THE CENTER FOR
CLIMATE STRATEGIES

Appendix: Maryland LEAP Model Structure, Modeling Approach, and Data Sources

Appendix to *Comprehensive Analysis of Maryland's Short- and Long-term Climate Stabilization and Clean Energy Goals and Investment Requirements*

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Technical Appendix

Center for Climate Strategies
www.climatestrategies.us
tpeterson@climatestrategies.us

Table of Contents

Abbreviations

$	United States dollar
$B	Billions of United States dollar
$M	Millions of United States dollar
AC	Alternating Current
ACC II	Advanced Clean Cars II
AEO	Annual Energy Outlook (USDOE EIA)
AIM	American Innovation and Manufacturing Act
BES	Battery energy storage
BEV	Battery electric vehicle
Btu	British thermal unit
CAPEX	Capital expenditures (initial investment costs)
CARB	California Air Resources Board
CCS	Center for Climate Strategies
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CRF	Capital recovery factor
CSNA	Climate Solutions Now Act
DC	Direct current
EIA	USDOE Energy Information Administration
EPA	US Environmental Protection Agency
FiT	Feed-in Tariffs
FPV	Floatovoltaics
GDP	Gross domestic product
GGRA	Greenhouse Gas Reduction Act
GHG	Greenhouse gas
GHI	Global horizontal irradiance
GIS	Geographic information system
GJ	Gigajoule (billion Joules, a measure of energy)
GW	Gigawatt
GWh	Gigawatt-hour
GWP	Global Warming Potential
Ha	Hectare
HDV	Heavy-duty vehicles

HDT	Heavy-duty trucks
HH	Households
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent power producer
IPPU	Industrial processes and product use
kg	kilogram
km	kilometer
kW	Kilowatt
kWh	Kilowatt-hour
kWh/m^2	Kilowatt-hour per square meter
kWp	Kilowatt-peak
lb	Pound
LBNL	Lawrence-Berkeley National Laboratory
LCOE	Levelized cost of energy (or levelized cost of electricity)
LDA	Light-duty autos
LDT	Light-duty trucks, includes sports utility vehicles (SUVs)
LDV	Light-duty vehicles (typically, LDA plus LDT)
LEAP	Low Emissions Analysis Platform
LED	Light-emitting diode (Lighting technologies)
LFG	Landfill gas
LI	Low Income (households)
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas (a mixture of propane and butane)
LULC	Land use/land cover
m^2	Square meter
MARC	Maryland Area Rail Commuter
MCC	Maryland Climate Change Commission
MCEC	Maryland Clean Energy Center
MD	Maryland
MDE	Maryland Department of Environment
MD DHCD	Maryland Department of Housing and Community Development
MDOT	Maryland Department of Transportation
mi	Miles
$MMtCO_2e$	Million metric tons of CO_2e

MPG	Miles per gallon
MPGe	Miles per gallon equivalent (used for electric vehicles)
MSW	Municipal solid waste
MV	Medium voltage
MW	Megawatt
MWh	Megawatt-hour
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
NREL ATB	NREL Annual Technology Baseline
O&M	Operations and maintenance
OPEX	Operating expenses
Pass-mi	Passenger-miles
PHEV	Plug-in hybrid electric vehicles
PJM	Pennsylvania/Jersey/Maryland regional transmission organization
POWER	Promoting Offshore Wind Energy Resources Act
PPA	Power purchase agreement
PV	Photovoltaic
PVOUT	Photovoltaic electricity output
RGGI	Regional Greenhouse Gas Initiative
RPS	Renewable Portfolio Standard
SCC	Social cost of carbon (environmental externality adder)
SEI	Stockholm Environment Institute
SEI US	Stockholm Environment Institute United States Centre
STP	Standard temperature and pressure
T&D	Transmission and distribution
TJ	Terajoule
Tg	Teragram (10^{12} grams, or million metric tons)
TWh	Terawatt-hour (or billion kWh)
US DOE	United States Department of Energy
US EPA	United States Environmental Protection Agency
VMT	Vehicle-miles traveled
W	Watt
WACC	Weighted Average Cost of Capital
WtE	Waste-to-energy

1. Modeling Approach

1.1 Steps in Analysis

At the outset of the project, CCS assembled a comprehensive new state dataset for Maryland for energy technologies and practices related to current activities and future climate mitigation. This was done by starting with an older existing dataset created in the Low Emissions Analysis Platform (LEAP) software tool by the E3 Group for the Maryland Department of Environment (MDE) and then adding and replacing data from national, statewide, and local sources to create an updated and elaborated dataset for Maryland. CCS assembled additional data for non-energy sectors (agriculture, forestry, and waste) using the CCS GHG Strategy Tool.

The Maryland LEAP model describes virtually all significant direct and indirect (such from as electricity use) sources of greenhouse gas emissions (GHGs) from both the energy sector (including energy demand and supply) and from non-energy sources of GHGs in the state. Most of these sources (and all major ones) are included in the periodic statewide emissions inventories prepared by MDE, the first of which was for 2006, and the most recent for 2020. With a few minor exceptions, CCS' modeling has used emission factors and related parameters similar to those used by MDE in preparing its inventories.

The base year, in this case 2021, was the last year for which complete data was routinely available, and historical data were updated from dozens of local, state, and national sources. To the extent possible, base year parameters were assembled for specific technologies and practices at the sector level (for example, including specific residential space heating technologies) throughout the Maryland economy.

Following preparation of a base year dataset as the starting point for future GHG emissions, the next step was to prepare a baseline of future energy and non-energy emissions under a BAU Current Policies scenario. This started with projections of parameters affecting energy use and GHG emissions, such as state population; state GDP; output of key industrial goods, such as cement; growth in the commercial building stock; changes in the number, efficiency, and energy sources used by vehicles; and types of electricity generation used in Maryland and for electricity imported to Maryland. Many of these projections were derived from Maryland state statistics and/or from US Department of Energy's Annual Energy Outlook 2023 (USDOE AEO) Reference case national or regional projections.

