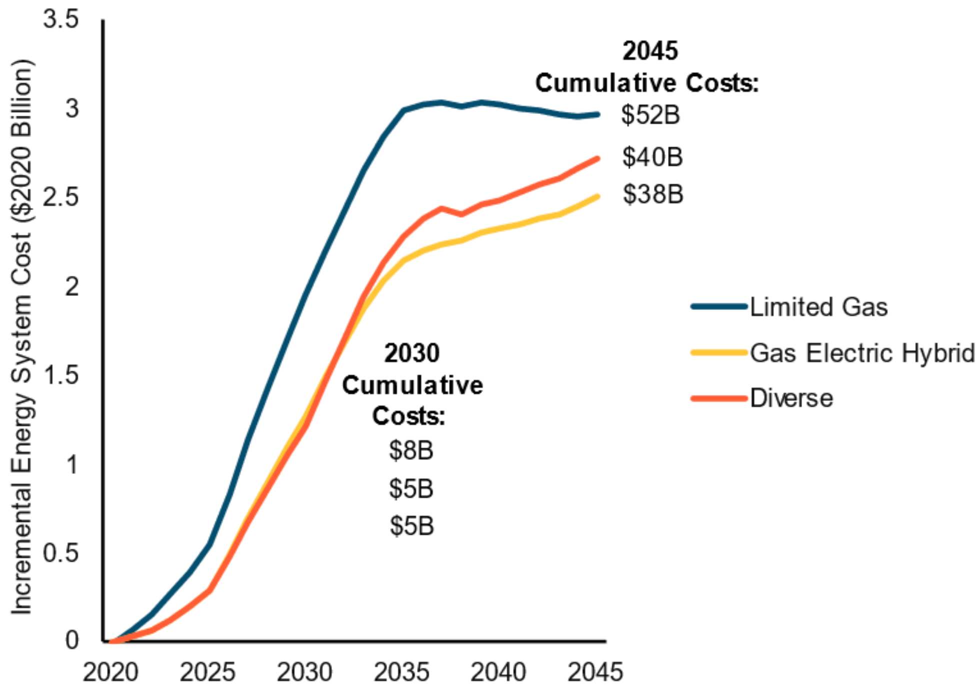
The subsequent sections of this chapter describe E3's evaluation of each scenario with respect to the scenario criteria listed in Figure 15.

Energy System Cost

Decarbonization scenarios require incremental investments in energy supply and demand transformations relative to a Reference Scenario.[8] For those transformations to occur, investments must begin to scale immediately such that, over the period from 2022 through 2050, total investments reach $40 and $52 billion in cumulative incremental cost – which consist of electric generating capacity, electric transmission and distribution, customer capital costs, renewable and fossil fuels costs and costs of gas and networked geothermal infrastructure, as shown on Figure 16 and described in the section that follows. The Hybrid and Diverse scenarios define the lower range of that bound, while the Limited Gas scenario sets the upper bound. These costs represent the estimated investment needed across sectors in BGE's geography to achieve net zero GHG emissions by 2045 using these scenarios as compared with a business-as-usual future, and this reflects a significant transformation.

[8] Our Reference Scenario is in line with the business-as-usual assumptions in the 2021 GGRA Plan and include current population, household, and VMT trends, current EMPOWER efficiency targets, state zero-emission vehicle adoption goals, and current renewable portfolio standard (RPS) required by the Clean Energy Jobs Act.

Figure 16. Total incremental energy system cost over time by scenario



Though these scenarios reflect real investments needed across the economy and the cumulative number is sizable, it is informative to put these costs in context, and two helpful reference points are (1) the size of the State's economy and (2) the benefits of meeting climate targets. For the size of the State's economy, Maryland's gross state product (GSP) in 2020 was $411B, and assuming it grows at 2% per year, cumulative GSP over this time horizon would be $13,830B.[9] The benefits of meeting climate targets include improved air quality and decreased incidence of related health conditions and avoided extreme weather events. This analysis did not include a detailed climate benefits analysis, but as a proxy we can estimate the economic impacts using the EPA's social cost of carbon, which is about $50/tonne of CO2e avoided.[10] Estimating the cumulative GHG emissions savings of our scenarios, the cumulative societal cost of carbon is approximately $25B, which does not include the air quality benefits of reduced air pollution, nor higher estimates of the social cost of carbon that appear in the literature[11].

Figure 17 shows the relative cost of each scenario in 2045, broken out by key cost components. The distinctions between scenarios shown on Figure 17 occur as follows:

- **Electric Capacity**. In all scenarios, Maryland's power generation and regional electric supply must get bigger and cleaner, expanding to meet increasing electric demands and concurrently decarbonizing rapidly to meet climate goals. The extent and cost of electric infrastructure additions that are needed varies by scenario. Limited Gas requires more decarbonized electric

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[9] https://fred.stlouisfed.org/series/MDNGSP
[10] Assuming the 3% average value as $54 escalated to $2020 from https://19january2017snapshot.epa.gov/sites/production/files/2016-12/documents/sc_co2_tsd_august_2016.pdf
[11] Wagner, Gernot. "A tale of two carbon prices." Gernot Wagner (gwagner.com)

energy and higher levels of firm generation capacity relative to the Hybrid and Diverse scenarios. A key difference between Limited Gas and Hybrid/Diverse is that the latter two scenarios continue to take advantage of the existing BGE gas distribution system to meet heating capacity requirements, which reduces the need for new firm capacity on the electric system. [12]

- **Electric Transmission and Distribution**. As electricity demand grows, additional investment will be needed in transmission and distribution (T&D) infrastructure. New and existing T&D infrastructure must be strengthened in order to reliably deliver the increase in electric supply to customers; this would include new feeders, upgrading existing feeders, and building new or upgrading existing substations using innovative technologies like microgrids, grid and customer scale storage, vehicle to grid, among many other investments. Due to increased dependence on the electric system, BGE will also need to invest in making its electric infrastructure more resilient.
- **Customer Capital Costs**. Each scenario requires a transition of customers' energy-consuming equipment. In all scenarios internal combustion engine vehicles are replaced with electric drive trains in both passenger and freight vehicles, furnaces and boilers are replaced with heat pumps, household appliances are replaced with higher efficiency alternatives, industrial processes are converted to electricity or low-carbon fuels, and a diverse set of energy efficiency measures are deployed. On net, across all end-uses, BGE's customers can expect to pay higher up-front costs for their energy-consuming equipment in scenarios that are consistent with the state's decarbonization goals. Customer Capital Costs are highest in the Limited Gas scenario because that case requires more extensive building retrofits, particularly in harder-to-electrify buildings within BGE's service territory, requiring additional expense.
- **Renewable Fuels**. All scenarios, including Limited Gas, rely on renewable fuels to some extent, and those fuels carry incremental costs over the fossil alternatives they replace. Renewable fuels include a role for green hydrogen and advanced biofuels such as renewable natural gas and renewable diesel. Spending on renewable fuels is largest in the Diverse scenario, where higher costs are driven by the need for costly synthetic natural gas. However, none of the scenarios relies on renewable fuels as a primary driver of emissions reductions, but rather each leverages them strategically to reduce the GHG intensity of remaining fuel demands.
- **Avoided Fossil Fuels Investment.** This cost metric includes spending on liquid and gaseous fossil fuels including gasoline, diesel, jet fuel, natural gas, and their renewable equivalents. The incremental costs of decarbonization are partially offset by avoided direct costs on fossil fuels, which leads to cost savings that show up as negative incremental costs relative to a Reference Scenario. The largest sources of savings are avoided expenditures on liquid fuels like gasoline and diesel in transportation end uses. The fuel costs assumed here represent delivered fossil fuel prices and do not include any price on carbon.
- **Gas + Networked Geothermal Infrastructure**. The Limited Gas scenario sees decreasing gas system utilization, raising the possibility of decommissioning some gas infrastructure to reduce

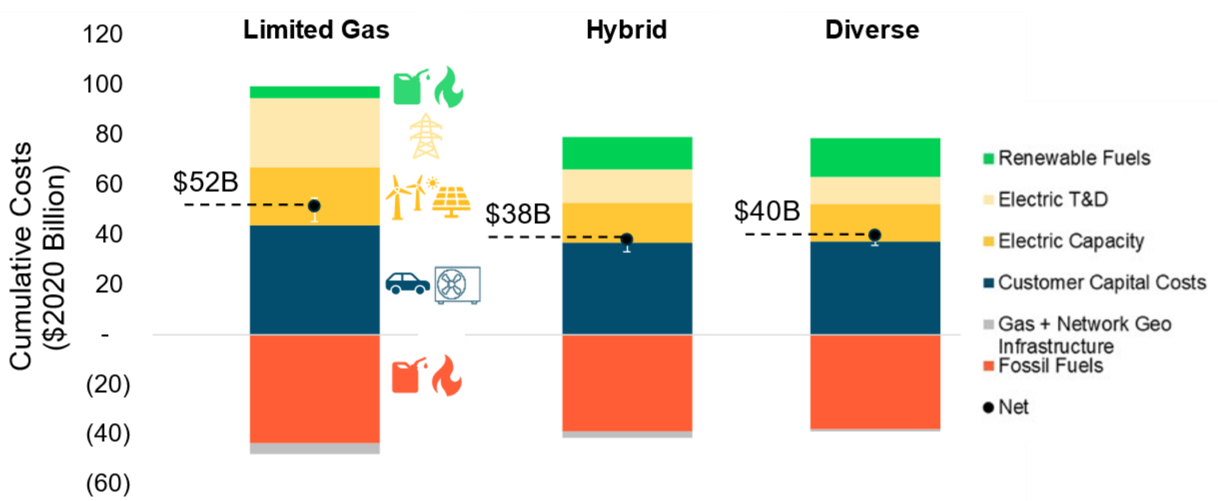
[12] Note that this study did not do new economic or engineering modeling of electric capacity, transmission, and distribution needs. This study leveraged assumptions from recent PJM modeling estimate the costs of new 100% zero-carbon generation and BGE estimates of costs for new transmission and distribution infrastructure.

total energy system costs. However, the scale of those potential savings from decommissioning is small relative to incremental expenditures in other sectors of the economy for several reasons. First, the gas system infrastructure is long-lived, with assets like gas main lines having 60+ year useful lives, so opportunities for avoided reinvestments will only be a fraction of the total value of the system between 2022 and 2050. Furthermore, not all gas infrastructure that is up for replacement can be replaced, and ongoing investments will be needed for reasons ranging from safety and reliability to the feasibility challenges inherent in implementing electrification projects at neighborhood scale. In addition, investments in the gas system, in particular STRIDE, have an additional benefit of reducing methane emissions.

Taking each cost component into account, the Hybrid and Diverse scenarios carry lower overall energy system costs than Limited Gas. The largest drivers of this outcome are the incremental electric system expenditures required to reliably serve building heating loads using an electric only strategy. The Hybrid and Diverse scenarios substantially reduce incremental electric system expenditures by leveraging the existing capacity of BGE's gas infrastructure. In addition, the Hybrid and Diverse scenarios see cost savings due to lower overall requirements for extensive building retrofits, particularly in harder-to-electrify segments of BGE's building stock.

These economy-wide cost findings support the hypothesis that a strategy that uses an integrated energy delivery system, rather than relying on an electric-only approach, reduces total cost of achieving the state's decarbonization ambitions within BGE's service territory.

Figure 17. 2045 Incremental costs by component relative to Reference Scenario[13]



Customer Costs

All scenarios rely on a transformation in how BGE's customers currently use energy, including substantial building retrofits. Given that role, E3 developed an assessment of cost impacts on BGE's customers for

[13] Chart error bars include a range of costs for T&D investments and a lower cost to achieve 100% decarbonized electricity

building investments within each decarbonization scenario. This cost assessment focuses on how customer bills and upfront costs will change given shifts from heating services currently delivered via natural gas to the primary alternative technologies that distinguish the decarbonization scenarios. Key metrics used to assess consumer costs include:

- **Upfront capital cost**, or the cost of retrofitting a building from traditional gas service to an all-electric, hybrid, networked geothermal or gas heat pump-based arrangement.
- **Bill impacts**, inclusive of changes in electric and gas rates due to decarbonization of energy supply, growth or contraction of infrastructure and changes in the utilization of infrastructure.
- **Levelized cost of ownership**, which evaluates the combined bill impact plus upfront capital costs, assuming the latter can be amortized or spread evenly over the lifetime of the appliance. This provides a view as to what the monthly expenditures on household heating could look like.

Across all scenarios, the keystone technologies required to achieve decarbonization in buildings are currently more costly than equipment relying on traditional gas service. Those costs occur primarily because of the higher upfront costs of electrification technologies. For example, a new electric heat pump or network geothermal system will range from $7,000 and $16,000 in incremental cost, compared to conventional gas alternatives. In addition, each scenario sees an increase in the operating costs of decarbonized heating technologies over time, largely driven by costs associated with achieving zero-GHG electric supply.

E3 modeled how adopting different technology packages would impact energy consumption and customer costs for a range of households representative of the BGE's customers under each of the decarbonization scenarios. Figure 18 highlights capital costs and energy bills for a 1960s vintage single-family home. This figure reflects costs for space heating, water heating, clothes drying, cooking, and air conditioning. Building shell measures are shown separately because only a subset of customers receive a shell retrofit in the economy-wide scenarios. Reference case electricity and gas usage for this customer are modeled to be 12,000 kWh/year and 620 therms/year.

Figure 18. Upfront and energy bill costs for a residential customer

				Monthly household energy bills in 2045		
Scenario	**Customer Type**	**Capital Cost Equipment**	**Capital Cost +Shell**	**Gas**	**Electric**	**Total**
Limited Gas	Traditional gas	$10,500	$23,000	$640	$270	$910
	All electric	$17,900	$30,400	$0	$525	$525
Hybrid	Traditional gas	$10,500	$23,000	$480	$220	$695
	Hybrid	$15,900	$28,400	$60	$390	$445
Diverse	Traditional gas	$10,500	$23,000	$320	$210	$525
	Gas heat pump	$20,200	$32,700	$260	$170	$435

Note that Figure 18 is focused on the capital costs and monthly household bills associated with household appliances and does not include a perspective on vehicle use. The scenarios we model include a transition for electric passenger vehicles to replace traditional gasoline vehicles, which are expected to reach cost parity around 2030 for upfront sticker price in addition to fuel savings due to the high efficiency of electric vehicles.

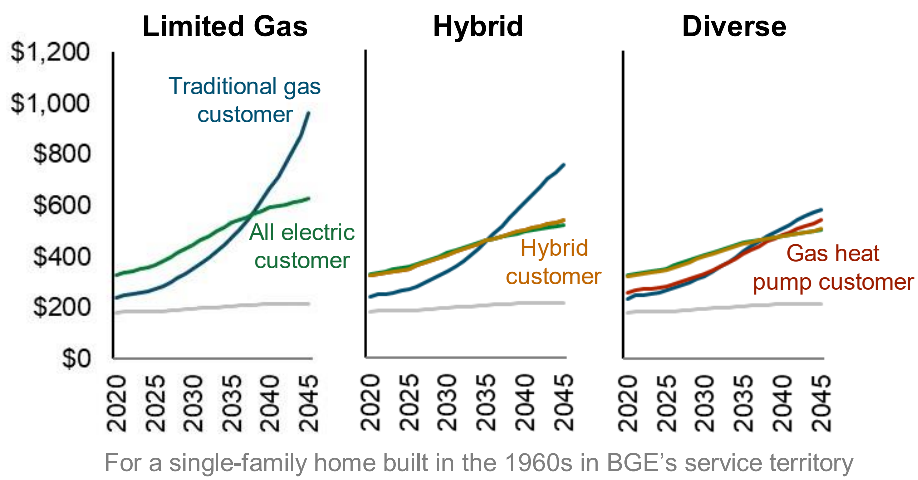
Notably, as shown in Figure 19, the cost of traditional gas service increases in each scenario such that decarbonization heating technologies become more cost effective in the 2030s. The reasons why this switchover occurs differ by scenario as follows:

- In **Limited Gas**, traditional gas customer costs increase primarily due to the fixed costs of BGE's gas infrastructure being spread over a declining number of customers. Those fixed costs are driven by the infrastructure in use, rather than the number of customers connected to the system. By the mid-2030s, the cost of being a traditional gas customer is greater than that of an all-electric customer, raising the prospect of an unmanaged transition where, absent policy interventions, a small number of customers are burdened with the costs of a gas system built for a much higher level of utilization. This cross-over point could engender a feedback loop through which increasing the numbers of customers departing gas service and the costs of the gas system are no longer recoverable through rates.
- In **Diverse**, costs for a traditional gas customer increase primarily due to impacts of renewable fuels on BGE's gas supply cost. With those higher supply costs, opting for alternative forms of heating becomes a financially favorable prospect for customers in the mid-2030s. Customers who adopt gas heat pumps or hybrid heating systems require less overall gas to heat their homes, so are less impacted by the higher cost of gas supply relative to traditional gas customers. Notably, this scenario does not appear to engender a feedback loop of gas customer

departures because of the availability of hybrid, gas heat pump and networked geothermal options.