Determining how current policies, as presently funded and projected to be implemented, will contribute to Maryland's CSNA and other goals over the time period 2024 through 2045/2050 is crucial to pursuing the next step in climate mitigation policy development in the state, and in determining what additional policies need to be implemented to reach the CSNA and other climate goals. Establishing the extent to which current policies will contribute to achieving Maryland's climate change mitigation goals was a key milestone in the study and is described in more detail in this report. In general, the Current Policies scenario was assembled by preparing a list of current and recent policies expected to affect GHG emissions by examining US Department of Energy (USDOE) energy and economic forecasting guidelines, working with climate stakeholders in Maryland. and including input from Maryland GHG emissions modeling efforts by other groups. CCS then assessed the potential impact of those policies on emissions using criteria consistent with those used in the development of the USDOE Energy Information Administration's (EIA's) most recent (2023) Annual Energy Outlook (AEO), or AEO2023, by asking:

- Was a given policy sufficiently fully enacted as of the time of modeling of the Current Policies Case (April/May of 2023) to be certain or highly likely to come into effect?
- Does the policy have sufficient funding, if needed, and/or regulatory authority to be fully implemented?

- Are those agencies responsible for implementing certain policies likely to have sufficient staffing and organization to implement the policy to the degree and on the timescale implied by the policy?
- Are there major barriers to the implementation of policies that, in the estimation of the experts consulted, would prevent those policies from being fully developed during the expected period?

If the answers to any of the first three questions above appeared to be "no," and/or the answer to the last question was "yes," or there were significant uncertainties in answering the questions, CCS either did not include an estimate of the emissions reduction from the policy in the Current Policies Case, or reduced the estimated impact of the policy to a level that seemed consistent with expected policy implementation, funding, institutional capabilities, and barriers to implementation. These assessments for each policy formed the basis for the estimations of Current Policies case parameters in LEAP and in the Greenhouse Gas Strategy Tool. The parameters were then used in calculating the projected impacts of policies on energy demand and supply and on associated energy- and non-energy sector GHG emissions.

With the effects of current policies on GHG emissions in the state estimated, the next step in this study was to identify a set of additional GHG emissions mitigation actions for implementation throughout the Maryland economy in the next two-plus decades. These additional actions were drawn from initial lists compiled by the Maryland Climate Change Commission (MCC) Mitigation Work Group,[1] Maryland stakeholders,[2] and others, and augmented through work with a group of stakeholders, incorporating ideas from other emissions reduction studies and from groups working toward climate change mitigation, within and outside Maryland. Most of these actions are based on policies suggested by organizations participating in climate change and clean energy policy fora in Maryland,[3] but some GHG reduction options offering significant additional savings have been added recently by the CCS modeling team. These options were added based on CCS's review of interim modeling results and on additional technical input and expertise from subnational climate mitigation and clean energy planning and were judged as consistent with or beneficial to reaching Maryland's emissions reduction goals.

1.2 Development of Actions

The impacts of Additional Actions on GHG emissions were estimated for each modeling year (through 2050), along with the costs of those actions relative to Current Policies. Working with stakeholders, CCS prepared estimates for the implementation goals, level of effort, and timing (years of deployment and level of effectiveness by year) for each action. Technical conferrals with stakeholders included identifying the best available data sources for additional actions, as well as preparation of analytical and design assumptions. These conferrals were carried out with full transparency in identification of information sources and assumptions, to be readily updated and revised as policies, technologies, costs of technologies, or other factors change.

Parameters for each action populated a set of scenarios for emissions reduction spanning the Maryland energy demand and supply sectors, along with selected non-energy greenhouse gas emissions sources.

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[1] MWG recommendations for 2022 - discussion draft 10-17-22.pdf (maryland.gov)

[2] Maryland stakeholders (Climate Partners) - Preliminary Priorities (Community Climate Plan) (squarespace.com)

[3] A number of the Additional Actions included in this analysis have had their genesis or been refined in discussions with Maryland stakeholders and others participating in Technical Working Group and other discussions organized by Maryland stakeholders, as well as with experts from Maryland and beyond. Variants of the Additional Actions have been included in other modeling efforts undertaken by or on behalf of Maryland agencies, as well implemented in, planned, or suggested for implementation in other jurisdictions.

CCS then evaluated those scenarios individually, in aggregate cases by sector (buildings, transport, and energy supply, for example), and as an overall summary "Additional Actions" case.

1.3 Modeling Tools

Evaluation of the current policies and additional actions cases has been carried out using LEAP, which is an accounting-based modeling tool, augmented with the use of the Excel-based CCS GHG Strategy Tool for non-energy sectors. The scenario descriptions and results provided, in aggregate and by sector, describe the estimated GHG reductions, energy demand impacts, and energy supply changes from implementing a set of additional actions beyond recent policies in Maryland, which we refer to as Additional Actions. These results focus on non-cost impacts of the scenarios (energy use or production by fuel and sector, and resulting GHG emissions), but also provide a set of estimates summarizing cost impacts, including social costs and investment costs, of GHG-reduction actions beyond current policies that will likely be required to move Maryland closer to its climate mitigation goals.

1.4 Key Data Sources

In addition to the LEAP dataset inherited by CCS as described above, CCS has used the following major sources of information on energy use, economic activities, demography, and GHG emissions in Maryland, in some cases with adjustments to national and regional data for use in the Maryland model:

- AEO2023 inputs and Reference case results, available by region in some cases. In some cases, where applicable, results of other AEO2023 scenarios were also consulted.[4]
- MDE GHG inventories for 2014, 2017, and 2020.[5]
- USDOE EIA historical energy use statistics, by fuel types and sector at the state level.[6]
- Other USDOE and EPA statistics, as well as statistics from other federal agencies such as the US Department of Transportation (USDOT) and the Federal Highway Administration.[7]
- National and regional results of the USDOE surveys of energy use in the residential (RECS), commercial (CBECS) and manufacturing sectors (MECS). [8]
- State of Maryland Statistics, including population, state output, and many others.[9]
- County-level statistics for Maryland.
- Websites of counties and local agencies, including transportation agencies and systems such as the Maryland Department of Transportation (MDOT), the Maryland Transit Administration (MTA) and the Maryland Area Rail Commuter (MARC) train system.[10]

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[4] For example, USDOE EIA (2023), "Annual Energy Outlook 2023, Table 54. Electric Power Projections by Electricity Market Module Region, Case: Reference case, Region: PJM / East," was used as a starting point for future trends in the Maryland electricity sector.

[5] See Maryland Department of Environment, Greenhouse Gas Inventory.

[6] For example, the USDOE EIA (2023) publishes statistics on natural gas use by state as "Natural Gas Consumption by End Use," with annual Maryland data through 2022.

[7] For example, USDOT Federal Highway Administration Policy and Governmental Affairs, Office of Highway Policy Information (2023), Highway Statistics 2021 [and earlier versions of same], dated February 2023.

[8] The periodic national and regional surveys of energy use are provided as USDOE EIA (various years), "Residential Energy Consumption Survey (RECS)," "Commercial Buildings Energy Consumption Survey (CBECS)," and "Manufacturing Energy Consumption Survey (MECS)". In general, CCS used results from the smallest available region that included Maryland to inform LEAP modeling. Data from these surveys adapted for use in LEAP included shares of fuel use by end use, energy intensities, and other information.

[9] For example, Maryland State Archives (2023), "MARYLAND AT A GLANCE, ECONOMY, MANUFACTURING," dated September 25, 2023.

[10] For example, MDOT/MTA (2021), *Rebuilding Better: Committed to an Equitable Transit Future*, September, 2021.

- Inputs and results of Maryland applications of the USEPA's US State Energy Data System (SEDS).
- Inputs and outputs of other modeling tools applied to energy-using sectors in Maryland, such as for transportation subsectors.
- Statewide and county websites describing current climate and energy policies, as well as other existing and planned activities and infrastructure, such as plans for transportation systems.
- Existing analyses of climate and energy policies on the national and state levels.
- Cost projections for renewable and other energy technologies from the National Renewable Energy Laboratory (NREL) and others.[11]
- Information from news articles and the academic literature, including, for example, information on plans for industrial plants.

The above presents only a subset of the information sources consulted to prepare the Maryland LEAP model. Specific references used in development of model inputs are described in annotations to the LEAP dataset itself and in data collection workbooks in which data are assembled and processed for use in the model. The amount of detail included in any LEAP modeling effort can always be expanded to meet needs for policy analysis, if additional data are available, or can be developed, for example, via energy user surveys. CCS has not exhausted the information sources available to inform the development of the Maryland energy model and welcomes input from stakeholders and other parties on additional information sources that might be tapped to improve further iterations of the model.

1.5 Data Sources for Projections and Scenario Assumptions

The level of detail in the Maryland LEAP model is extensive, and required base year and historical data, as well as projections and assumptions for a large number and wide range of activities, energy intensities,[12] costs, and other parameters. Examples range from projections in major economic and demographic trends, such as state GDP and population; to sector- and subsector-specific parameters such as the shares, efficiencies, and costs of different types of residential heating appliances; the square feet of commercial and institutional floorspace in Maryland; sales, fuel economies, and annual miles traveled for different types of light duty vehicles; number of air travel departures and arrivals; and tons of cement produced annually. On the energy supply side, projections are needed, for example, for the rate of electricity and natural gas losses per unit of throughput in their respective transmission and distribution systems, the number of megawatts (MW) of distributed and central-station solar power deployed, and the output of liquefied natural gas for export. Overall, many hundreds of base/historical year data and projections of parameters are needed to populate the energy demand and energy supply portions of the Maryland LEAP model. Each of these parameters can be updated to reflect the passage of time and different projections of future conditions in the state, the nation, and the global economy.

For many of the parameters used in the model, starting-point projections for the Current Policies case have been adapted from national and regional projections produced as part of the AEO2023.[13] These adapted trends serve, in part, to define the baseline for current and future GHGs and related results in

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[11] NREL (2023), "Electricity Annual Technology Baseline (ATB) Data Download."

[12] Energy intensity is the amount of energy used by a device (for example, an appliance or vehicles) per unit of time or some other measure of usage. Examples are kWh per year per household for a residential refrigerator, gallons of fuel per mile of travel by a locomotive, gigajoules or kWh of electricity used in griding and other processing to produce a ton of cement. Energy intensity is the inverse of parameters such as efficiency, for example, measuring the fraction of energy in natural gas that is transferred to heated water in a residential water heater, or fuel economy, measured in miles traveled per gallon of gasoline or diesel fuel.

[13] AEO2023 data and results are available from USDOE EIA (2023), "Annual Energy Outlook 2023,," release date March 16, 2023.

Maryland. AEO2023 and previous AEO modeling used the NEMS (National Energy Modeling System),[14] which produces outputs on a national, and in some cases regional, level for the United States. AEO2023 outputs projected trends in technology, energy-using activities, and other parameters. In some cases, AEO2023 national values can be, and have been, used directly as reasonable assumptions for Maryland parameters. In other cases, where AEO2023 outputs are available on a regional basis, Mid-Atlantic or South Atlantic values, or an average of the two, were used for Maryland. State of Maryland and/or Maryland-specific historical energy use data were used wherever possible as "control totals" to make sure that estimated energy use by residential end use, for example, adds to the base year/historical energy figures for the residential sector reported by the USDOE.