- The **Hybrid** case reflects a combination of the gas delivery and supply cost dynamics from the Limited Gas and Diverse cases, though to a lesser extent. Average gas delivery rates increase due to declining overall gas usage, however there is still a large customer base which results in a more modest impact on customers' gas bills. Gas supply costs also increase, but those impacts are tempered relative to Diverse due to lower overall reliance on renewable fuels, particularly costly SNG.

Figure 19. Monthly BGE residential customer cost, inclusive of energy bills and amortized equipment costs for building appliances, but not including building shell retrofits



All scenarios see increasing costs associated with heating buildings in BGE's service territory. These higher costs stem in part from the higher equipment costs discussed above, as well as the impacts from decarbonized energy supply, which put upward pressure on both electric and gas rates. An integrated approach to decarbonizing building heating can reduce those rate impacts by reducing electric system infrastructure requirements and by reducing reliance on costly renewable fuels.

Regardless of the technology, the upfront costs associated with converting buildings from traditional gas service are high and will likely be burdensome, particularly to populations without ready access to financial resources. This implies that support will be needed for customers to adopt decarbonized heating technologies. Such support will be especially critical for low- and moderate-income customers who may not be able to afford the upfront cost of a retrofit or who are renters and do not have the ability to choose the heating technologies installed in their homes. Similar challenges occur with respect to transportation electrification. Notably, the recently passed Inflation Reduction Act offers support for low- and moderate-income customers to electrify, which will help to reduce upfront cost barriers to adoption.

Constructability

In all scenarios, the regional electricity system must decarbonize and expand, while at the same time BGE must appropriately size its electric infrastructure to maintain reliability and increase resilience. This will require additions and replacements of infrastructure at a scale that exceeds recent history, more akin to the post-WWII period of the electric system.[14] Achieving the level of scale envisioned in the scenarios will require overcoming challenges including siting of both renewable and firm capacity, siting of transmission and distribution infrastructure, workforce and supply chains. All else equal, there will be a higher degree of challenge with respect to electric sector constructability in the Limited Gas case relative to other scenarios.

The Hybrid and Diverse scenarios require less overall electric infrastructure by strategically leveraging the gas system, renewable fuels and networked geothermal, though this integrated gas-electric approach comes with its own constructability challenges. For example, production of hydrogen-based renewable fuels (e.g. green hydrogen and synthetic natural gas) will require large amounts of renewable energy and associated production infrastructure. In addition, networked geothermal requires neighborhood-level conversions of gas distribution systems, which will require both a high level of coordination and significant construction to be accomplished at the scale envisioned here.

Technology readiness

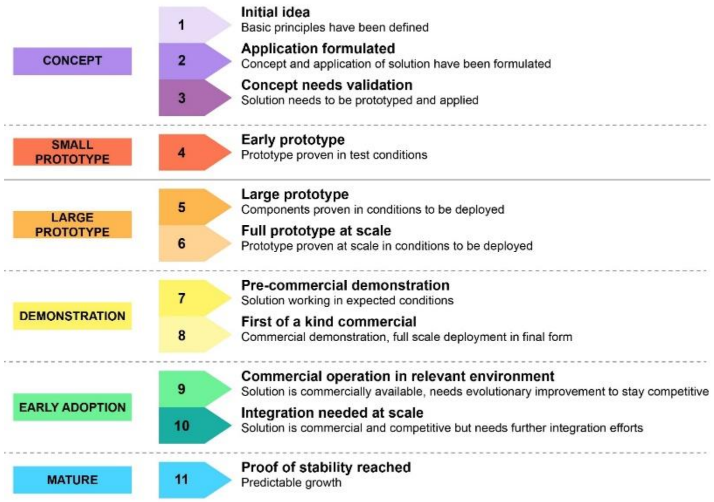
Electrification is the primary driver of decarbonization across all three scenarios. Electric vehicles and heat pumps are both commercially mature technologies across many use cases, meaning that each scenario has a high degree of near-term technology readiness.

Longer-term, the scenarios diverge in their reliance on emerging technologies that have a lower level of commercialization. For example, the Diverse scenario includes a ramp up of gas-fired heat pumps, networked geothermal and synthetic natural gas technologies after 2030. None of those technologies has achieved widespread commercialization. The risks inherent in relying on these strategies are mitigated to an extent by the overall portfolio approach in the Diverse scenario, which does not rely on any one technology to achieve decarbonization, reflecting the opportunity to incorporate new technologies as they become available. The Hybrid scenario leverages proven, commercially available demand-side technologies, but requires a higher level of renewable fuels relative to Limited Gas; as with the Diverse scenario, a Hybrid path would offer opportunities to shift between approaches as renewable fuels either successfully scale or fail to effectively develop. The Limited Gas case also relies on proven demand-side technologies and requires lower levels of less-commercialized renewable fuels, but provides less ability to pivot between new and/or evolving technologies and pathways. The Limited Gas scenario does require, notably, the emergence of a form of zero-GHG firm generation to ensure that its substantial new winter peak demands, particularly multi-day cold-snaps, can be served reliably. There are several promising technologies that could fill that role, hydrogen or advanced nuclear are two examples, but none of those technologies are commercially mature today.

[14] For a discussion of historical rates of electric load growth vs growth in electrification scenarios see: https://www.nrel.gov/docs/fy18osti/71500.pdf

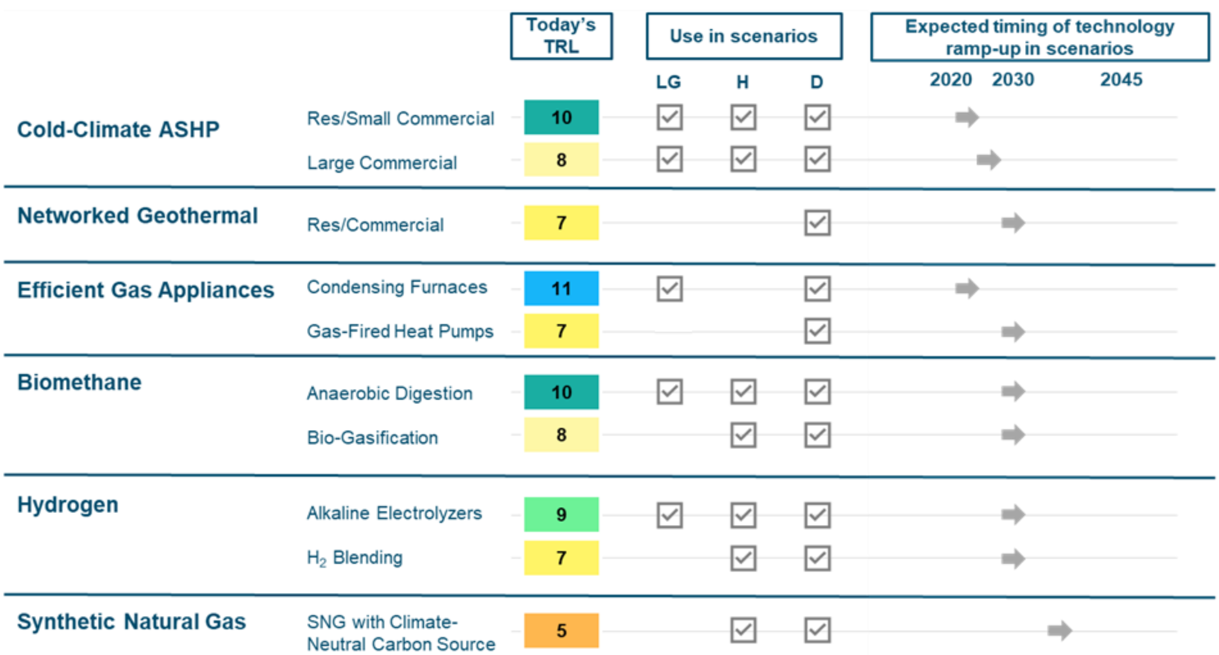
The International Energy Agency (IEA) has established a Technology Readiness Level (TRL) scale for decarbonization measures. A technology with a TRL of 11 is ready to scale, options lower than that may need research, development, and commercialization support. Portfolios of decarbonization options that rely on lower TRL measures carry additional risk. The IEA's TRL scale is shown in Figure 20.

Figure 20. Technology Readiness Scale



E3 and other deep decarbonization researchers generally screen out technologies that are less than a 5 on the TRL scale because of their speculative nature and the short time horizon of mid-century climate goals. A comparison of the technology readiness of building decarbonization measures is shown in Figure 21.

Figure 21. Technology Readiness Levels (TRLs) for building decarbonization measures and their deployment timing in scenarios[15]



[15] TRLs are based on values from an IEA database, modified in some cases by E3 based on our professional judgement, including an assessment of geographic context.

Customer Adoption and Practicality

All scenarios require high levels of consumer adoption of new building heating technologies to achieve levels of scale consistent with Maryland's climate goals. The pace of consumer conversions envisioned is without recent precedent, with such a transition not seen since past conversions from solid fuels or manufactured gas to natural gas for heating[16]. Achieving that scale will require overcoming the higher upfront costs associated with heat pumps and other electric technologies. Customers typically replace their energy consuming equipment or vehicles at end-of-product-life or failure. Those replacements happen infrequently, so early action and rapid market transformation are needed to achieve the scale of adoption considered in the three scenarios.

With respect to customer adoption of building sector retrofits, the number of homes that undergo a conversion is similar across scenarios, though the extensiveness of the actual retrofit projects varies. The Hybrid scenario offers a relatively lower-cost, lower-disruption path to electrify large amounts of heating loads in BGE's service territory, primarily targeting replacement of central-air conditioners with electric heat pumps. The Limited Gas scenario requires more extensive building retrofits to fully replace traditional gas heating systems with electric heat pumps, while at the same time improving the thermal efficiency of buildings. The Diverse scenario falls in-between, with some customers undergoing substantial retrofits and others do not. In addition, the Diverse scenario envisions the installation of networked geothermal systems, which would require a higher level of customer engagement and neighborhood level coordination compared to other technologies. However, the multiple technologies included in the Diverse scenario may allow for more extensive retrofits to be applied in cases where they are lower in cost, with less intensive measures targeted at harder-to-electrify use cases.

Equity

Absent policy interventions, decarbonization scenarios could have deleterious impacts on equity, particularly because in all scenarios the cost of heating homes in BGE's service territory increases. For example, in the Limited Gas case, the costs of being a traditional gas customer increase substantially over time as the fixed costs of the gas system are spread over fewer customers. In the Diverse scenario, traditional gas customers incur higher energy bills as renewable fuels are blended into BGE's gas supply. In both cases, customers can insulate themselves from those cost impacts, provided they can pay the high upfront costs of adopting electrification or gas heat pump technologies. All else equal, customers with higher incomes will be better able to incur those costs, while lower-income customer or renters will not. It will be critically important to support customers in managing the costs of the transition, both for early adopters and those unable to adopt new technologies until later in time.

Table 4 illustrates the energy burden for a median residential customer. Energy burden reflects energy costs as a share of household income. Here, gross household income is modeled as approximately $84,000/year in 2020, the median income for the service area, and is assumed to grow at 0.6%/year[17] in

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[16] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/760508/hydrogen-logistics.pdf

[17] Average historical annual income from St. Louis Fed from 2008-2020. Data available online: https://fred.stlouisfed.org/series/MEHOINUSA672N

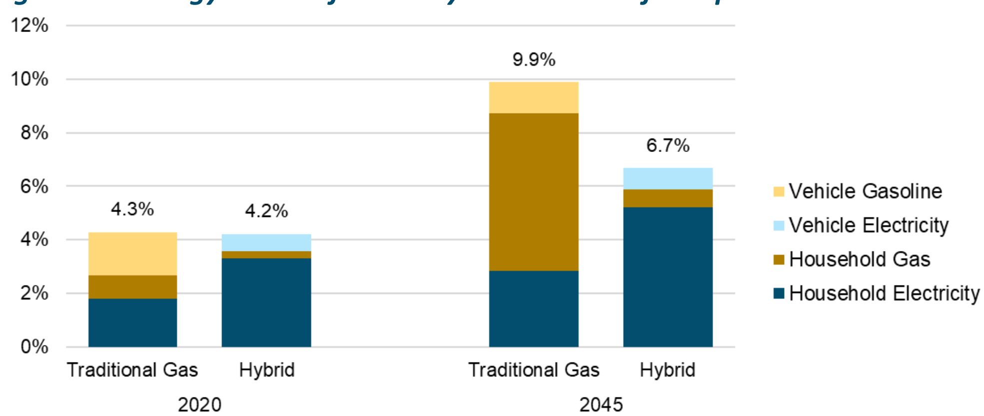
real dollars. This table also includes the energy costs associated with one personal vehicle, assuming that customers who adopt novel building technologies also replace a conventional car with an electric vehicle.

Table 4. Energy burden for a representative residential customer

Scenario	Customer Type	Household Electricity		Household Gas		Vehicle Electricity		Vehicle Gasoline		Total	
		2020	2045	2020	2045	2020	2045	2020	2045	2020	2045
Limited Gas	Traditional Gas	1.8%	3.6%	0.9%	7.8%	0.0%	0.0%	1.6%	1.2%	4.3%	12.6%
	All Electric	3.3%	6.6%	0.0%	0.0%	0.7%	1.0%	0.0%	0.0%	4.0%	7.6%
Hybrid	Traditional Gas	1.8%	2.8%	0.9%	5.9%	0.0%	0.0%	1.6%	1.2%	4.3%	9.9%
	Hybrid	3.3%	5.2%	0.3%	0.7%	0.7%	0.8%	0.0%	0.0%	4.2%	6.7%
Diverse	Traditional Gas	1.8%	2.7%	0.9%	3.9%	0.0%	0.0%	1.6%	1.2%	4.3%	7.8%
	Gas HP	1.4%	2.1%	0.7%	3.0%	0.6%	0.8%	0.0%	0.0%	2.8%	5.9%

Figure 22 illustrates the energy burden under the Hybrid Scenario. By 2045, energy burden is forecast to increase both for customers who retain traditional gas technologies and those who adopt hybrid building technologies and electric vehicles. However, comparing the technology options in 2045, the hybrid customer achieves a significantly lower energy burden than the customer who retains traditional equipment, due primarily to the significant increase in gas rates by 2045.

Figure 22. Energy burden for the Hybrid Scenario for representative residential customer



This evaluation of energy burden indicates that energy costs are likely to be a growing burden for customers. To help reduce energy burden for low-income customers, it will be key to ensure that these customers can afford novel technologies that can reduce their energy costs relative to a reliance on traditional devices. However, even with these technologies, energy burden is forecast to increase. Ultimately, it may be necessary to provide additional financial support to customers and/or to increasingly finance the societal project of decarbonization using government funds, like the programs that will support low-income customer electrification in the Inflation Reduction Act, rather than relying on customer bills.

Workforce Impact

The large amount of infrastructure added to each scenario will require an expanded energy workforce, creating economic opportunity and job creation across scenarios. In particular, the central role of electrification across all decarbonization cases will require skilled labor to decarbonize and expand the state's electricity system and support customer installations and retrofits. Along the same lines, an expanded building performance industry will be needed to achieve the scale and depth of building electrification and energy efficiency retrofits envisioned in all scenarios. Other sectors of the economy, especially those associated with the production and delivery of fuels, are more likely to see workforce declines. For example, in the Limited Gas scenario, the gas workforce may need to be reskilled over time though, importantly, even in that case the transition occurs over a multi-decade period.

Safety, Reliability and Resilience

All scenarios are assumed to comply with existing standards as defined by organizations including the Maryland Public Service Commission, the US Department of Transportation, the PJM Interconnection and others. However, it is important to note that gas and electric infrastructure have markedly different characteristics. Gas infrastructure is largely underground and therefore is less likely to be impacted by factors like inclement weather. However, loss-of-load events for gas are substantially more challenging to recover from. As a result, gas systems are designed with stricter criteria on the frequency of outages that may occur. Because of those considerations, gas customers have historically been much less likely to experience a service interruption than electric customers[18] and, absent large-scale undergrounding of electric distribution, a similar trend is likely to hold into the future. A final consideration with respect to the comparative reliability of electric versus gas is that appliances fueled by both fuels rely on electricity to operate.