Adoption of the AEO2023 data as the initial basis of the Current Policies case ensures that the Current Policies case reflects the US federal policies affecting the energy sector that are implicit to the Reference case modeling in AEO2023. AEO2023 results, however, were heavily augmented for the Maryland LEAP model by considering GHG emissions impacts of state, federal, and sometimes county level current policies. Input on current policies was collected from many stakeholders statewide, from the national and international literature, and from existing national and Maryland-specific modeling. The overall goal in compiling the Current Policies case, as described in more detail in section 4 of the Technical Report, has been to identify whether a given policy meets the following criteria: 1) is sufficiently fully enacted as to be certain or highly likely to come into effect, 2) is sufficiently funded and/or has regulatory authority to be fully implemented, 3) whether the agencies responsible for implementing policies have or will have sufficient staffing and organization to implement the policy as needed, and 4) whether there are major barriers to the implementation of policies that would prevent those policies from being fully developed enough to meet policy goals.

For the Additional Actions case, individual LEAP scenario components were developed to model GHG emissions reduction across the various energy demand sectors and energy supply elements of the economy, as well as across the non-energy GHG emissions sources in Maryland. LEAP scenarios were based on projected implementation, assuming adequate policy and financial support, of specific technologies and practices. Many of the Additional Actions elements are based on suggested GHG emissions reduction strategies developed by Maryland government agencies and through various climate-related stakeholder processes ongoing in Maryland. Some Additional Actions case elements were developed by CCS based on technologies and practices applied or suggested for other jurisdictions.

The transparency and level of detail in the LEAP model makes it appropriate for use as a tool for Maryland's climate policy stakeholders, including government and non-governmental entities, to reference in exploring GHG emissions policies for Maryland, particularly in the energy sector. LEAP can be used to produce required results directly; LEAP outputs can also be used for detailed planning of the implementation of individual policies, including detailed financial analysis from the perspective of different financial actors in GHG emissions reduction projects and programs. The Maryland LEAP model and GHG Strategy Tool, in combination, are designed to accept additional input, detail, and refinement to explore climate change mitigation options across the spectrum of energy and non-energy emissions sources.

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[14] See, for example, USDOE EIA (2023), "Documentation of the National Energy Modeling System (NEMS) modules," and USDOE EIA (2023), *The National Energy Modeling System: An Overview*, dated May 2023.

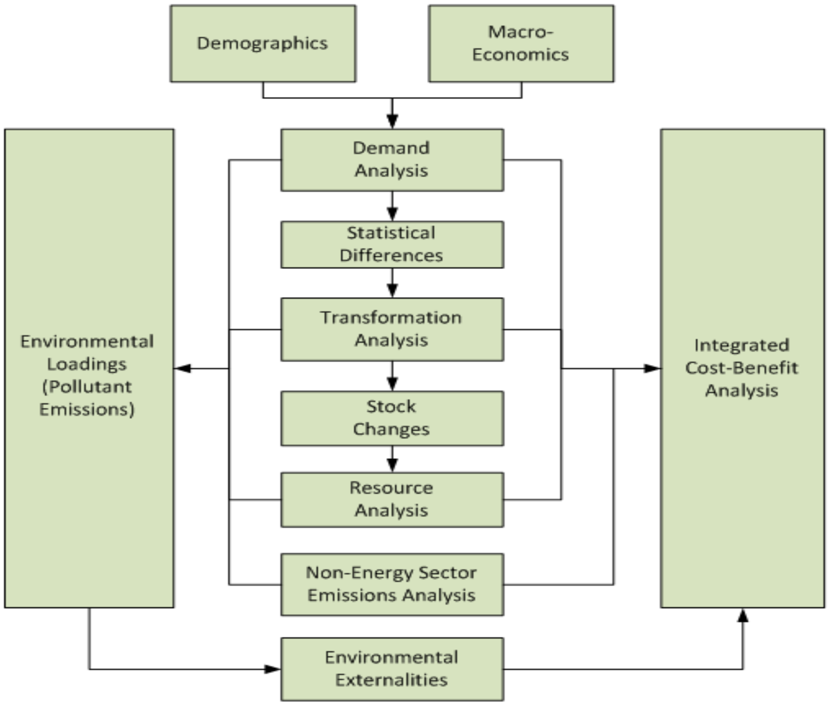
2. LEAP Model Structure

2.1 Introduction to the LEAP Modeling Platform

The following brief description of key elements of the LEAP modeling and planning tool is adapted in part from an introduction provided by the Stockholm Environment Institute United States (SEI US), the developer of LEAP:[15]

"The Low Emissions Analysis Platform modeling and planning tool, or LEAP, is centered around an integrated modeling framework for the evaluation of future energy demand and energy supply scenarios—including both energy conversion and resource extraction—and their associated environmental emissions and costs. LEAP does, however, include additional capabilities such as the modeling of non-energy environmental emissions, emissions impacts, and optimization of energy (particularly electricity) supply. LEAP is a flexible model-building tool, not a fixed model of a particular system, and as such, models can be developed at virtually any level of detail and for any type of energy system. LEAP provides demand-driven, accounting-based calculations of energy flows, based on energy demand and energy supply (or energy "transformation") data structures specified by the user, and therefore provides excellent transparency in modeling—that is, inputs and assumptions are clearly visible and can be fully documented within the model, and straightforward calculational structures make it possible to easily trace changes in modeling outputs to changes in inputs. LEAP also provides a structure for gathering and adapting the modeling data needed to comprehensively describe current and future energy use and its associated costs and emissions in a jurisdiction; this process of data collection, review, and adaptation is crucial to forming an understanding of the trends and future options for evolution of the energy system in an area. Figure A-1 shows the interaction of LEAP modeling elements."

Figure A-1: LEAP Calculational Elements and Interactions



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[15] See SEI, "LEAP: Introduction".

For the Maryland project described in this Report, the approach has been to use LEAP to evaluate the emissions and costs/benefits associated with different energy demand and supply scenarios for the state (with some accounting for non-energy emissions), focusing on scenarios designed to move the state toward its climate change mitigation goals.