Resilience is a concept that does not have a formal definition that has been established in the energy industry. Definitions of resilience range from an ability to quickly recover from or withstand shocks to the system, but can also include a broader set of technical, political, social and other factors. It is clear, however, that a resilient energy system is a critical need of any decarbonized energy system to avoid outages of critical energy systems such as space heating in the winter. In principle, having multiple energy delivery systems, as is the case in the Hybrid or Diverse scenarios, provides a degree of redundancy that a single energy delivery system cannot provide. Retaining a degree of energy infrastructure diversity and redundancy may be particularly valuable as the majority of economy-wide energy usage shifts to the electric system. Absent redundancy, disruptions in electric systems would have a more disruptive impact on Maryland's economy and society, with implications for human comfort, health, safety and mobility. As a result, an all-electric approach, as is the case in the Limited Gas scenario, may require stricter reliability standards than the 1-in-10 year standard considered here and increased investments in resilience than today, which could further increase the cost of such an approach. In addition, an all-electric approach may

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[18] https://www.gti.energy/wp-content/uploads/2018/11/Assessment-of-Natural-Gas-Electric-Distribution-Service-Reliability-TopicalReport-Jul2018.pdf

require more extensive investments in building shell retrofits than was envisioned in this study, to ensure building temperatures remain safe[19] during electric outages that occur in cold temperatures.

Regulatory and Policy Implications

Regulatory and policy support will be necessary to both manage the challenges associated with decarbonization and capture new opportunities. In this section, E3 suggests a set of regulatory and policy changes that we recommend be explored in Maryland.

Rate design

Ensuring cost-reflective pricing for both electric and gas systems will be a critical step to ensuring customer decision-making is aligned with efficient use of BGE's infrastructure. For electric rates, this would imply an emphasis on time-varying prices to ensure customers are incentivized to adopt technologies that manage the peak demand implications of electrification. For gas, net-zero consistent rates might shift to subscription or other fixed-price means of collecting gas infrastructure costs from hybrid customers with much lower volumes than today.

Utility and customer incentives

In addition to earning a rate of return on traditional infrastructure, utilities in Maryland could be offered the opportunity to invest in selected infrastructure investments to support customer adoption of electrification technologies that carry upfront costs. For example, Southern California Edison has recently filed to earn a return on incentives they provide to support behind-the-meter infrastructure like upgraded electrical panels or wiring in their customers' buildings.[20] Incentives funded by rate-payers will need to be designed to be complementary to provisions of federal programs such as those that may result from the Inflation Reduction Act.

Procurement and sale renewable gases.

Renewable gases are used in all scenarios. Maryland should consider policy regulatory modifications to allow for the procurement of these fuels. Such modifications might include approval of voluntary renewable gas offerings, a renewable portfolio standard for gas, inclusion of a social cost of carbon in gas supply planning, or as part of a technology neutral clean heat standard.

[19] See, for example, https://rmi.org/insight/hours-of-safety-in-cold-weather/
[20] https://docs.cpuc.ca.gov/PublishedDocs/Efile/G000/M432/K773/432773552.PDF

Accelerated depreciation

The results of this study suggest that gas system utilization is likely to fall in net-zero scenarios. As a result, shorter depreciation periods may be warranted to reflect a lower overall useful life for certain gas infrastructure. Doing so would better align the costs of the system with its usage and more fairly allocate on an intergenerational basis. Both National Grid in Massachusetts and PG&E in California have proposed modifications to gas infrastructure depreciation given the decarbonization initiatives underway in those states.[21]

Redirect incremental gas investment

All decarbonization scenarios envision reductions in the cost of BGE's gas system relative to business-as-usual. Achieving those cost reductions will require regulatory support, including consideration of BGE's obligation to serve its existing gas customers and ability to leverage cost savings from non-pipe alternative projects to support decarbonization initiatives like targeted electrification or networked geothermal. These and related issues have begun to be explored in both California and New York.[22] Initial findings from work in those states indicates that redirecting investments will involve substantial changes to utility planning practices, including more extensive coordination between electric and gas distribution planning.

Electric to gas benefit payments

An integrated energy delivery system provides benefits by leveraging BGE's gas system to reduce the overall size and cost of its electric system. As a result, transfer payments from the company's electric business to its gas business could help to ensure that the costs of BGE's gas system are shared among all ratepayers who benefit from the capacity and other benefits it provides. Such a benefit sharing approach is currently being implemented in Canada, where Hydro Quebec, an electric utility, is currently compensating Energir, a gas utility, for infrastructure it maintains that supports hybrid heating customers.[23]

A summary of the regulatory and policy changes recommended for consideration is provided in Figure 23. The initiatives are sorted into those that are common across scenarios and E3 recommends be pursued and those that need further exploration or that are scenario-specific.

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[21] D.P.U. 20-120; https://www.pge.com/pge_global/common/pdfs/about-pge/company-information/regulation/general-rate-case/PGE-GRC-Application-2023.pdf

[22] https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/natural-gas/long-term-gas-planning-oir/presentation-for-r2001007-track-2-workshop-1_2022-01-07.pdf;

[23] D-2021-172 File R-4169-2021 Phase 1, "Demande Relative Aux Mesures De Soutien À La Décarbonation Du Chauffage DesBâtiments," Regie De L'Energie (September 2021) http://publicsde.regie-energie.qc.ca/projets/597/DocPrj/R-4169-2021-B-0005-Demande-Piece2021_09_16.pdf

Figure 23. Regulatory and policy initiatives

Solution	Limited Gas	Hybrid	Diverse	Example
Recommended				
Rate design Cost reflective pricing on electric and gas (TOU, subscription -based)	✓	✓	✓	Various
Utility and customer incentives e.g., BGE investments to support customer adoption	✓	✓	✓	SCE
Procurement of renewable gasses e.g., Voluntary tariffs or updated gas supply procurement standards	✓	✓	✓	Various
Needs Further Exploration				
Accelerated depreciation Ties the pace of recovery to remaining system utilization	✓			PG&E National Grid
Avoided incremental gas investment Strategically reduce incremental rate base	✓		✓	PG&E
Benefit payments e.g. compensate the gas system for avoided incremental investment		✓	✓	Energir/Hydro Quebec

Key Takeaways and Recommendations

This study examined three distinct decarbonization scenarios for BGE's service territory that are consistent with achieving net-zero GHG emissions in Maryland. None of these scenarios are intended to be viewed as a 'preferred' strategy. Instead, their individual features and outcomes are intended to inform BGE's and the state's decarbonization planning, in particular by identifying actions for the near-term and nascent strategies that warrant further examination.

Key Takeaways

1. **Pathways that rely on an integrated energy system carry a lower overall cost and level of challenge relative that rely more exclusively on electrification or renewable gases.** There are multiple viable paths to decarbonization, but any future that meets net zero will require significant transformations and investments across the economy and a role for electrification in buildings and transportation. Electrification is the core engine of decarbonization across all scenarios considered in this report because of its high level of commercialization, scalability, and complementarity to an increasingly decarbonized electricity system. Key trade-offs include types of electrification technologies that are adopted and the overall level of electrification vs reliance on efficient gas technologies. Scenario findings identify ongoing value for gas infrastructure that deliver an increasing blend of renewable gases[24] as a complement to electrification. Key trade-offs include types of electrification technologies that are adopted and the overall level of

[24] Renewable gases considered in this study encompass renewable natural gas from biogenic sources produced via anaerobic digestion and gasification, hydrogen produced via electrolysis powered by renewable energy, and synthetic natural gas produced using hydrogen and a climate neutral source of CO2.

electrification vs reliance on efficient gas technologies. Investments in gas infrastructure, including the STRIDE Program, help to modernize the system, reduce methane emissions and improve safety and reliability. Those investments could be balanced against future opportunities to pursue targeted electrification that enable gas infrastructure savings where such initiatives produce system and ratepayer cost savings. An integrated approach that leverages the advantages of both electric and gas infrastructure can help to reduce both total energy system and consumer costs, while also reducing challenges associated with large-scale electric infrastructure additions and customer retrofits.

2. **All scenarios that achieve net-zero require significant investments in electric generation and delivery infrastructure, but those costs can be mitigated via an integrated approach**. Clean electric generation capacity will need to be sited, permitted, built and interconnected into the grid. BGE's electric delivery system will need to increase in capacity and modernize to accommodate new electrification loads while at the same time the energy it delivers via both gas and electricity will need to become cleaner. Relying on a dual energy approach reduces the overall scale of infrastructure additions required to achieve net-zero goals. As a result, pathways that rely on an integrated energy system are lower cost than all-electric or all-renewable gas-based pathways and have a lower level of challenge in terms of the constructability of new infrastructure, while providing more flexibility to navigate rapidly-changing technological and market developments to continue to allow the most appropriate choices for all customers throughout the energy transition. Those advantages are tempered by higher reliance on renewable fuels, which have a comparably lower level of technology readiness compared to all-electric measures.

3. **Consumers are central to the transformations required to achieve net-zero** and achieving the scale of adoption envisioned here will require developing solutions that are affordable and work for customers, equitably. All-electric solutions can lead to higher retrofit costs for existing buildings, particularly older buildings, relative to alternatives. Decarbonization pathways that include a diverse set of heating technologies enable strategic application of all-electric solutions where they are most appropriate, while allowing for alternative strategies in cases where all-electric solutions are more challenging. Lower income customers are expected to face higher energy burdens, particularly in the Limited Gas scenario, so identifying strategies to mitigate those impacts will be critical to achieving a just transition to net-zero. Relative to Limited Gas, the Hybrid and Diverse scenarios offer potential pathways through which the energy burden of decarbonization can be managed. In all cases, customers will need to adopt electric vehicles, supported by a combination of private and public charging infrastructure.

4. **As Maryland's largest utility, BGE will have an important role in supporting customer adoption of decarbonization options by introducing and scaling new products, programs, and services required to achieve net zero** through, for example, pilot programs, incentives and new types of infrastructure investments. Examples where BGE could have a role in facilitating and scaling decarbonization technologies include, but are not limited to, strategic electrification, networked geothermal, and green hydrogen production and delivery. BGE's role could also include working to ensure that all its customers are able to participate in and share the benefits of the decarbonization transition by, for example, ensuring equitable electric vehicle charging infrastructure in disadvantaged communities, supporting efficient heating technologies adoption

for low-income customers, and finding additional ways to protect low-income customers from bearing undue burdens through the energy transition.

5. **Regulatory and policy support will be necessary to manage the challenges associated with decarbonization.** Regulatory and policy interventions are needed in several areas including, but not limited to, enabling BGE and its customers to support the state's decarbonization ambitions in order to manage the cost impacts of implementing decarbonization, supporting customer adoption of electrification technologies, and implementing non-pipe alternatives projects.

Based on the key findings of this study, E3 recommends the following strategies to BGE, its regulators, policymakers and other key stakeholders in Maryland:

1. **Increase funding for energy efficiency programs and align measures to support decarbonization.** All scenarios include levels of energy efficiency savings that go beyond even Maryland's current ambitious targets through traditional efficiency measures and electrification. For that to happen, additional funding is likely to be needed. Achieving higher levels of energy efficiency progress will likely require additional funding beyond that offered today. In addition, the emphasis of energy efficiency programs may need to shift, including an emphasis on building shell retrofits that reduce both customer bill and utility electric system impacts from building thermal decarbonization. Energy efficiency funds could also be used to support the commercialization of emerging technologies gas heat pumps.

2. **Develop programs and incentives to support building and transportation decarbonization**. Customer incentives will be needed to support the adoption of decarbonization technologies. For example, expanding the remit of BGE's current programs to include fuel-switching could be a practical initial strategy to support customers in managing the incremental cost of electrification. Current programs that incentivize high-efficiency cooling could be reoriented to require installation of a heat pump, rather than a stand-alone air conditioner, to be eligible for an incentive. Such an intervention could be a feasible initial step to encourage hybrid electrification of BGE's customers.

3. **Support development of electric vehicle charging infrastructure and vehicle adoption**. Transportation electrification is a common feature of all the scenarios evaluated. For transportation electrification to scale to levels consistent with decarbonization, sufficient at home, workplace and public charging infrastructure will be needed. While much of that infrastructure will be provided via non-utility market actors, there are gaps that BGE could fill like, for example, installations of charging infrastructure in multi-unit dwellings or in disadvantaged communities. In addition, make-ready investments that prepare customer sites for the eventual installation of charging equipment are warranted to ensure customers who want to adopt an electric vehicle can do so in a timely manner. Alongside those infrastructure additions, upfront incentives will be needed until electric vehicles reach upfront cost parity with gasoline and diesel vehicles. In addition, allowing BGE investments in advanced electric vehicle charging management technologies may be warranted to help defray costs that might otherwise be required for certain physical infrastructure upgrades.

In addition to those initiatives, E3 recommends that BGE, its regulators and policymakers in Maryland pursue the following types of research and development or pilot activities to support GHG reductions within BGE's gas delivery service:

1. **Develop and pilot hybrid electrification operations and control strategies.** Like past work for the state, this work confirms that a building electrification strategy that includes hybrid heat pumps has lower overall costs than an electric-only approach. However, the extent to which those benefits are captured will depend on how the hybrid systems are operated. Historically, hybrid systems have been operated via contractor- or user-defined temperature set points at which backup thermal system takes over from the heat pump. However, utilities in both Canada and the United Kingdom have begun to pilot alternative control strategies that leverage differences in gas vs electric pricing, weather conditions and other factors to optimize the operation of hybrid systems. Similar to those initiatives, E3 recommends that BGE pilot alternative hybrid heat pump operations alongside the deployment efforts for these systems described above.

2. **Develop a networked geothermal pilot program.** Networked geothermal systems hold the potential to provide all-electric heat in a manner that substantially reduces electric system impacts, offers a transition path for BGE's gas workers, and represents a potential evolution for BGE's business. However, there are many uncertainties with respect to the technical and economic feasibility of this solution in BGE's service territory, as well as the extent to which customers will be interested in receiving networked geothermal service. Initial pilots, similar to those being conducted by Eversource Energy and National Grid in Massachusetts, would help to resolve these uncertainties.

3. **Develop a process to identify opportunities for non-pipeline alternatives to conventional gas infrastructure investments.** All-electric solutions like networked geothermal or air-source heat pumps are most likely to be cost effective in instances where gas infrastructure can be avoided and where the electric system has sufficient capacity. Developing a process to assess the technical feasibility, customer acceptance and net-benefits or costs of non-pipeline programs would therefore help to identify where all-electric vs integrated gas-electric approaches are most warranted. Any non-pipeline alternative initiatives will need to be balanced against the safety, reliability and methane emissions reduction benefits of ongoing gas infrastructure replacement programs, including the Strategic Infrastructure Development and Enhancement (STRIDE) program.

4. **Support the emergence of renewable natural gas (RNG) supply sources and associated regulatory support and rate development**. RNG resources are leveraged in all scenarios though, given the modeled pace of electric sector decarbonization and electrification, these resources are not blended into the gas delivered by BGE until after 2030. In practice, BGE should consider procuring initial quantities of RNG before then to gain familiarity with the technology and support the development of regulatory standards through which these resources can be procured and developed.

5. **Pilot blends of hydrogen and dedicated hydrogen infrastructure.** The Hybrid and Diverse cases envision blends of hydrogen to reduce the greenhouse gas intensity of BGE's gas supply. Like RNG the use of hydrogen does not need scale until after 2030, so the remainder of this decade will be an opportunity to explore the technical and operational requirements of both dedicated hydrogen and hydrogen blends. Several gas utilities throughout the United States and abroad are pursuing similar initiatives[25], so BGE can both learn from and contribute to broader learnings in this space. Finally, the scenarios modeled here focus on hydrogen blending in the gas system, but other studies have explored a potential for dedicated hydrogen clusters if greater ambition in industry is pursued in Maryland.

[25] https://www.capitaliq.spglobal.com/web/client?auth=inherit#news/article?KeyProductLinkType=2&id=65570349

Appendix A: Comparisons between recent E3 studies in Maryland

Discussion of Recent Decarbonization Analyses in Maryland

E3 has a history of developing decarbonization scenario analysis in Maryland. E3 supported the Maryland Department of the Environment in their development of scenarios for the Greenhouse Gas Reduction Act (GGRA) in 2017, and the update in 2021 The most recent statewide analysis was published in early 2021 after broad stakeholder engagement through the state's Mitigation Working Group under the Maryland Commission on Climate Change (MCCC)[26]. This work explored economy-wide scenarios to achieve a minimum of 40% GHG reductions below 2006 levels by 2030.

Following on the work for GGRA work, E3 provided technical support to the MCCC by modeling different pathways to decarbonize building emissions by 2045 and engaging with the Buildings Sub-Group to the Mitigation Working Group. This analysis informed a Buildings Energy Transition Plan that was published in November 2021 by MDE.

In 2022, E3 was retained by BGE to explore economy-wide scenarios that are consistent with the State's new GHG targets of net zero GHG emissions by 2045 but tailored to their service territory. Our intent was to build on and be aligned with the existing foundation of the work for the State by using the same methodology while aligning with the BGE geography and appropriate data sources. Each of these three studies has a slightly different viewpoint and set of objectives, but still have largely consistent findings. This appendix serves as a comparison and crosswalk of key objectives and assumptions between studies.

All three studies explore deep decarbonization in Maryland, but the key differences are related to overall ambition, geography, and sectoral scope.

> **Ambition**: The GGRA Plan explored the potential to meet GHG Targets set under the 2006 GGRA, which includes 40% reductions by 2030 and 80% by 2050. The most recent GGRA plan exceeds the 2030 target but falls short of 2050. The MD Buildings and BGE studies both target net zero GHG emissions by 2045.
>
> **Geography**: The GGRA and MD Buildings study are exploring statewide GHG emissions, while the BGE study focused on BGE's service territory and energy consumption, which is roughly half of the state.
>
> **Sectoral Scope**: The GGRA and BGE studies looked at economy-wide GHG emissions, including emissions from buildings, industry, electricity generation, transportation, agriculture, waste, and forestry. The MD Buildings work focused primarily on buildings and included upstream emissions from electricity generation.

Table 5 below highlights some of the key similarities and differences between the three studies.

[26] https://mde.maryland.gov/GGRA

Table 5. Comparison of key design parameters of recent E3 work in Maryland

	2030 GGRA Plan	Maryland Building Decarbonization	BGE Integrated Decarbonization Scenarios
Year Published	2021	2021	2022
Project Sponsor	MDE	MCCC/MDE	BGE
Sectors Covered	Buildings Industry Transportation Electricity Generation Agriculture Waste Forestry	Buildings	Buildings Industry Transportation Electricity Generation Agriculture Waste Forestry
GHG targets	40x30, 80x50	Net zero by 2045	60x31, Net zero by 2045
Geography	Statewide	Statewide	BGE Service Territory
Economy-wide Net GHG Reductions Achieved by 2045 (vs. 2006)	76%	100%	100%
GHG Reductions achieved by sector in 2045			
Buildings	23%	86-100% (depending on scenario)[27]	86%
Transportation	65%	N/A	81-85%
Industry	54%	N/A	57-69%
Electricity Generation	93%	100%	100%
Other Sources	31%	N/A	66%
Natural and Working Land Sinks	+15% in net carbon sinks	N/A	+15% in net carbon sinks

[27] The high electrification scenario, electrification with fuel backup scenario, and high decarbonized methane scenario all achieve 100% decarbonization in buildings. The MWG policy scenario achieves an 86% reduction in direct building emissions and remaining emissions are subject to an alternative compliance payment.

Comparison of Key Assumptions

In the tables below we will compare key assumptions from the three analyses: (1) key building space heating technologies, (2) role of electric vehicles, (3) role of low-carbon fuels, (4) natural gas throughput, and (5) decarbonization of electricity supply.

Table 6. Percent of stocks of key technologies in 2030 and 2045 in residential space heating

Project		GGRA	MD Buildings			BGE		
Scenario	Year	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
ASHP	2030	25%	40%	25%	11%	40%	31%	28%
	2045	63%	80%	40%	14%	85%	55%	50%
GSHP	2030	~0%	4%	~0%	0%	4%	4%	4%
	2045	~0%	9%	~0%	0%	9%	9%	9%
Hybrids	2030	0%	0%	20%	0%	0%	13%	5%
	2045	0%	0%	40%	0%	0%	28%	12%
Efficient Gas	2030	2%	4%	4%	24%	8%	2%	10%
	2045	4%	1%	1%	54%	2%	0%	8%
Gas HP	2030	0%	0%	0%	0%	0%	0%	9%
	2045	0%	0%	0%	0%	0%	0%	8%
Networked geothermal	2030	0%	0%	0%	0%	0%	0%	2%
	2045	0%	0%	0%	0%	0%	0%	8%

Table 7. Percent of new sales of key technologies in residential space heating

Project		GGRA	MD Buildings			BGE		
Scenario	Year	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
ASHP	2030	50%	90% by 2035 and after	90% by 2035 in new construction	14%	86%	53%	47%

	2045	80%	90%	90% in new construction	14%	89%	58%	55%
GSHP	2030	0.3%	10% by 2035	10% by 2035 in new construction	0%	9%	9%	9%
	2045	0.3%	10%	10% in new construction	0%	10%	10%	10%
Hybrids	2030	0%	0%	100% by 2035 in non-new construction	0%	0%	30%	12%
	2045	0%	0%	100% in non-new construction	0%	0%	30%	12%
Efficient Gas	2030	25% of gas sales	25% of gas sales	25% of gas sales	100% of gas sales	3%	0%	8%
	2045	25% of gas sales	25% of gas sales	25% of gas sales	100% of gas sales	0%	0%	8%
Gas HP	2030	0%	0%	0%	0%	0%	0%	5%
	2045	0%	0%	0%	0%	0%	0%	2%
Network geothermal	2030	0%	0%	0%	0%	0%	0%	9%
	2045	0%	0%	0%	0%	0%	0%	6%

Table 8. Percent of stocks of zero-emission vehicles (ZEVs) in 2030 and 2045 by vehicle class

Project		GGRA	MD Buildings			BGE		
Scenario	Year	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
LDA	2030	24%	N/A	N/A	N/A	29%	23%	23%
	2045	75%	N/A	N/A	N/A	95%	76%	76%
LDT	2030	7%	N/A	N/A	N/A	28%	22%	22%

	2045	61%	N/A	N/A	N/A	88%	70%	70%
MDV + HDV	2030	9%	N/A	N/A	N/A	10%	8%	7%
	2045	61%	N/A	N/A	N/A	69%	56%	49%

Table 9. Percent of new sales of ZEVs in 2030 and 2045 in transportation

Project		GGRA	MD Buildings			BGE		
Scenario	Year	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
LDA	2030	64%	N/A	N/A	N/A	96%	77%	77%
	2045	88%	N/A	N/A	N/A	100%	80%	80%
LDT	2030	24%	N/A	N/A	N/A	96%	77%	77%
	2045	88%	N/A	N/A	N/A	100%	80%	80%
MDV + HDV	2030	35%	N/A	N/A	N/A	52%	42%	36%
	2045	84%	N/A	N/A	N/A	95%	76%	66%

Table 10. Energy consumed from low-carbon fuels [TBtu] in 2045

Project	GGRA	MD Buildings (buildings sector only)			BGE (economy-wide, BGE geography only)		
Scenario	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
Renewable Diesel	0	N/A	N/A	N/A	0.2	15.1	14.5
Renewable Natural Gas	0	9.4	58.0	120.2	4.1	23.7	30.9
Renewable Jet Fuel	0	N/A	N/A	N/A	0	0	0
Hydrogen	0	0.7	4.4	9.0	8.8	7.0	9.2

Table 11. Natural Gas throughput in buildings [% decline vs. 2020] in 2045

Project	GGRA	MD Buildings			BGE		
Scenario	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
Gas throughput	37%	93%	59%	16%	87%	74%	65%

Table 12. Electricity generation decarbonization [% zero-carbon electricity generation] in 2045

Project	GGRA	MD Buildings			BGE		
Scenario	GGRA Plan	High Elec	Elec with Backup	High Decarb. Methane	Limited Gas	Hybrid	Diverse
Share of zero-carbon electricity generation	77%[28]	100%			100%		

E3 model updates in 2022

E3 made two categories of model updates in 2022 relative to past work in Maryland: (1) updated representation of local BGE territory, and (2) updated assumptions reflective of better and more recent data.

Representation of BGE Territory

- **Downscale of GHG emissions sources to BGE geography.** E3 developed an economy-wide Pathways model of BGE's service territory by downscaling each category of the Maryland GHG inventory and benchmarking to BGE data sources.
- ***Buildings.*** BGE's service territory has approximately half of the population but more than half of current building emissions for the state. E3 used BGE consumption data to benchmark to energy usage by fuel.
- ***Industry.*** Similar to Maryland as a whole, BGE's territory has a fairly small amount of industry. Total industrial energy consumption is approximately 10% of energy consumption within BGE's territory.

[28] Calculated as % of generation coming from solar, wind, biomass, hydroelectric, and nuclear power. Excludes imported power.

- ***Transportation.*** The transportation sector within BGE's territory has similar characteristics to Maryland as a whole. Around 50% of total transportation energy consumption is assumed to occur within BGE's service territory, aligned with its share of the state's population.
- ***Electricity***. Electricity generation in Maryland is served by in-state power plants and imports from neighbors in PJM. GHG emissions from the electric sector are largely outside of BGE's control but are assumed to decline in line with the ambition from other net zero decarbonization studies.
- ***Non-Energy and Other GHGs***. Remaining GHG emissions include categories such as agriculture, wastewater, and refrigerants, which have been downscaled to BGE territory by population.
- **Alignment with BGE data on energy consumption and building types.** Residential, commercial, and industrial energy consumption for electricity and natural gas was aligned with BGE sales data for 2019. The study aligned starting stock penetration of key space heating device types with the existing space heating stock in BGE's service territory. Throughout the study, E3 considered the age and building characteristics of residential buildings within BGE's service territory. Approximately half of the residential units within BGE's territory were built before 1980, with 20% built before 1950. Around 25% of residential units are in multifamily buildings and a third are rented.
- **Renewable fuels.** In modeling a role for low-carbon fuels, E3 assumed approximately half of Maryland's renewable fuel availability would be available to BGE. For biomethane, synthetic natural gas, and pipeline hydrogen, the fraction was the ratio of BGE's pipeline gas demand (fossil natural + biomethane + synthetic natural gas + pipeline hydrogen) to MD's pipeline gas demand. Similarly for renewable diesel, the fraction was the ratio of BGE's total diesel demand (fossil diesel + renewable diesel) to MD's total diesel demand. Depending on scenario and the modeled year, this fraction was about 55% for biomethane, pipeline hydrogen, and synthetic natural gas, and about 45% for renewable diesel.

Updated model assumptions

- **More diversity in building shell options**. Only one type of deep building shell retrofit was considered in the Maryland Buildings Study, consisting of wall insulation, roof insulation, glazing, air-tightness, and heat recovery. Feedback from stakeholders in that work suggested that the deep shell retrofit modeled was expensive and assuming a binary option of deep shell retrofit or no retrofit at all was too simplistic. In this study for BGE, E3 reflected this feedback and included several options for building shells for both residential and commercial buildings. For both residential and commercial buildings, new construction standards were assumed to reduce those buildings' space heating services demands between 45%-53% (single family to multifamily homes) and 31% for commercial buildings, relative to the average building in BGE's service territory. Existing residential buildings were assumed to have an efficient shell retrofit available, which reduced their service demands by 33% for single family homes and 22% for multifamily homes relative the average residential building. Existing commercial buildings were also assumed to have an efficient shell retrofit available, which reduced their service demands by 37% relative to the average commercial building.
- **Updated commercial building electrification load shapes.** E3 updated the modeling of commercial building electrification load shapes for the BGE study from the GGRA study and the Maryland Buildings Study. The updated shapes are smoother and less "peaky", consistent with commercial heating demand profiles derived from historical gas data available through the Energy Information Administration and provided by BGE.

- **Updated perspective on availability and cost of biofuels.** Biofuels were not included as part of the GGRA Plan, but were considered for application in buildings through blend in pipelines in the Maryland Buildings Study. The Maryland Buildings Study assumed Maryland has access to the population-weighted share of national biomass feedstock in an optimistic scenario of biomass availability. The BGE study limits the biomass availability to east of the Mississippi, reflecting E3's most recent view consistent with E3's work for the Massachusetts Department of Public Utilities Docket 20-80. The BGE study includes additional biomethane sources from landfill gas and wastewater treatment plant based on the American Gas Foundation's "Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment" report. In addition, the BGE study also provided a holistic view of the use of biofuels among various sectors to provide the highest value in carbon abatement, whereas the Maryland Buildings Study only focuses on residential and commercial buildings.

Comparison of Key Findings

Though each of the three studies reviewed in this appendix had different primary objectives, we draw consistent conclusions from them.

Both economy-wide analyses (GGRA and BGE) point to the need for ambitious action across all sectors of the economy to reach deep decarbonization goals, with critical roles for electrification, efficiency, and low-carbon electricity.

The Maryland Buildings Study and BGE study found that there are multiple pathways to decarbonize buildings, but that electrification has an important role to play, especially in new construction. These studies both pointed to cost benefits in leveraging additional building space heating solutions that can lessen impacts on the electric grid, such as hybrid heat pump systems.

The Maryland Buildings Study and BGE Study found increasing electric peak demands in any scenario with building electrification and, depending on the pace and scale of electric technology deployment and level of flexibility loads, a transition to a winter peaking system in the 2020s or early 2030s.

The BGE study explored the potential for emerging technologies such as network geothermal and gas heat pumps to be part of the solution, and found that if they can reach scale they can also be part of a cost-effective building decarbonization solution.

The Maryland Buildings Study and BGE study also found that in order to achieve net zero by 2045, technology deployment and policy ambition will need to go beyond the levels explored in the 2021 GGRA scenario planning exercise.

Appendix B: Model Methodology

Economywide Modeling

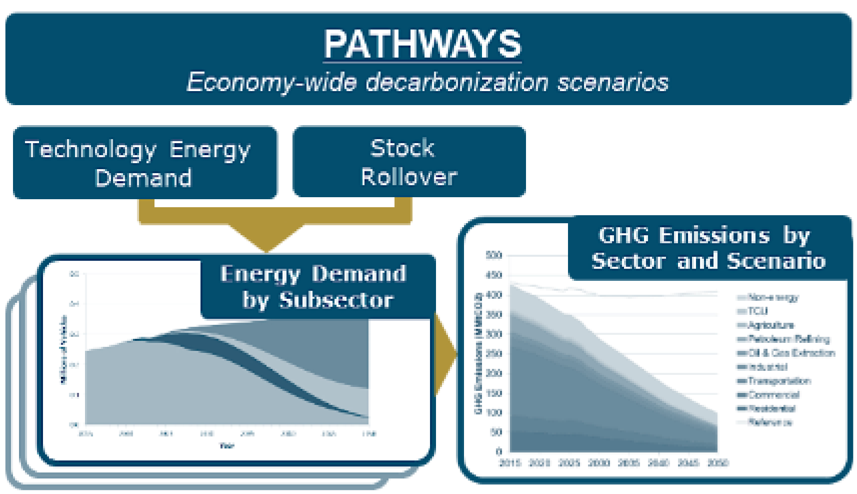
E3 assessed the role of BGE in supporting Maryland's decarbonization policy goals within an economywide modeling framework. Taking an economywide approach helps to clarify the level of greenhouse gas mitigation effort required across different sectors like buildings, transportation, or industry. An economywide approach also captures the impacts of decarbonization on electric and gas infrastructure and other sources of decarbonized energy supply, such as renewable gasses or liquid fuels. Finally, an economywide view provides further indication of how BGE's electric and gas delivery systems will need to transform as both energy demand and supply change over time.

PATHWAYS

The PATHWAYS Model

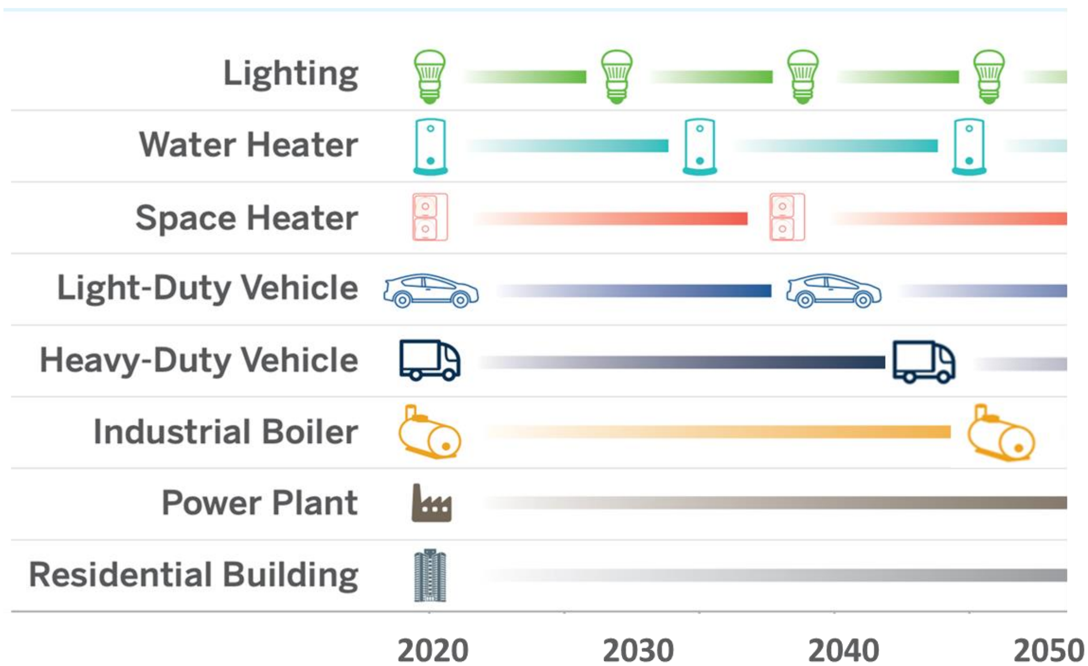
E3's PATHWAYS model is an economywide representation of infrastructure, energy use, and emissions within a specified geography. E3 developed PATHWAYS in 2008 to help policymakers, businesses, and other stakeholders analyze trajectories to achieve deep decarbonization of the economy; the model has since been improved over time in projects analyzing jurisdictions across North America. Recent examples include working with the Maryland Department of the Environment, New York State Energy Research and Development Authority in New York, with the Calpine Corporation in New England, the California Energy Commission, Xcel Energy in Minnesota, Nova Scotia Power in Nova Scotia, and the Massachusetts Department of Public Utilities 20-80 Future of Gas proceeding.