LEAP has been adopted by thousands of organizations in more than 190 countries worldwide. Its users include government agencies, academics, non-governmental organizations, consulting companies, and energy utilities. It has been used at many different scales ranging from cities and states to national, regional, and global applications. LEAP is widely use in integrated resource planning, GHG mitigation assessments, and Low Emission Development Strategies (LEDS) particularly in the developing world, but in most industrialized countries as well, and many countries have also chosen to use LEAP as part of their commitment to report to the United Nations Framework Convention on Climate Change (UNFCCC). At least 32 countries used LEAP to create energy and emissions scenarios that were the basis for their Intended Nationally Determined Contributions on Climate Change (INDCs): the foundation of the historic Paris climate agreement intended to demonstrate the intent of countries to begin decarbonizing their economies and invest in climate-resilience.

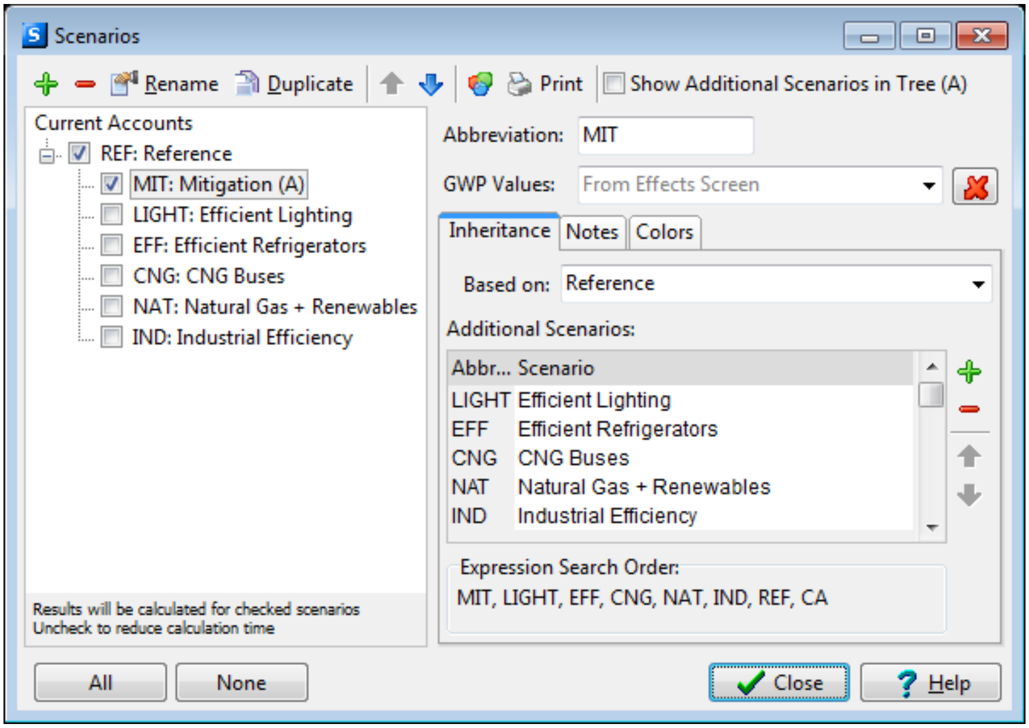
Using LEAP involves several major steps. First, **data are collected** on energy consumption and production for a base year (typically the last year for which historical data on energy use and associated demographic and economic activity data are available) and for historical years as desired. Data are collected for energy-using activities ranging from household end-uses to transportation subsectors and manufacturing of goods, data on the supply of different fuels and energy sources, such as electricity, plus energy sector emissions factors and non-energy sector GHG emissions and are then mounted within a LEAP data structure prepared by the user. Preparation of the data structure is done considering the types of data available, the structure of the economy to be described, and the types of policy and other questions that the modelers wish to answer. For example, demand analysis in LEAP calculates energy consumption and associated costs and emissions in an area. The most basic LEAP data structures tend to use bottom-up end-use accounting where energy end-use for a given LEAP branch (for example, a particular kind of residential appliance) is calculated as activity level (such as number of households with TVs) times an annual energy intensity (kWh used by TVs per household with TVs per year). Other options for treatment of energy demand in LEAP, however, include modeling of stocks and sales of devices such as appliances and vehicles, and econometric modeling where energy use is a function of GDP or other measures of economic output. LEAP supports the use of multiple methodologies, which can also be used together, and all the modeling approaches described above are used in the Maryland LEAP model. Users can also prepare their own "expressions"—equations indicating how activities (such as the number of households, or square feet of commercial space), and/or the energy uses associated with those activities— will change over time, to customize LEAP models. LEAP models are often organized by economic sector, subsector, end-use and device, but any level of aggregation or detail that is consistent with the modeling mission and the data available can be used. LEAP data structures can be easily modified as needed and can be made more detailed as the typically iterative process of data gathering, analysis, and policy development continues.

Next, one or more **"baseline" or "reference" case projections** are prepared that provide projections of future supply and demand in the area being modeled, typically under a "business as usual," "recent trends," or "reference" set of assumptions. Reference case projections present the modeler's views of how energy demand and supply, and the activities and trends that drive the energy (and non-energy) sectors, will change over time, typically in the absence of additional policies.

Finally, **scenarios** are developed to project energy demand, supply, and associated emissions and costs, under futures that are different from the reference case. Those differences can be driven by different policies, different assumptions about technology development and technology costs, or other changes from the reference case. Scenarios are self-consistent storylines of how an energy system might evolve over time. Using LEAP, policy analysts can create, and then evaluate, alternative scenarios by comparing their energy requirements, their social costs and benefits, and their environmental impacts. Each scenario includes one or more changes in future assumptions from the reference case. Scenarios can be combined to model futures in which many policies come together to build different futures, as was done with the Maryland model.

The LEAP Scenario Manager, shown in Figure A-2, below, can be used to describe individual policy measures that can then be combined in different combinations and permutations into alternative integrated scenarios. This approach allows policy makers to assess the impact of an individual policy, as well as the interactions that occur when multiple policies and measures are combined. For example, the benefits of appliance efficiency standards combined with a renewable portfolio standard might be less than the sum of the benefits of the two measures considered separately, whereas the combination of electrification of the transport sector with the accelerated implementation of renewable electricity sources might be greater than the sum of the separate impacts on GHG emissions. In the screen shown right, individual measures are combined into an overall GHG Mitigation scenario containing various measures for reducing greenhouse gas emissions.