Figure 24. Schematic overview of the PATHWAYS model.



A key feature of PATHWAYS is a characterization of stock rollover of equipment in major sectors of the economy like buildings and transportation. Stock rollover describes a methodology where the total number of devices (stocks) are tracked and retired at the end of a deemed lifetime and replaced with new technologies over time (sales). A stock rollover approach tracks infrastructure turnover of energy-consuming devices while accounting for changes in performance, such as improved efficiency over time. This approach explicitly tracks the time lag between changes in annual sales of new devices and changes in device stocks over time in key building and transportation sectors. Different types of equipment have different lifetimes, which are captured by this approach. For example, some technologies, such as lightbulbs, have life spans of just a few years, while others, such as the built environment, have multi-decade or longer life spans. Tracking technology and infrastructure lifespans informs the pace of transformation necessary in each sector to achieve economywide greenhouse gas (GHG) targets while capturing potential path dependencies. As an example, Figure 25 shows example lifetimes of different end uses and the potential number of replacements that could realistically be achieved between now and 2050. The Pathways model also has the ability to track "early retirements" where devices are assumed to retire before the end of their natural life; this modeling exercise for BGE assumes natural replacement of devices and does not include early retirements.

Figure 25. Common timelines for stock rollover of different appliance types and infrastructure. Replacement cycles are illustrative and do not precisely reflect values used in modeling.[29]



Representation of Maryland and BGE Service Territory Energy Demands and Emissions

As noted in the main text of the report, E3 updated its MD PATHWAYS model by benchmarking to the state's 2017 GHG inventory, using IPCC AR5, 100-year global warming potentials (GWPs). BGE's service territory was initially represented in PATHWAYS as a population-weighted scale down of PATHWAYS's MD region. Using BGE-provided data and data from S&P Global, key stock-based subsectors, such as building space heating, and sectoral natural gas and electricity demands were subsequently benchmarked by E3

[29] This figure was published originally by E3 (Williams et al. 2014) and modified with graphic design improvements by the Building Decarbonization Coalition.

to BGE specific characteristics. E3 represented BGE's non-energy, non-combustion emission sources and sinks, including agricultural emissions and land sinks as a population-weighted share of MD's. This final benchmark indicated that BGE's service territory is approximately 50% of MD energy use and emissions.

Sector Representation and Key Drivers

The PATHWAYS model includes representations of the following sectors: residential and commercial buildings; transportation; industry; and other non-energy, non-combustion sectors including agriculture and waste. Growth in energy demands and/or emissions is driven by a variety of factors, shown in Table 13.

Table 13. PATHWAYS sectors and primary drivers.

Sector	Primary Driver	Compound Annual Growth Rate (%)	Sources
Buildings	Residential: Number of households Commercial: Commercial square footage	Households: 0.7% Square footage: 1.0%	AEO 2021 Reference
Transportation	Per-vehicle vehicle-miles traveled (VMTs); Number of vehicles: population growth	LDV VMT: 0.3% MDV VMT: 0.8% HDV VMT: 0.8% Population: 0.6%	AEO 2021 Reference
Industry	Varies by fuel and industrial subsector	Overall fuel demand growth: 0.6%	AEO 2021 Reference
Electricity	Buildings, transportation, and industrial electricity demand growth	Varies, dependent on level of electrification by scenario	N/A
Other Non-Energy, Non-Combustion	Various	Various	2030 GGRA Plan[30]

Buildings. As discussed in the main report, buildings within BGE's service territory represent key opportunities for decarbonization through electrification. Energy demands and emissions within this sector are driven by HVAC demands, particularly from fossil fuel combustion for space and water heating.

Transportation. The transportation sector represents the largest set of emissions within BGE's service territory. Energy demands and emissions are expected to grow with population and per-vehicle vehicle-miles traveled (VMTs) under reference assumptions.

Industry. Industry within BGE represents a smaller portion of energy demands and emissions relative to

[30] The Greenhouse Gas Emissions Reduction Act 2030 GGRA Plan. https://mde.maryland.gov/programs/Air/ClimateChange/Documents/2030%20GGRA%20Plan/THE%202030%20GGRA%20PLAN.pdf.

buildings and transportation. In particular, the chemical industry consumes approximately 30% of total industrial energy in BGE territory. Fuel demand growth varies across industrial subsectors and fuel types.

Electricity. Currently, electricity emissions are primarily driven by loads from buildings and industry and the emissions factors of generation within Maryland and from imports from other regions of PJM. Under scenarios of high transportation electrification, electricity emissions will also be influenced by transportation-driven loads.

Other Non-Energy, Non-Combustion. Remaining emissions include those not associated with fuel combustion, such as agriculture, wastewater, and refrigerants. Most subsector emissions were assumed to decline throughout the course of the study period, consistent with the 2030 GGRA Plan.

Key Pathway Parameters

All sectors were assumed to decarbonize to some extent through a variety of strategies, including electrification and efficiency on the demand side and the decarbonization of electricity and fuels on the supply side. Each scenario was primarily distinguished by the types and levels of building electrification and secondarily by the decarbonization strategies employed by industry. All scenarios are assumed to reach net-zero emissions by 2045. Table 14 provides an overview of the key parameters in each scenario.

Table 14. Key scenario parameters across all sectors.

Parameter	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
Buildings	High electrification	High electrification with role for hybrid heat pumps	Diverse mix of electric and thermal solutions.
Transportation	Electrification of LDVs and a mixture of electrification and low-carbon fuels for MHDVs		
Industry	Electrification where possible	Mixture of low-carbon fuels and electrification	
Electricity	Emission rates based on electric sector modeling approach from 2021 Maryland Building Decarbonization MWG scenario. Incremental costs based on 100% decarbonized electricity EPSA PJM RESOLVE modeling.		
Other Non-Energy, Non-Combustion	Includes emissions from agriculture, waste, forestry, and industrial processes. Consistent assumptions across scenarios that align with the 2030 GGRA Plan Assumptions but have more ambition in specific sectors in line with other recent studies as detailed in the "Other Sectors" section below.[31]		
Renewable Fuels	Low volumes of bioenergy, due to prioritization of electrification	Used to decarbonize peak heat, hard-to-electrify industry, and part of HDV fleet	Used to decarbonize hybrid and thermal building equipment, moderately hard-to-electrify industrial sectors and part of HDV fleet

[31] NY Integration Analysis Key Drivers and Outputs. https://climate.ny.gov/-/media/Project/Climate/Files/IA-Tech-Supplement-Annex-2-Key-Drivers-Outputs.xlsx.

Building Shells

All scenarios assume some level of adoption of more efficient building shells. Efficient building shells can reduce space heating demands by reducing heat loss to the environment and reducing the amount of heat needed to bring a building to its desired set point, which in turn reduces peak and annual demands in the electric and gas sectors. The PATHWAYS modeling includes three different shell types for residential buildings:

- Reference shells are those found in the average residential building prior to the study period and represent no savings relative to the average Maryland residence.
- New Construction Reference shells are shells built for new homes. Such buildings have significantly reduced space heating demands due to the improved nature of these shells relative to the average home in Maryland. These shells result in new construction heating demands that are 45% and 53% lower[32] than existing building heating demands in single-family and multifamily buildings, respectively.
- Existing efficient shells are retrofits for existing homes. They represent building shell measures that reduce the space heating demands by 33% and 22%[33] in single-family and multifamily buildings, respectively. Based on feedback from stakeholders following the 2021 Maryland Building Decarbonization Study and through more recent work in Massachusetts, E3 identified that building shell impacts could be achieved for a lower cost for a subset of the buildings than was assumed in the previous study.

Table 15. Residential building shell penetration by scenario.

Year	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
2030	Existing efficient: 9% New construction: 3%	Existing efficient: 5% New construction: 3%	Existing efficient: 9% New construction: 3%
2045	Existing efficient: 19% New construction: 8%	Existing efficient: 11% New construction: 8%	Existing efficient: 19% New construction: 8%

Table 15 shows efficient building shell penetration for each scenario. The Limited Gas and Diverse scenarios assume a higher adoption of efficient shells than the Hybrid scenario. In the Limited Gas scenario, the efficient shells are implemented as a measure to reduce electric peak, resulting from the high levels of building electrification deployed in this scenario. In the Diverse scenario, the efficient shells are implemented as part of a range of technologies to reduce gas usage through efficiency and some electrification. The Hybrid scenario, which uses the gas system as a backup to avoid electric peak, assumes a lower adoption trajectory for efficient building shells.

[32] The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals. https://thefutureofgas.com/content/downloads/2022-03-21/3.18.22%20-%20Independent%20Consultant%20Report%20-%20Decarbonization%20Pathways.pdf.

[33] *Ibid.*

Building Electrification

Building electrification is one of the key parameters varied across the scenarios. It refers to buildings converting their space heating to air source heat pumps (ASHPs) or networked geothermal systems. The scenarios also consider electrification by use of ASHPs with gas backup (hybrid HPs). Table 16 and Table 17 show the stock penetration of key space heating technologies across scenarios in residential and commercial buildings, respectively.

Table 16. Residential space heating heat pump stock penetration by scenario.

Year	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
2030	ASHP: 40%	ASHP: 31% Hybrid HP: 13%	ASHP: 28% Hybrid HP: 5% Networked geothermal: 2%
2045	ASHP: 85%	ASHP: 55% Hybrid HP: 28%	ASHP: 50% Hybrid HP: 12% Networked geothermal: 8%

Table 17. Commercial space heating heat pump stock penetration by scenario.

Year	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
2030	ASHP: 34%	ASHP: 13% Hybrid HP: 13%	ASHP: 18% Hybrid HP: 4% Networked geothermal: 2%
2045	ASHP: 74%	ASHP: 40% Hybrid HP: 30%	ASHP: 43% Hybrid HP: 12% Networked geothermal: 7%

All scenarios also electrify other end uses, including water heating, cooking and clothes drying at rates similar to space heating. Electrification levels are set at those similar to the penetration of ASHP, hybrid HPs, and networked geothermal in space heating.

Transportation Decarbonization

E3 implemented high levels of transportation electrification across all mitigation scenarios, with the most emphasis in Limited Gas. All scenarios assume MDVs and HDVs electrify at slower rates than LDVs due to their relatively low technological readiness and their low energy densities, which slows adoption in general and limits their use in long-haul trucking. For MDVs and HDVs, scenarios assume hydrogen fuel cell technologies (FCEVs) are a key path to decarbonization, in addition to electrification.

Table 18. Zero emission vehicle stock penetration by scenario. The remainder of vehicles are powered by fossil fuels.

Year	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
2030	LDV: 29% BEV MDV: 11% BEV, 1% FCEV HDV: 2% BEV, 6% FCEV	LDV: 23% MDV: 9% BEV, 1% FCEV HDV: 2% BEV, 4% FCEV	LDV: 23% MDV: 8% BEV, 1% FCEV HDV: 2% BEV, 4% FCEV
2045	LDV: 90% BEV MDV: 90% BEV, 10% FCEV HDV: 25% BEV, 62% FCEV	LDV: 70% BEV MDV: 72% BEV, 8% FCEV HDV: 20% BEV, 50% FCEV	LDV: 70% BEV MDV: 63% BEV, 7% FCEV HDV: 17% BEV, 61% FCEV

In addition to electrification, E3 assumed that renewable diesel would be used to partially decarbonize remaining diesel demands after electrification. The specific details of low-carbon fuel modeling will be discussed in a latter section, but a preview of the outcomes for such modeling are shown in Table 19. No renewable diesel is assumed to be blended into transportation prior to 2030. By 2045, E3 assumed that renewable diesel was blended at varying levels – about 1% in the Limited Gas Scenario and 50-60% in the Hybrid and Diverse scenarios – to help the state achieve its net-zero target.

Table 19. Renewable diesel blending for the transportation sector by scenario.

Year	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
2030	0%	0%	0%
2045	1%	61%	53%

Industrial Electrification

E3 developed a high-level assessment of industrial electrification opportunities in BGE's service territory, based on the Manufacturing Energy Consumption Survey (MECS)[34] and the Industrial Energy Data Book[35], which describes industrial energy usage by end-use and fuel type. Based on that data, E3 characterized industrial electrification opportunities into the following tranches:

- High Electrification Potential – including facility HVAC loads, on-site transportation, and boilers.
- Difficult to Electrify – including high-temperature process heating and other process uses of fuels.

The Limited Gas scenario has the highest amount of industry electrification with 16% of final energy electrified in 2050, compared to 10% for Hybrid and Diverse. In all scenarios, industry electrification is assumed to occur exclusively in the High Electrification Potential category.

[34] 2018 Manufacturing Energy Consumption Survey (MECS). https://www.eia.gov/consumption/manufacturing/data/2018/.
[35] 2018 Industrial Energy Data Book. https://data.nrel.gov/submissions/122.

Other sectors

In addition to the energy sector measures described above, all scenarios include emissions reductions from non-combustion, non-energy sector emissions. Emissions from these sectors, excluding natural sequestration, decrease by 66% from 2006 levels by 2045 across all scenarios. All emissions from these sectors were allocated to BGE based on population.

- **Agriculture**: Agricultural emissions decline 27% by 2045 from 2006 across all scenarios. These reductions are aligned with the MWG scenario from the 2030 GGRA Plan.
- **Waste**: Waste emissions decline 46% from 2006 across all scenarios. These reductions are aligned with the 2030 GGRA Plan.
- **Industrial Processes and Product Use (IPPU)**: IPPU emissions are reduced by 88% from 2006 across all scenarios, which exceed reductions in the 2030 GGRA Plan (about 40% by 2045). Industrial process emissions reductions are consistent with trajectories from the EPA Non-CO2 Greenhouse Gas report. HFC emissions follow reduction trajectories consistent with the Kigali Amendment.
- **Oil and Gas System**: Fugitive emissions from the oil and gas system are reduced by 70% from 2006, consistent with the reductions in the 2030 GGRA Plan.
- **Sequestration**: Natural sequestration increases by 15% from 2006, consistent with the growth in land sinks included in the 2030 GGRA Plan.

Renewable Fuels Module

E3's Renewable Fuels Module was employed to allocate low-carbon fuels to satisfy a portion of remaining fuel demands within BGE's service territory after efficiency and electrification measures. These fuels are considered to have net-zero lifecycle emissions and are phased into scenarios after 2030. The low-carbon fuel types identified by the Renewable Fuels Module for use in this study are the following:

1. Biofuels, including biomethane and renewable diesel;
2. Green hydrogen produced through renewable electrolysis, either blended directly into BGE's pipeline gas network or used directly for transportation end uses;
3. Synthetic natural gas.

Biofuels

E3's Renewable Fuels Module assesses the most cost-effective way to deploy scarce biomass resources to produce liquid and gaseous fuels to economic sectors. E3 derived the biomass resource availability used in the Module based on the United States Department of Energy Billion Ton Update.[36] E3 then supplemented that study with the American Gas Foundation Renewable Sources of Natural Gas study,[37]

[36] U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. https://www.energy.gov/sites/default/files/2015/01/f19/billion_ton_update_0.pdf.

[37] Renewable Sources of Natural Gas: Supply and Emissions Reduction Assessment. https://gasfoundation.org/2019/12/18/renewable-sources-of-natural-gas.

which has a greater resolution on in-region landfill gas, wastewater treatment gas, and manure resources than the Billion Ton Report.