Figure A-2: An Example of the Scenario Screen in LEAP



Current Accounts
- ☑ REF: Reference
  - ☑ MIT: Mitigation (A)
  - ☐ LIGHT: Efficient Lighting
  - ☐ EFF: Efficient Refrigerators
  - ☐ CNG: CNG Buses
  - ☐ NAT: Natural Gas + Renewables
  - ☐ IND: Industrial Efficiency

Results will be calculated for checked scenarios
Uncheck to reduce calculation time

Abbreviation: MIT

GWP Values: From Effects Screen

Based on: Reference

Additional Scenarios:

Abbr...	Scenario
LIGHT	Efficient Lighting
EFF	Efficient Refrigerators
CNG	CNG Buses
NAT	Natural Gas + Renewables
IND	Industrial Efficiency

Expression Search Order:
MIT, LIGHT, EFF, CNG, NAT, IND, REF, CA

Note that LEAP is intended as a **medium- to long-term modeling tool**. Most of its calculations occur on an annual time-step, and the time horizon can extend for an unlimited number of years. Studies typically include both a historical period known as the Current Accounts, in which the model is run to test its ability to replicate known statistical data, as well as multiple forward-looking scenarios. Typically, most studies use a forecast period of between 20 and 50 years. Some results are calculated with a finer level of temporal detail. For example, for electric sector calculations the year can be split into different user-defined “time slices” to represent seasons, types of days, or even representative times of the day. These slices can be used to examine how loads vary within the year and how electric power plants are dispatched differently in different seasons. In the Maryland model, for electricity generation, years are divided into 192 time slices, representing four seasons, two types of days (weekend days and weekdays), and 24 hours per day, allowing demand for electricity to be matched up to the seasonal, daily, and hourly availability of power from different sources.

2.2 Overall Structure of the LEAP Dataset

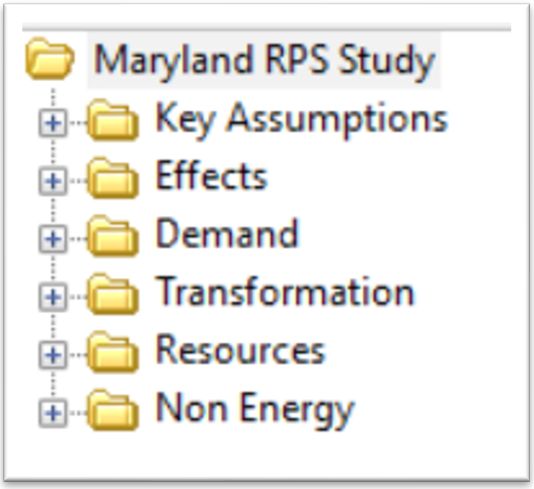
The Maryland LEAP model consist of seven major components:

- **Key Assumptions** provides parameters used throughout the model, including, for example, projections of population, GDP, vehicle mileage, and many other variables used to project activities that, in turn, drive estimates of future GHG emissions.
- **Effects** lists the emissions for which externality costs are specified when used to calculate social costs of emissions.
- **Demand** lays out the structure of energy (fuels and other energy forms) demand by end users in Maryland.
- **Load Shapes** specifies the variation of electricity loads over time during the year.
- **Transformation** describes how fuels and other energy are supplied to end users.
- **Resources** list the domestic and imported fuels and other energy forms that are used in, or produced by, the Maryland energy sector.
- **Non-Energy** describes GHG emissions from non-energy sources, including results from the GHG Strategy Tool.

Other key LEAP elements include:

- Key Assumptions, used to define additional variables used in the model. Examples include population/population growth, current and future costs for renewable energy systems, transportation parameters such as vehicle miles traveled per year, and many others.
- Resources, which describes the extent of energy resources, including both fossil fuels and renewable fuels, and including both primary resources (such as natural gas, crude oil, coal, and solar energy), and secondary resources (fuels/energy forms such as diesel, gasoline, hydrogen, or electricity, made from primary resources), and includes important parameters such as import costs and export value.
- Non-energy emissions categories, including sources of emissions of GHGs outside of the energy sector such as emissions from industrial processes, agriculture (such as from fertilizer use and animal husbandry), and waste management, plus sources and “sinks” (net negative emissions) of greenhouse gases in the forestry and other land use sectors. Also included here are emissions of methane from coal mines abandoned in Maryland. Calculation of most non-energy GHG emissions for both the Current Policies and Additional Actions cases were in many cases carried out using CCS’s Greenhouse Gas Strategy Tool, which was deployed as described below (and in more detail in section 2.7).

Figure A-3: Overall Structure of the Maryland LEAP Dataset



Base year data and future parameters for each of the individual and collective scenarios modeled in the Maryland LEAP dataset share the same data structure. Summaries of the major components of the Maryland LEAP data structure are described below; additional details by sector are presented in section 4 of this document below.

This structure begins with a set of demand sectors, subsectors, and end uses. As shown in Figure A-4, the Residential and Commercial sectors (together, the "Buildings" sector) are each represented by energy end uses ranging from space and water heating to cooking, lighting, and others. In turn, each end use includes devices varying, for example, by type of fuel/energy source (such as natural gas or electricity), types of technology (resistance heat or heat pumps), and in some cases, level of efficiency. Each device, in addition to its fuel and technology designation, has its own parameters for quantities such as fraction of stocks, sales, initial ("capital") costs, operating and maintenance costs ("O&M"), energy intensity (amount of fuel used per year per household, for example), and device-specific factors to calculate GHG and local air pollutant emissions, if applicable. Each of these parameters can change over time. The Transportation sector includes categories for the major types of motor vehicles in use in Maryland, plus an "other" category with sub-categories ("branches") for air travel, freight and passenger rail, off-road motor vehicle use, and more. The Industrial sector separates the cement subsector from other industrial subsectors, and covers all fuel uses for