Sustainable biomass is defined as consisting of municipal solid waste (MSW), landfill gas, manure, agricultural residues, and forest residues. As in E3's prior work, purpose-grown crops and forests used primarily for bioenergy production were excluded from all scenarios due to sustainability concerns like emissions from indirect land-use change, as well as uncertainty around the plausibility and cost of developing the supply chains necessary to grow, deliver, and process new types of purpose-grown crops for biofuels.[38]

Anaerobic digestion and thermal gasification are two processes that can be used to produce biomethane. Today, biomethane is primarily made today using anaerobic digestion in the context of landfill gas, wastewater treatment gas, manure-derived gas, and food waste projects. Thermal gasification of agricultural residues, forest residues, or MSW has not yet been widely deployed. Thus, there is a risk that thermal gasification does not fully materialize in the future as a method to produce biomethane. As a result, E3 assumed commercialization of anaerobic digestion and thermal gasification resources occurs over time and that the resources are not leveraged at scale until after 2030.

E3 assumed that biomass resource availability to the state of Maryland is equal to its population-weighted "fair share" of biomass available east of the Mississippi. The use of a population weighted share is meant to reflect competition for scarce biomass resources from other states and regions. The amount of biomass available to Maryland could be higher if less biofuels procurement occurs elsewhere or lower if there are more demands in other regions. Assessing biomass east of the Mississippi was meant to reflect resources that are deliverable on existing pipelines that deliver natural gas to Maryland today. Using the above method, E3 allocated about 3.2% of east of Mississippi biomass availability to the state of Maryland. Biomethane and renewable diesel were subsequently allocated to BGE's service territory proportionally to the service territory's demand for each fuel relative to that of Maryland's.

E3 assumed all advanced biofuels would have net zero CO_2 emissions based on the negative carbon sink of the biomass feedstock.[39] Combustion emissions associated with CH_4 and N_2O are counted for all fuels, both fossil and biogenic.

Hydrogen and Synthetic Fuels

E3 also used the Renewable Fuels Module to assess the cost trajectory of hydrogen and synthetic natural gas (SNG) resources.

The hydrogen and SNG assessment in this analysis stemmed from E3's and the University of California (UC) Irvine's work on the California Energy Commission's *The Challenge of Retail Gas in California's Low Carbon Future* Report. That analysis defined trajectories for assumptions related to the cost and efficiency of the production of hydrogen and SNG using electrolysis and, in the case of SNG, methanation using a source

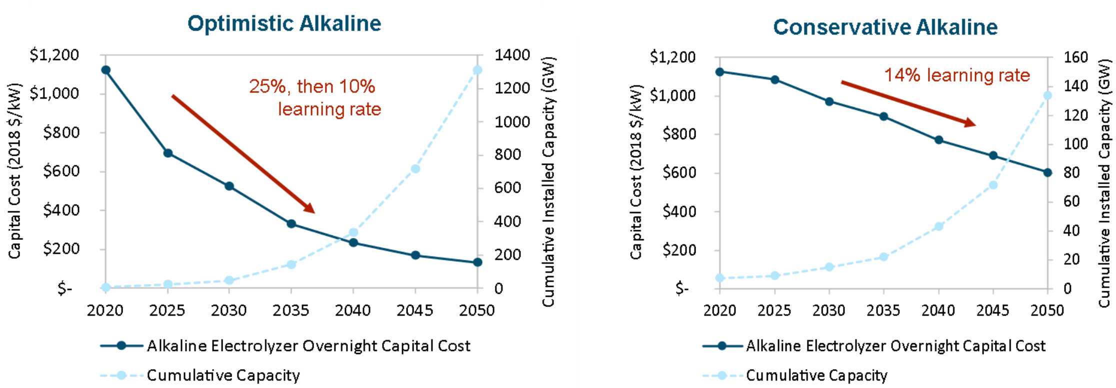
[38] The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals. https://thefutureofgas.com/content/downloads/2022-03-21/3.18.22%20-%20Independent%20Consultant%20Report%20-%20Decarbonization%20Pathways.pdf.

[39] This accounting approach aligns with the 2021 MD Buildings Study.

of renewable CO_2. The assumptions consist of inputs indexed by fuel, electrolysis technology, CO_2 input, year, and level of industry learning assumed to occur between 2020 and 2050. CO_2 sources include direct air capture (DAC) and biorefining co-product, which both result in a net zero CO_2 process. Inputs consist of the levelized capital cost and annual fixed O&M cost, variable O&M cost, and overall energy efficiency, considering only renewable electricity as the energy input, including for heat input, if applicable.

E3 assumed that alkaline electrolysis cells (AECs) are the primary means of producing green hydrogen and SNG[40] due to its low cost and technologically mature attributes.[41] E3 developed two cost trajectories for AEC based on the cumulative installed capacity (i.e., reflecting hydrogen need), as shown in Figure 26.

Figure 26. Electrolyzer costs for producing hydrogen and SNG. The secondary y-axis shows the potential electrolyzer market size.[42]



To develop a cost for delivered hydrogen, E3 applied additional assumptions with respect to the cost of producing, storing, and delivering hydrogen. Based on *An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization,* E3 identified western Pennsylvania as a potential source of future hydrogen production that could be deliverable to Maryland. With that, E3 assumed that wind power in Pennsylvania was the source of renewable electricity input for hydrogen production. Further, hydrogen produced in Pennsylvania was assumed to be stored in underground salt caverns, with delivery occurring via the existing inter-state natural gas pipeline system. As such, hydrogen costs are delivered costs, which includes electrolyzer, storage, clean electricity, and transmission costs.

The use of hydrogen in all scenarios was limited to blending into existing gas infrastructure. Drawing from findings from NREL (Melania et al 2012), E3 limited hydrogen blends to 7% of BGE's pipeline gas throughput.

SNG is more costly than hydrogen due to the significantly higher energy requirements and the need for a climate-neutral source of CO_2. E3 assumed two sources of climate-neutral CO_2: CO_2 that is a byproduct of

[40] Hydrogen produced by breaking water into hydrogen and oxygen using an electric current in which electricity is renewable.
[41] As opposed to producing clean hydrogen through a proton-exchange membrane (PEM) or steam methane reforming or coal gasification with CCS.
[42] Derived from E3's work for the California Energy Commission in partnership with UC Irvine, called The Challenge of Retail Gas in California's Low Carbon Future: https://www.energy.ca.gov/publications/2019/challenge-retail-gas-californias-low-carbon-future-technology-options-customer.

biofuels production (SNG-Bio) and CO_2 that is sourced from direct air capture (SNG-DAC). SNG-Bio production plants were assumed to be co-located with biorefineries within states east of the Mississippi. As such, the availability of SNG-Bio is limited in availability for the same reasons as those described for biomethane. The amount of SNG-DAC was modeled as the remaining renewable fuel needed to meet each scenario's demand. This implies that E3 assumed that SNG-DAC is effectively "unlimited" in its availability, as it is not restricted by the limited supply of either hydrogen or CO_2.

It is important to note that this study was completed prior to the passage of the Inflation Reduction Act, which contains subsidies for hydrogen and, potentially, SNG production. Such subsidies lower the costs of these fuels for end-users and likely influence the development and availability of these resources in ways not captured by this study.

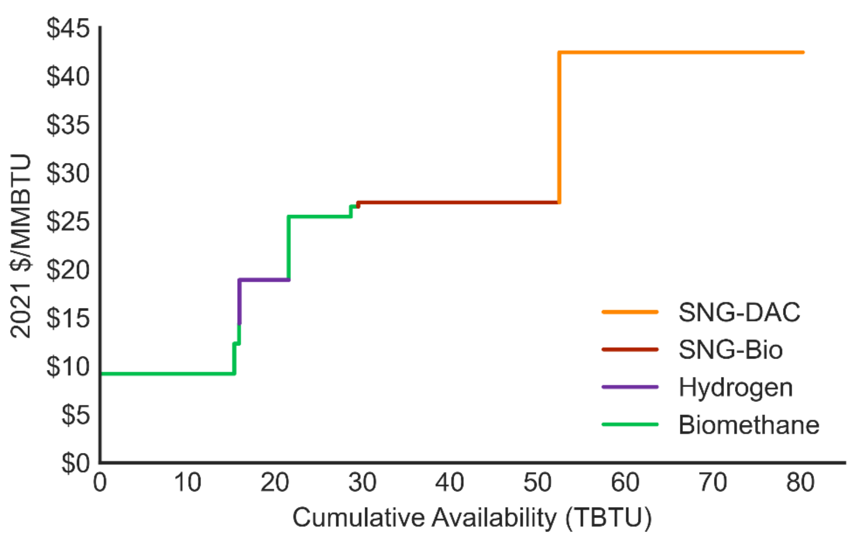
Renewable Fuel Supply

In past work, such as in our analysis supporting the Massachusetts Future of Gas 20-80 proceeding, E3 has developed both Optimistic and Conservative views on renewable fuel availability and cost:

- Optimistic view: Biomethane and renewable diesel are sourced from feedstocks that can be converted into biomethane through either anaerobic digestion or gasification. Lower hydrogen and SNG costs are driven by optimistic electrolyzer costs.
- Conservative view: Biomethane and renewable diesel are sourced from feedstocks that can be converted into biomethane only through anaerobic digestion. Higher hydrogen and SNG costs are driven by conservative electrolyzer costs.

For the purposes of this study, E3 has assumed an optimistic perspective that includes more potential available feedstock types in addition to anaerobic digestion (see "Biofuels" above) and lower costs for hydrogen and SNG. In the case of hydrogen and SNG, this is potentially more aligned with the influence of the IRA on fuel availability and cost, but further investigation is required. For an example supply curve, please see Figure 27.

Figure 27. Renewable natural gas supply curve for Maryland for the Diverse scenario in 2045.



E3 modeled the supply of and demand for renewable fuels on an annual basis. The price for biomethane and hydrogen resources were assumed to be set at a market-clearing price based on annual demand. E3 then treated the cost of SNG separately. The final cost of renewable gas supply was assumed to be blended into the pipeline gas system at the weighted-average price of SNG and the most expensive of biomethane and hydrogen. For renewable diesel, the most expensive type of renewable diesel sets the market-clearing price.

This bifurcated approach is meant to reflect that, in practice, the cost of gas is currently not set on an annual basis. Instead, the cost of gas shows distinct seasonality, with prices typically being highest during the winter. In addition, like renewable electricity generation, renewable gas projects would likely be developed based on long-term power purchase agreements, which would add a degree of price stability to BGE's gas supply costs over time. For those reasons, E3 did not believe it would be accurate to assume that SNG sets a market clearing price for all gas resources procured by BGE.

Table 20. Maryland renewable fuel demands (TBTU) by fuel type and scenario.

Year	Limited Gas	Gas-Electric Hybrid	Diverse Energy Solutions
2030	All renewable fuels: 0	All renewable fuels: 0	All renewable fuels: 0
2045	Biomethane: 7 Blended hydrogen: 0 SNG: 0 Renewable diesel: 1 Transportation hydrogen: 17	Biomethane: 24 Blended hydrogen: 4 SNG: 13 Renewable diesel: 33 Transportation hydrogen: 14	Biomethane: 24 Blended hydrogen: 6 SNG: 33 Renewable diesel: 31 Transportation hydrogen: 12

The final renewable fuel demands for Maryland are shown in Table 20. As expected, the Limited Gas scenario requires less renewable fuel, as emissions are more directly mitigated through electrification and efficiency. Hybrid and Diverse scenarios require a larger amount of renewable fuels due to lower amounts of direct economywide ambition.

Electric Sector Modeling

Introduction

Electricity supply has a critical role to play in meeting state decarbonization goals by reliably supporting new electrification loads and simultaneously reducing GHG emissions. E3 evaluated the impact of electrification on the electric sector through 2045 by:

1. Establishing annual load growth across the economy in BGE's service territory, as discussed in the PATHWAYS section;
2. Developing hourly loads based on the timing of electricity usage of key devices and weather dependency across multiple weather years to establish 1-in-10 peak conditions;
3. Using previously established capacity expansion scenarios for the PJM region to estimate electric sector costs at high levels of decarbonization.

Load Shaping

The goal of E3's load shaping approach was to characterize how the high levels of electrification in each scenario would impact BGE's hourly loads. To capture a wide variety of future planning conditions, E3 drew on 40 years of weather data from the National Oceanic and Atmospheric Administration North American Reanalysis (NARR). E3 used the NARR data to identify how BGE's existing baseline loads and new electrification loads changed in a weather-matched fashion.

Baseline Loads

E3 assessed how BGE's baseline loads might vary across over the 40 historical weather years using a neural network model (NN) to correlate weather with historical loads within BGE's service territory. The load shapes derived from this correlation were used to shape existing space heating, water heating, and electric vehicle loads from 2019 and all other forecasted baseline loads from PATHWAYS. E3 then pairs this baseline simulation with weather-matched incremental loads from decarbonization measures like heating or transportation electrification. This approach is an element of E3's broader RECAP model, which has been used to determine portfolio reliability under high levels of renewable resource penetration in a variety of jurisdictions.[43,44]

Space and Water Heating Shapes

Heat Demand Benchmarking

RESHAPE was designed by E3 to simulate heat pump operations given sensible space heating demands in a variety of building typologies across the residential and commercial building subsectors. Using these simulations, RESHAPE produces 40 historical weather years (1980-2019) of space heating load shapes. RESHAPE's sensible heating demands were benchmarked to replicate the seasonality of monthly residential and commercial gas sales as reported by the US Energy Information Administration (EIA) in Maryland from 2015-2019. By using this benchmarking approach, E3 assumed that seasonal gas sales are representative of the seasonality of space-, and to a lesser extent water-, heating. Furthermore, because gas space heating appliance efficiencies are largely insensitive to temperature, E3 assumes that the seasonal gas throughput is representative of sensible heat demand. As shown on Figure 28, E3's simulated sensible heating demand shape and the shape derived that from EIA datasets align well across the five weather years used for benchmarking.

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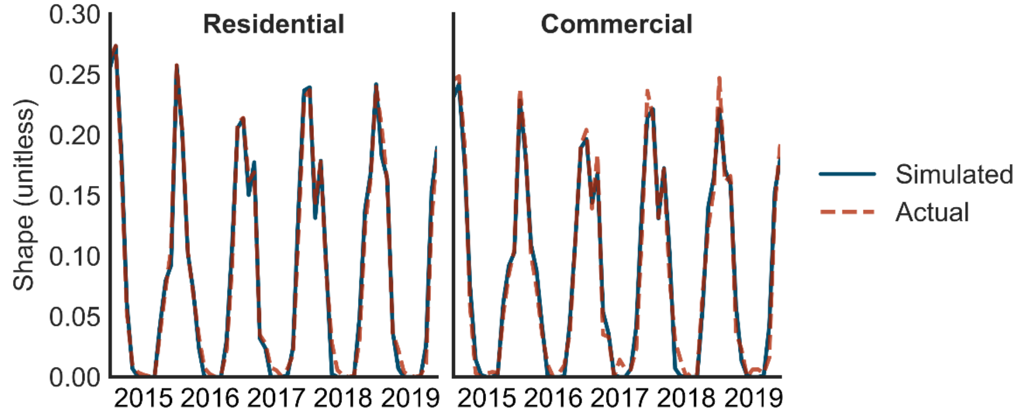
[43] Net-Zero New England: Ensuring Electric Reliability in a Low-Carbon Future. https://www.ethree.com/wp-content/uploads/2020/11/E3-EFI_Report-New-England-Reliability-Under-Deep-Decarbonization_Full-Report_November_2020.pdf.

[44] Omaha Public Power District Pathways to Decarbonization. https://www.oppdcommunityconnect.com/13022/widgets/38762/documents/28554.

Figure 28. Seasonal monthly gas throughput shapes from RESHAPE (simulated) and the Energy Information Agency (actual).

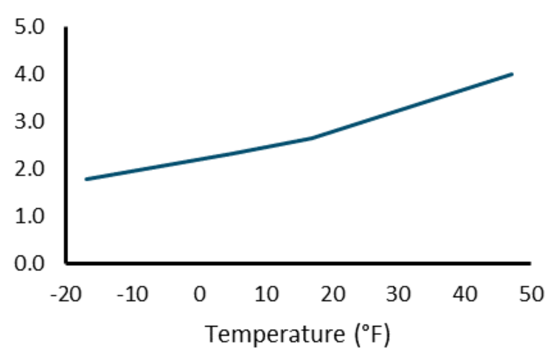


In addition to benchmarking at the state level, RESHAPE was further parametrized and refined to reflect BGE's gas service territory. Using BGE's daily gas throughput in 2019, E3 calculated BGE's peak-to-average daily gas throughput ratio to be 3.2. Using RESHAPE's outputs, E3 calculated BGE's peak-to-average daily gas throughput ratio to be 3.1, further indicating a reasonable parametrization of sensible heat demand within RESHAPE.