Figure A-4: Maryland LEAP Energy Demand and Supply Structure

Energy Demand	Residential Air Conditioning
	Residential Building Shell
	Residential Cooking
	Residential Clothes Drying
	Residential Clothes Washing
	Residential Dishwashing
	Residential Freezing
	Residential Lighting
	Residential Refrigeration Primary
	Residential Refrigeration Secondary
	Residential Water Heating
	Residential Other
	Commercial Air Conditioning
	Commercial Cooking
	Commercial Lighting
	Commercial Refrigeration
	Commercial Space Heating
	Commercial Ventilation
	Commercial Water Heating
	Commercial Other
	Transportation Light Duty Autos
	Transportation Light Duty Trucks
	Transportation Heavy Duty Trucks
	Transportation School Buses
	Transportation Transit and Other Bus
	Transportation Other
	Industry
	Agriculture and Logging
	Construction and Mining
	District Heat Use
Transformation (Energy Supply)	Rooftop Solar PV
	District Heat Provision
	Hydrogen Production
	Transmission and Distribution
	LNG Exports
	Electricity Generation
	Natural Gas Pipelines
	MD Coal Production
	Natural Gas Production
	Biogas Production

each subsector. Agriculture and Logging, and Construction and Mining round out the main energy demand sectors used in the LEAP model.

Maryland energy supply (including imports) is covered in the “Transformation” section of the model, as shown in Figure A-4. Energy supply functions model processes that change one or more fuels into a fuel/energy form for final consumption, such as when distributed solar PV systems (rooftop and community systems) transform solar energy into electricity, or move a fuel from one place to another, as do electricity and gas transmission and distribution systems. The electricity generation “module” of the Maryland LEAP model includes the main types of electricity generation facilities operating and projected to operate in Maryland, plus imports of electricity from the rest of the PJM (Pennsylvania/Jersey/Maryland) grid. Other energy supply sources with key GHG emissions implications include liquefied natural gas (LNG) export, coal and natural gas extraction, and natural gas pipeline compressor energy use. Parameters tracked for energy supply processes include input and output fuels/energy forms, efficiencies or losses, capital and O&M costs, fuel costs, GHG and air pollutant factors, and more. For the electricity sector in particular, additional parameters are used to roughly determine how different types of plants are “dispatched” (operated over the course of a day, week, or year) to meet electricity demand. These dispatch parameters are used in conjunction with load curves that show how demand varies by hour over weekdays and weekends in each of the four seasons.

2.3 Energy Demand Dataset

The Energy Demand portion of the Maryland LEAP model (see Figure A-4) includes categories (“branches”) for the following:

- Residential End Uses
- Commercial End Uses
- Transportation (on-road and offroad)
- Industry
- Agriculture and Logging
- Construction and Mining

Residential end uses include air conditioning, clothes drying, clothes washing, cooking, dishwashing, freezing, lighting, refrigeration (primary and secondary), space heating (primary and secondary), water heating, and “other,” including electronics and other smaller devices. Commercial end uses include air conditioning, cooking, lighting, refrigeration, space heating, ventilation, water heating, and “other,” including electronics and office equipment. Under most of these end uses, individual device types using different fuels or different technologies (such as heat pump and conventional electric water heat) are included as separate branches.

Demand for energy in the Maryland transportation is represented by branches for:

- Light-duty Autos (LDAs), including several different technology and fuel combinations, modeled using a stock modeling approach in which new vehicles are phased in as old ones are retired and the market grows, with assumptions as to miles traveled per year and fuel economy particular to each category of vehicles.

- Light-duty Trucks (LDTs), meaning light pickups and sports utility vehicles, again including several different technology and fuel combinations, and modeled using a stock modeling approach. LDTs make up a progressively larger fraction of total light duty vehicles (LDVs, including autos and trucks) over time in Maryland.

- Medium- and heavy-duty vehicles, largely for freight delivery, again including several different technology and fuel combinations, and modeled using a stock modeling approach.
- Buses, including separate branches for school buses and transit buses.
- "Transportation Other," with sub-branches including, motorcycles, air travel, rail transport (freight and passenger), vessel bunkering (marine shipping), marine pleasure vessels, lawn and garden equipment, recreational equipment, the planned Purple Line extension in Maryland of the DC-area Metro system, and vehicle fueling/charging infrastructure.

2.4 Energy Supply Dataset

The Energy Supply (or energy "Transformation") portion of the Maryland LEAP model moves fuels and resources from where they are produced or imported to processing facilities, and ultimately to end-users. Energy supply elements of the model also convert resources into the fuels and other energy forms (for example, electricity and heat) used in the energy demand sectors (buildings, transportation, industry, and district heat).

The individual energy supply elements considered in the LEAP model include "modules" for rooftop solar PV (outputs not subject to transmission and distribution losses), district heat provision, hydrogen production,[16] electricity and gas transmission and distribution, LNG (liquefied natural gas) exports, electricity generation (central grid), natural gas pipelines, and coal production and natural gas production specific to Maryland. On the order of 20 different types of electricity generating units are included in the Electricity Generation module. Actions related to some, but not all, of these energy supply segments are reflected in the list of individual "scenarios" below, the results of which are compiled into an overall Energy Supply Summary, which itself is a component of the full Summary of Maryland Stakeholders Recommended Actions case.

2.5 Resources Dataset

The Resources element of the Maryland LEAP dataset lists all the domestic and imported fuels and other energy forms that are used in or produced by the Maryland energy sector, and specifies, as needed for each resource, parameters such as resource limits, import costs, and export benefits. Resources are described as either "primary," typically meaning the form that natural resources take as they are used or extracted (such as solar or wind energy, natural gas, or crude oil), or "secondary," meaning derived from primary resources—diesel, gasoline, and hydrogen, for example. A separate "Fuels" list includes the attributes of the fuels used in Maryland, including energy content, density, fuel composition, and other parameters.