Heat Pump Performance

In the early years, the heat pumps modeled by E3 reflect commonly installed technologies and current installation practices. However, E3 assumes that over time all of the heat pumps deployed in the economy meet the Northeast Energy Efficiency Partnerships Cold Climate Air Source Heat Pump Product Specification Version 2.0[45]. As a result, the installed performance of heat pumps increase due to the effects of technology improvements and changes to installation practices that reduce reliance on resistance supplemental heat.

Figure 29. Cold-Climate heat pump COP curve used to simulate heat performance.



[45] See https://neep.org/sites/default/files/ColdClimateAirSourceHeatPumpSpecification-Version3.0FINALMEMO.pdf

Hourly heat pump operations were simulated by scaling hourly heating demands by the heat pump's coefficient of performance (COP), which is itself a function of the hourly outside temperature. See Figure 29 for the heat pump performance curve used for air source heat pumps (ASHPs) and hybrid heat pumps (hybrid HPs) in this work. In 2022, the first modeled year, ASHPs were sized to cover all heating demands at temperatures greater than approximately 20° F, below which electric resistance provides supplemental heating alongside the heat pump. Under those assumptions, ASHPs achieve a COP of 1.4 during the coldest hour of a 1-in-10 year cold-snap, when the minimum temperature falls to 1° F. Over time, the heat pump performance increases. The cold-snap COP increases to over 2 as heat pump performance improves and as the heat pump is increasingly sized to cover a higher proportion of load without resistance supplement. Hybrid HPs were sized to cover all heating demands at temperatures greater than approximately 30° F, below which a backup gas furnace is used to meet heating demand. On average, the annual COP of an ASHP was assumed to improve from 2.4 to 3.5 by 2045, reflecting deployment of higher efficiency systems and less reliance on resistance supplemental heat over time. The Hybrid HP electric COP also improves from 2.8 to 4.0 by 2045. Hybrid HP electric COPs are higher than all-electric systems because they largely operate at warmer temperatures when heat pumps perform most efficiently.[46]

RESHAPE was also used to simulate water heating demands and shapes, drawing on metered data provided by the Northwest Energy Efficiency Alliance for residential systems and from the California Energy Use Survey for commercial systems. Water heating is less weather-dependent on a year-to-year basis. As a result, a single water heating shape each was applied for residential and commercial buildings across all weather years.

LDV Shapes

E3's EV Load Shape Tool (EVLST) was used to calculate load shapes from LDV charging. To model charging behavior, EVLST uses a bottom-up approach that simulates the driving and charging behavior of thousands of EV drivers within BGE's service territory. Driving behavior is captured using travel survey data and converted into 15-minute driving patterns through a Markov-Chain Monte Carlo method. The driving population is characterized by drivers' access to charging, spanning a combination of residential, workplace, and public charging access. For personal LDVs, there are four EV types (short and long range of each plug-in-hybrid and full battery electric) and six combinations of workplace, home, and public charging access, resulting in twenty-four combinations of customer types. Normalized load shapes for each customer are generated through linear optimization subject to various charging constraints. Load shapes are then scaled by the portion of drivers representing that customer type. The final load shape therefore captures the diversity of driving behavior, charging access, and EV adoption across the driving population.

The shapes used for initial load shaping are unmanaged. Unmanaged shapes are representative of drivers charging at different locations (home, workplace, public L2, and public DCFC) based on their driving patterns and charging access. There is some preference given based on relative price of charging at each location, but under an unmanaged charging scenario, drivers are not exposed to time-varying charging

[46] While they do not contribute to electric sector modeling, gas heat pumps were also used in this study. The hourly performance of these heat pumps were not evaluated, but the annual COPs were assumed to be 1.4 and 1.3 for residential and commercial systems, respectively.

rates and charge immediately upon arrival at a charging location. This contrasts with a managed charging scenario, where drivers are exposed to time-varying charging rates and will manage their charging schedules at each location to minimize their total cost of charging. As a preview, LDV load management (also known as load flexibility in latter sections) is applied *after load shaping* (described below in more detail), wherein on-peak evening home charging is assumed to be shifted to later in the evening and early in the following morning.

Electric System Load Shaping

As noted in the introduction to this section, annual loads from PATHWAYS are shaped by the load shapes described above. Table 21 below summarizes the sources for the shapes for each of the load categories below.

Table 21. Load category and hourly shape sources.

Load Category	Shape Source
Residential Space Heating	RESHAPE
Commercial Space Heating	RESHAPE
Residential Water Heating	RESHAPE
Commercial Water Heating	RESHAPE
LDV	EVLST
MHDV	Flat
All Other Loads	RECAP NN Model

As both the baseline and the space heating shapes represent forty years of historical data, E3 forecasted the 1-in-10 system peaks used for electric sector planning.

Table 22. Load category flexibility during peak load hour.

Load Category	Flexibility (%)	Time of Day when Applied
Residential Space Heating	5.9%	Anytime
Commercial Space Heating	1.9%	Anytime
Residential Water Heating	2.9%	Anytime
Commercial Water Heating	1.4%	Anytime
LDV	51%	Evening
MHDV	0%	Anytime
All Other Loads	2.9%	Anytime

Finally, E3 adapted the load flexibility assumptions in the report *An Assessment of Electrification Impacts on the Pepco DC System* (called the *Pepco Assessment*), which proposed load flexibility programs and estimated their customer-wide participation. Using these estimates, the load flexibility on peak for each load category was estimated, as shown in Table 22. Consistent with the *Pepco Assessment*, E3 assumed that most load categories were not particularly flexible in aggregate owing to the relatively low 15% customer-wide participation in the flexibility programs. LDV loads were the sole exception, for which 100% of home charging customer loads are flexible, pushing evening LDV loads later into the evening and early morning. It is important to note that there is very little home LDV charging in the mornings according to EVLST simulation; as a result, LDV flexibility is assumed to only apply if the system peak is coincident with the evening LDV peak.

Electric Supply Modeling

No new capacity expansion modeling was completed for this work. Instead, E3 assumed a 100% decarbonized electricity supply in Maryland by 2045 in line with the Optimistic Sensitivity from the MDE GGRA Plan, and calculated costs based on E3 past modeling in PJM. For the costs of clean electricity, E3 directly leveraged PJM-wide capacity expansion modeling previously conducted for the Electric Power Supply Association (EPSA). Specifically, E3 applied results from a scenario that achieves 100% GHG-free generation[47] in 2050 and downscaled the results for BGE. Embedded electric generation, transmission, and distribution costs were derived from BGE data, while incremental electric generation costs were derived from the results of this scenario. Please refer to the E3 report *Least Cost Carbon Reduction Policies in PJM* for more detailed assumptions regarding this model.

Like the discussion of renewable hydrogen and SNG above, E3 caveats that this analysis was completed before the passage of the IRA. The IRA includes substantive changes in subsidies for a variety of electric resources, including wind, solar, battery storage, hydrogen, and others. As a result, the cost of electric supply decarbonization for BGE's consumers may be lower under the IRA.

Economywide Costs

Introduction

E3 and other energy system researchers often use energy system costs (sometimes referred to as total resource costs) to evaluate impacts of long-term deep decarbonization strategies. E3 modeled the costs of the energy system on an incremental basis, meaning that costs were compared against a reference pathway in which decarbonization targets are not met. This perspective elucidates and isolates the effects of decarbonization strategies on energy system costs specifically.

Economywide costs include all energy-related decarbonization costs, including the costs of demand-side capital, including electric vehicles, space heating appliances, and building shells; costs of energy infrastructure, such as electric, gas, and networked geothermal investments; and costs of fuels, including natural gas, fossil fuels and renewable fuels. An overview of cost categories is provided in Table 23.

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[47] This scenario is called the "100% GHG" scenario in the report, which can be accessed here: https://epsa.org/wp-content/uploads/2020/10/E3-Least_Cost_Carbon_Reduction_Policies_in_PJM-FINAL.pdf.

Table 23. Energy system cost components.

Cost Component	Includes	Source
Capital Costs	All consumer appliance costs (vehicles, space and water heating, building shells, etc.)	PATHWAYS stock rollovers, upfront capital costs
Electric Capacity	Electricity system costs for generation	Electric RR model (see section "Electric Revenue Requirement" below)
Electric T&D	Electricity system costs for transmission and distribution	Electric RR model (see section "Electric Revenue Requirement" below)
Fossil Fuels	Commodity costs for natural gas and other fossil fuels	EIA AEO 2021 – Reference scenario, Mid-Atlantic prices
Renewable Fuels	Commodity costs for low carbon fuels. Includes biomethane, hydrogen, synthetic natural gas, biodiesel	Renewable fuels module
Gas & Networked Geothermal Infrastructure	Costs for gas distribution and transmission supply, installation costs of the networked geothermal system	Gas RR model (see section "Gas Revenue Requirement Model" below)

Costs were calculated on a levelized basis and include a society-wide financing rate of 3.6% real. Energy system costs do not include the social costs of carbon or the avoided costs related to potential health or environmental damages resulting from climate change. E3 notes that past research efforts[48] that have included those and other benefits of climate action have found that benefits of achieving net-zero exceed the types of direct costs accounted for in this study.

Importantly, economywide costs represent total incremental costs for the BGE service territory without specifying how those costs should be paid for or allocated. For example, the capital costs primarily reflect the costs of upgrading buildings and home equipment, but the allocation of those costs (e.g., household expenses versus policy incentives or utility rate structures) is not defined in this part of the analysis.

End-Use Costs

The economywide costing approach relies on outputs form PATHWAYS, the RR models, the Renewable Fuels Module, and the electric sector modeling. Other key costing inputs include device capital costs and fuel prices. The main drivers of total costs are customer capital costs and electric sector costs contains a summary of key device costs used as inputs to the economywide costing. Key household costs are summarized in Table 24. Note that these are different from the costs shown in Table 30, which show costs for a representative customer in one year, as opposed to costs for an average customer over time.

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[48] New York State Climate Action Council Draft Scoping Plan. Appendix G: Integration Analysis Technical Supplement. December 2021. https://climate.ny.gov/-/media/Project/Climate/Files/Draft-Scopping-Plan-Appendix-G-Integration-Analysis-TechnicalSupplement.ashx. (See Section I page 47–52).

Table 24. Summary of key device costs for single-family homes ($2020/unit)

Subsector	Device	2020	2030	2045	Source
Residential Single Family Space Heating	Air Source Heat Pump	$14,300	$13,200	$11,700	2021 MD Buildings Report + E3 Supplemental Analysis
Residential Single Family Space Heating	Hybrid Air Source Heat Pump	$12,500	$11,500	$11,000	2021 MD Buildings Report + E3 Supplemental Analysis
Residential Single Family Space Heating	Gas Furnace + Central Air	$9,300	$9,300	$9,300	2021 MD Buildings Report
Residential Single Family Space Heating	Efficient Gas Furnace + Central Air	$10,700	$10,700	$10,700	2021 MD Buildings Report
Residential Water Heating	Heat Pump Water Heater	$2,800	$2,800	$2,800	2022 MA LDC Study
Residential Water Heating	Gas Storage	$1,400	$1,400	$1,400	2022 MA LDC Study
Residential Building Shell	Existing Building Shell Retrofit	$12,500	$12,500	$12,500	2022 MA LDC Study
Transportation LDVs	Gasoline ICE	$31,500	$32,800	$31,900	NYSERDA Draft Scoping Plan
Transportation LDVs	Battery Electric*	$48,500	$35,000	$33,200	NYSERDA Draft Scoping Plan

**Transportation EV device costs include charger and make ready investments.*

The primary sources for building sector costs are two reports by E3: the *2021 Maryland Building Decarbonization Study*[49] (2021 MD Buildings Report) and the 2022 report *The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals* (2022 MA LDC Study)[50]. Cost declines for heat pump technologies over time were derived based on the NREL Electrification Futures Study[51].

E3 primarily relied on the 2021 MD Buildings Report to reflect the cost of HVAC systems in the residential and commercial sectors. E3 then developed a BGE specific assessment of those costs based on an evaluation of the building stock in BGE's service territory. E3 assumed that all-electric conversions of

49 See: https://mde.maryland.gov/programs/Air/ClimateChange/MCCC/Documents/MWG_Buildings%20Ad%20Hoc%20Group/E3%20Maryland%20Building%20Decarbonization%20Study%20-%20Final%20Report.pdf

50 See: https://thefutureofgas.com/content/downloads/2022-03-21/3.18.22%20-%20Independent%20Consultant%20Report%20-%20Decarbonization%20Pathways.pdf

51 See: https://www.nrel.gov/docs/fy18osti/70485.pdf

buildings built prior to World War 2, or approximately 38% of the current BGE building stock, incur an upgrade cost of $3,400 per home that is meant to reflect costs of panel upgrades, wiring or ductwork. Those costs are not assumed for hybrid conversions. Conversely, E3 assumed that all-electric new construction includes a cost savings of approximately $5,000 associated with the avoided gas infrastructure within a customer premise.

E3 relied on the 2022 MA LDC Study for costs associated with heat pump water heaters and building shells. The values used from that study were chosen because they incorporate feedback from stakeholders on the cost of those measures that was received after the completion of the 2021 MD Buildings Report. One particularly notable point of feedback that E3 received was that the building shell interventions modeled were too ambitious and therefore unlikely to be cost effective. As a result, this study applied a "Light Shell" measure that costs substantially less for existing building retrofits than the measure assumed in the 2021 study. Finally, E3 did not apply an incremental cost for efficient shells in new construction because those same shell measures were assumed to occur in the business-as-usual Reference scenario.

Similar to renewable fuels and electric supply, E3 notes that this work was completed before the passage of the IRA. That bill includes provisions to subsidize heat pumps, building energy efficiency and electric vehicles. As a result, the direct costs of adopting these technologies as experienced by BGE's customers may be lower than those modeled here.

Revenue Requirement Modeling

Gas Revenue Requirement Model

Introduction

E3's gas revenue requirement and rate model ("gas RR model") is a bottom-up tool that evaluates the implications of the various scenarios on gas revenue requirements and customer rates at a high level. As described above, E3 used the PATHWAYS model to consider large-scale changes in the natural gas system and other energy usages throughout the economy. The gas RR model is designed to supplement PATHWAYS, adding a representation of capital assets, operating expenses, revenue requirements, and customer rates over time for each gas LDC and each scenario. For each of the decarbonization pathways, E3 used the gas RR model to evaluate impacts on customer rates accounting for capital investment, operations and maintenance expenses, changes in gas volumes, and the cost of renewable fuels associated with a given scenario.

The gas RR model also includes parameters to explore the range of gas system cost and rate impacts that could occur under a given economywide scenario. These parameters include cost reduction measures associated with reduced gas throughput, changes to investment in new gas system assets and/or decommissioning of existing assets, and regulatory measures that affect how and when customers recover costs. These parameters are described in greater detail below.

The gas RR model is based primarily on publicly available data regarding BGE's gas service territory and forecasts of gas throughput and customer count from the PATHWAYS scenarios described above. Data inputs for the model are included in Table 25.

Table 25. Model inputs for the Gas Revenue Requirement model.

Model Inputs	Data Source
Gas sales forecast	PATHWAYS energy demands
Gas demand forecast	PATHWAYS energy demands
Natural gas commodity price forecast	Natural gas forward prices for 2022-2026, transitioning to EIA long-term forecasts
Pipeline gas blend forecast	Renewable Fuels Module
Renewable fuel price forecast	Renewable Fuels Module
Existing utility plant including book reserve, depreciation rates, and asset removal costs	BGE 2018 Depreciation Study
Historical STRIDE investment	BGE Multi-Year Plan filings[52]
Planned STRIDE investment	BGE Multi-Year Plan filings[24]
Historical O&M costs	S&P
Cost allocation to customer classes	Based on current share of revenues as derived from BGE 2022 Gas Rates[53]

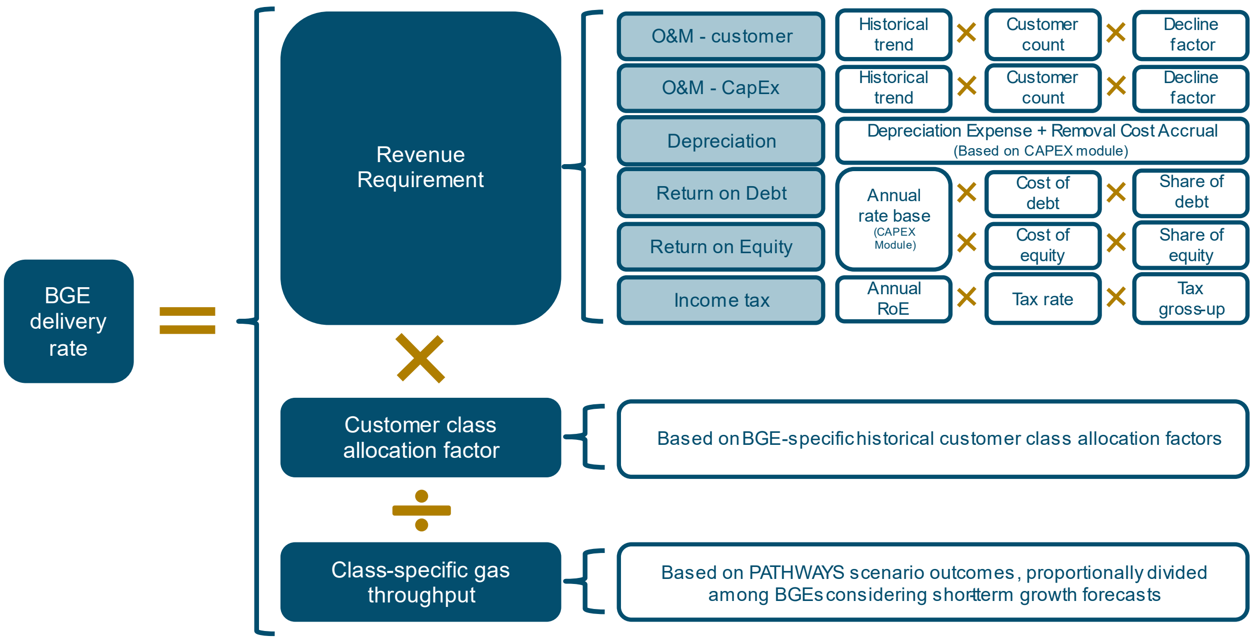
For each scenario modeled in PATHWAYS, the model assesses how the total costs of the gas system will change relative to its usage. For example, all scenarios include all-electric new construction from 2027 onwards, which reduces costs associated with growth-related investments like service and main extensions. In addition, reinvestments in BGE's existing system are assumed to be reduced from 2030 onwards, consistent with the potential for targeted electrification initiatives. The exact magnitude of those savings is highly uncertain given the lack of real-world examples of targeted electrification initiatives that avoid gas system investments at appreciable scales.

Following the calculation of the revenue requirement, the model then allocates the costs of the gas system to customer classes based on their historical share of BGE's revenues and divides that value by system utilization to arrive at class delivery rates, as illustrated in Figure 30.

[52] Application of Baltimore Gas and Electric Company for an Electric and Gas Multi-Year Plan and Other Tarif Revisions. https://www.bge.com/SmartEnergy/InnovationTechnology/Documents/200515-BGE-multi-year-customer-relief-energy-infrastructure-investment-plan-PSC-filing-combined.pdf.

[53] Gas Service Rates & Tariffs. https://www.bge.com/MyAccount/MyBillUsage/Pages/GasServiceRatesTariffs.aspx.

Figure 30. Overview of the gas RR model.



The primary purpose of the gas RR model in this analysis is to identify changes in the delivery portion of customer rates, expressed in the form of a customer and volumetric components. To identify a long-run view on retail rates, the gas RR model then adds scenario specific gas supply rates which incorporates the impacts of blending renewable gasses in BGE's gas supply as discussed above, as well as rate adders that reflect public purpose and other program costs.

STRIDE Program

E3's gas RR model includes a representation of BGE's STRIDE program which targets replacement of leak-prone-pipe. Based on testimony from BGE's most recent multi-year rate plan, E3 derived that 48 miles of main would need to be replaced to complete the program as planned in 2042. However, to reflect additional effort to mitigate methane emissions, in consultation with BGE, E3 assumed that the STRIDE program would be completed by 2037, requiring the replacement of approximately 56 miles of leak prone, largely cast-iron, pipe per year. The timing and pace of STRIDE investment was used to inform incremental gas system revenue requirements and the scale of gas infrastructure that might be plausibly avoided via targeted electrification initiatives. Additionally, STRIDE investments were used to size the opportunity for networked geothermal systems within BGE's service territory.

Networked Geothermal

In the Diverse scenario, E3 considered the potential for a portion of BGE's gas system to transition to networked geothermal infrastructure. E3 estimated the amount of networked geothermal infrastructure that could be deployed based on BGE's STRIDE program. This approach envisions a future where some share of STRIDE investments could be repurposed for alternative heating and cooling delivery infrastructure. In that scenario, the shift from STRIDE to networked geothermal investment begins at a pilot stage in the late 2020s and begins to achieve scale after 2030. Under this approach, E3 assumed that the networked geothermal infrastructure itself would be financed and owned by BGE.

Like our past work, E3 based most of the cost[54, 55] and performance characteristics of networked geothermal infrastructure on the GeoMicroDistrict Feasibility Study conducted by BuroHappold and commissioned by the non-profit HEET. The exception were costs related to operations and maintenance of these systems, which E3 based on data from the International Energy Agency.

Electric Revenue Requirement

E3 determined the total electric revenue requirement required to serve BGE's customers in each scenario as the electric system decarbonizes and electrification increases loads. Incremental costs associated with decarbonizing PJM electric supply were derived from E3's 2020 PJM decarbonization study. E3 drew on that study by scaling its incremental generation, transmission, fuel and O&M cost outputs based on BGE's changing share of load in each scenario. E3 assessed incremental transmission and distribution capacity costs based on changes in BGE's system peak, after load flexibility, using a 1-in-10 year planning standard. Generation capacity costs were assessed against 1-in-2 peak demands, also after load flexibility, plus an assumed planning reserve margin of 9%, consistent with E3's PJM decarbonization study. The marginal costs used to assess the capacity costs of each scenario are described in Table 26. Generation capacity marginal costs were derived from E3's 2020 PJM study, while transmission and distribution capacity costs were provided by BGE as an overnight cost and levelized by E3 using expected asset lifetimes and BGE's weighted average cost of capital.

Table 26: Marginal Capacity Costs

Category	Value
Generation capacity	$40/kW-year in 2022, $57 in 2030, $100 from 2040 onwards
Transmission + Distribution capacity	Modeled range of $203 kW-year to $258/kW-year

E3 then added incremental electric supply and delivery costs to a forecast of embedded costs for both categories to arrive at an annual revenue requirement. E3 developed customer rates by allocating the revenue requirement in each scenario based on the factors described in Table 27 to develop a class revenue requirement. The class revenue requirements were then divided by class electric sales to calculate a volumetric rate for each scenario and model year. These volumetric rates were then leveraged in the customer affordability assessment.

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[54] Note that the ground source heat pump infrastructure that is part of a networked geothermal installation may be eligible for incentives under the Inflation Reduction Act. Like other IRA impacts, this is not captured here.

[55] The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals. https://thefutureofgas.com/content/downloads/2022-03-21/3.18.22%20-%20Independent%20Consultant%20Report%20-%20Decarbonization%20Pathways.pdf.

Table 27. Customer cost allocation methodology.

Category	Allocation of costs based on (>2020)
Embedded system costs	Historical allocation of costs
Incremental distribution costs	Customer group's contribution to coincident 1-in-10 peak
Incremental transmission costs	Customer group's contribution to coincident 1-in-10 peak
Fuel costs and O&M	Customer group's contribution to electric load
Incremental generation costs	Customer group's contribution to electric load

Customer Affordability

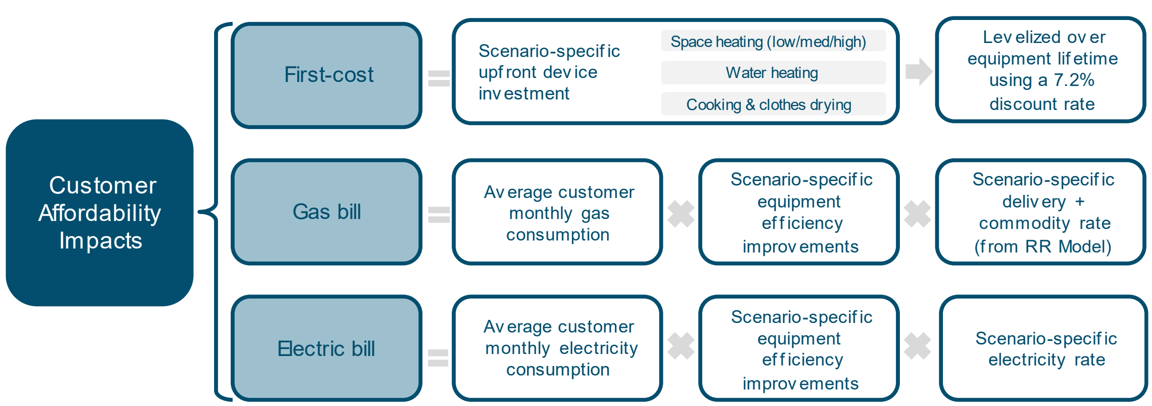
Introduction to Customer Affordability

The Customer Affordability Model evaluates how decarbonization scenarios influence energy and equipment costs over time and across different customer types, including low-income customers. This segmentation was used to gain insight into the impact of changing heating bills on low- and moderate-income customers and the extent to which those customers could afford the first cost of an all-electric conversion or deep energy efficiency retrofit.

Three different types of customer costs are calculated within the model: gas bill impacts, electric bill impacts and first cost (i.e., capital investment) impacts. These cost types are designed to represent the total energy-related costs faced by a customer. All costs are converted into monthly energy costs, which allows for a comparison of the costs faced by customers that select different appliances under the same scenario, as well as the costs faced by customers under different scenarios. Costs are also translated into an estimate of customer energy burden, or the percent of a customer's income spent on energy-related costs. As such, this analysis aims to shed light on the feasibility and equity of decarbonization strategies evaluated in the Independent Consultant Report on Decarbonization Pathways.

Figure 31 provides a schematic of how data flows into and through the customer affordability model. Each component of the model is explained in greater detail below.

Figure 31. Customer affordability methodology schematic.



Customer Affordability Approach

Baseline

While the PATHWAYS model describes the energy demand and cost changes across the entire BGE service area, the customer affordability model explores how individual residential customers might experience changes in building energy consumption.[56] E3 derived representative customer profiles using data from the American Community Survey (ACS) on building vintages, numbers of units, and resident income. Using that data, E3 selected the three residential profiles described in Table 28 for the primary focus of the report. According to ACS data, 74% of BGE households are in one-unit buildings, while 25% of households are in multi-unit buildings. The greatest share of housing units (29%) were built between 1980 and 1999, and the next greatest share of units (24%) were built between 1960 and 1979. The ACS data reveals a wide range in income levels within the BGE service area. 20% of households have an annual income less than $35,000, and 45% of households have an income less than $75,000; meanwhile, 23% of households have an annual income greater than $150,000.

E3 also relied on data from the Residential Energy Consumption Survey (RECS) to describe typical annual energy use. RECS data observations for metro area households in the South Atlantic region that use natural gas for both space heating and cooking were separated and averaged according to income level and housing type. From this, E3 constructed energy profiles for households representative of BGE customers, broken down by gas and electricity use for heating, cooling, lighting, clothes drying, cooking, water systems, and other miscellaneous end uses. As reflected in Table 28, single-family units consume more energy than multi-family units, and energy use increases with income.

Table 28. Summary of residential customer profiles used in the affordability assessment.

Building Category	Structure Type	Income Level Bracket	Approximate Household Income	Vintage	Reference Annual Electricity (KBTU)	Reference Annual Natural Gas (KBTU)
Residential 1	Single Family	$40,000 - $59,999	$50,000	1960 to 1969	40,550	62,443
Residential 2	Single Family	$80,000 to $99,999	$83,811	1980 to 1989	43,771	64,026
Residential 3	Multi Family	$20,000 - $39,999	$30,000	1980 to 1989	7,732	52,369

Residential Technology Packages

E3 assumed that a characteristic household would adopt a corresponding package of technologies representing the overall direction of each PATHWAYS scenario. The technology packages included primary household appliances, lighting, building shell measures, and vehicle selection. Taking building shell as an example, because most customers do not receive a shell retrofit in any scenario, the representative packages do not include that measure. The technical packages corresponding to each scenario are summarized in Table 29.

[56] While transportation costs do impact customer affordability, this study focuses on the impacts to buildings. As a result, transportation costs were excluded from this analysis.

Table 29. A summary of the technical packages selected for each scenario.

Package Measure/Parameter	Reference	Limited Gas	Hybrid	Diverse Energy Solutions
Primary Space Heating	Reference SH	Electric ASHP	Electric ASHP	Gas Heat Pump
Secondary Space Heating	None	None	Reference SH	None
Demand Share of Secondary Space Heating (%)	N/A	N/A	5%	N/A
Water Heating	Refence WH	Electric WH	Electric WH	Efficient Gas WH
Clothes Drying	Reference CD	Electric CD	Electric CD	Efficient Gas CD
Cooking	Reference CK	Electric CK	Electric CK	Efficient Gas CK
Lighting	Reference Lighting	Efficient Lighting	Efficient Lighting	Efficient Lighting
Shell	Reference Shell	Reference Shell	Reference Shell	Reference Shell

Energy Bills

Monthly energy bills are then calculated by assessing a combination of the customer and volumetric charges for electric and gas against changes in customer usage of those fuels in each package. The model begins with the reference residential energy profiles as defined with RECS data. For each of the alternative technology packages, the reference energy consumption for a particular end use is scaled according to how the selected technology performs relative to the reference technology. If a given technology is electrified, then the corresponding energy demand is switched from gas to electric. To allow a comparison of results, it is assumed that household consumer behavior (such as regularity of clothes washing, level of lighting, etc.) remains unchanged, and only the performance of technology at meeting set household needs is adjusted.

First-Costs

Each technology option includes a first cost. These estimates include the cost of space heating, space cooling, water heating, cooking, clothes drying equipment as well as building shell improvements. Total upfront costs are shown in Table 30. These costs are subsequently used to estimate the total first costs of a technology package for a customer prototype.

Table 30. First costs used in the customer affordability model.

Subsector	Technology	Single-Family Costs ($/unit)	Multi-Family Costs ($/unit)
Space Heating	Reference SH	$3,910	$3,450
Space Heating	Dual Fuel ASHP	$13,685	$12,075
Space Heating	Electric ASHP	$14,399	$12,705
Space Heating	Efficient Gas SH	$4,862	$4,290
Space Heating	Gas Heat Pump	$8,500	$7,500
Water Heating	Reference WH	$1,258	$1,110
Water Heating	Electric WH	$2,346	$2,070
Water Heating	Efficient Gas WH	$1,258	$1,110
Clothes Drying	Reference CD	$765	$675
Clothes Drying	Electric CD	$425	$375
Clothes Drying	Efficient Gas CD	$765	$675
Cooking	Reference CK	$629	$555
Cooking	Electric CK	$850	$750
Cooking	Efficient Gas CK	$629	$555
Cooling	Reference AC	$3,776	$3,776
Shell Measures	Reference Shell	$0	$0
Shell Measures	Existing Efficient Shell	$12,560	$11,082

As an output, first costs are presented for each scenario both in terms of (1) a total upfront cost that would be incurred to conduct a comprehensive building retrofit (see Table 29 and Table 30) and (2) in a monthly amortized form, with cost spread across the lifetime of the investment. Perspective (1) is intended to highlight the amount of capital investment required to convert customers, while perspective (2) is a high- level indication of the monthly outlays those customers may experience under an arrangement where the costs could be more evenly spread over time.

Key Affordability Model Inputs

Data on average customer energy consumption, equipment costs and efficiency, and scenario-specific rates from the gas and electric sector modeling are used to estimate changes in customer costs under different scenarios. The upfront cost of building electrification and energy efficiency measures were primarily derived from values published in the 2021 Maryland Building Decarbonization Study. Upfront costs, detailed in the modeling assumptions spreadsheet, are derived from a variety of sources, including EIA National Energy Modeling System (NEMS) and the Massachusetts Buildings Technical Report. Data inputs into the model are shown in Table 31.

Table 31. Customer affordability model input sources.

Model Inputs	Data Source
Electric Rates	Electric Revenue Requirement Model
Gas Rates	Gas Revenue Requirement Model
Baseline Energy Consumption	U.S. Department of Energy, 2015 Residential Energy Consumption Survey (RECS) Microdata
Equipment Efficiencies	E3 RESHAPE model simulations, EIA NEMS model documentation, NREL Energy Futures Study
Equipment Costs	Maryland Building Decarbonization Study, The Role of Gas Distribution Companies in Achieving the Commonwealth's Climate Goals
Income	U.S. Census Bureau, 2019 American Community Survey 5-Year Estimates
Housing Characteristics	U.S. Census Bureau, 2019 American Community Survey 5-Year Estimates
Household Energy Use Profiles	U.S. Department of Energy, 2015 Residential Energy Consumption Survey (RECS) Microdata