2.6 LEAP Model Scenarios

Scenarios in LEAP are explorations of alternative futures for the energy and/or non-energy elements of the LEAP dataset. Scenarios start with "Current Account," which describes base year—typically the most recent year for which reasonably complete data are available, and in the case of the Maryland dataset, 2021—and historical year parameters. A reference case, in this instance mostly derived from AEO2023 inputs, provides the first-level projection of energy supply and demand and related activities into the

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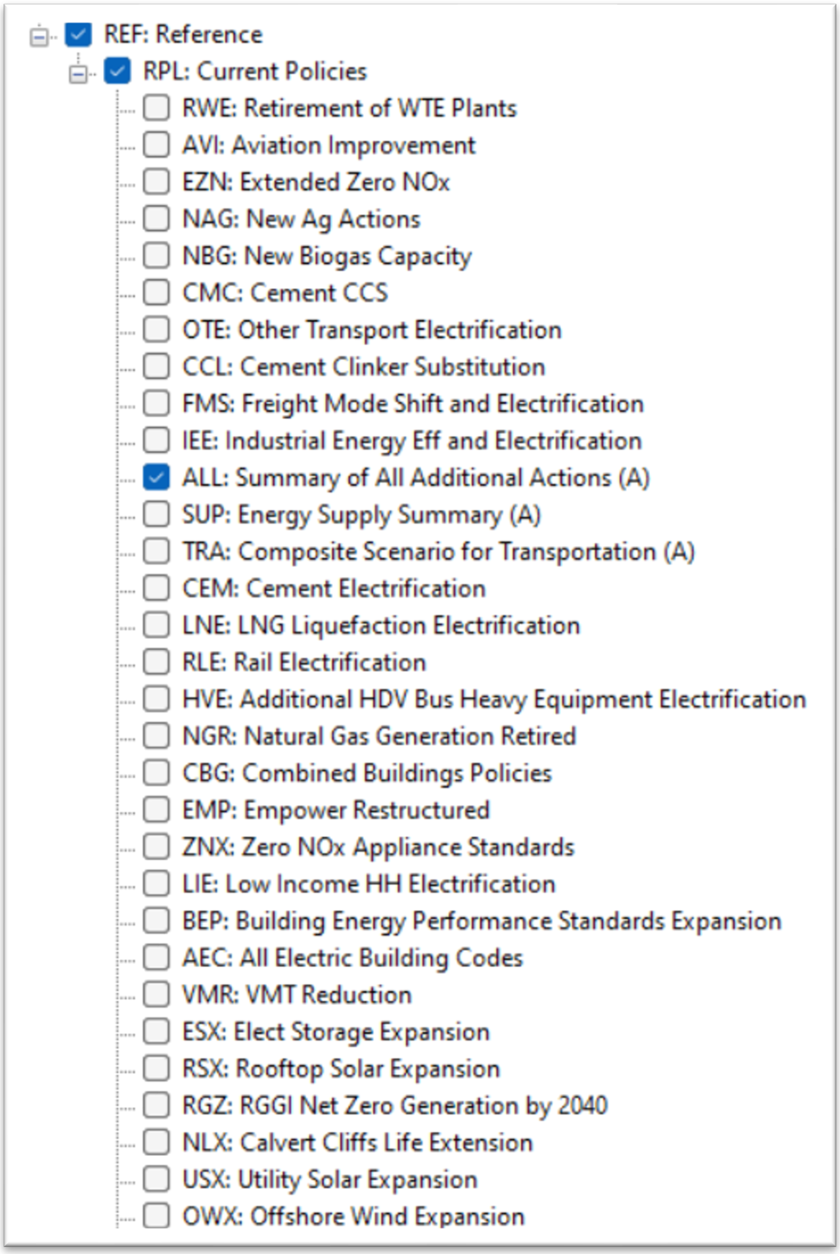
[16] There is a small amount of "green" hydrogen produced in the energy supply sector in the Current Policies and Additional Actions scenarios. The fuel produced is mostly consumed by hydrogen buses, as well as some trucks and other vehicles. This was a modeling design element to provide hydrogen fuel for vehicles already coming into the fleets, but not an explicit policy addition.

future, and is modified by the Current Polices case, as described in section 4 of the Technical Report. GHG emissions reduction actions are added to the Current Polices case to define emissions reduction scenarios. These scenarios specify future changes in the rate and/or extent of technology deployment in the energy sector and for non-energy sources of GHGs. A scenario in LEAP can include just one change in any future parameter in a single branch (fraction of sales, energy intensity, or cost, for example), or may specify many changes to multiple branches. As shown in Figure A-5, the Maryland LEAP dataset includes over 25 individual scenarios that are aggregated by sector, and then ultimately combined into the overall Additional Actions (ALL: Summary of All Additional Actions) case described in section 5 of the Technical Report.

Figure A-5: Scenarios in the Maryland LEAP Model



- ☑ REF: Reference
  - ☑ RPL: Current Policies
    - ☐ RWE: Retirement of WTE Plants
    - ☐ AVI: Aviation Improvement
    - ☐ EZN: Extended Zero NOx
    - ☐ NAG: New Ag Actions
    - ☐ NBG: New Biogas Capacity
    - ☐ CMC: Cement CCS
    - ☐ OTE: Other Transport Electrification
    - ☐ CCL: Cement Clinker Substitution
    - ☐ FMS: Freight Mode Shift and Electrification
    - ☐ IEE: Industrial Energy Eff and Electrification
    - ☑ ALL: Summary of All Additional Actions (A)
    - ☐ SUP: Energy Supply Summary (A)
    - ☐ TRA: Composite Scenario for Transportation (A)
    - ☐ CEM: Cement Electrification
    - ☐ LNE: LNG Liquefaction Electrification
    - ☐ RLE: Rail Electrification
    - ☐ HVE: Additional HDV Bus Heavy Equipment Electrification
    - ☐ NGR: Natural Gas Generation Retired
    - ☐ CBG: Combined Buildings Policies
    - ☐ EMP: Empower Restructured
    - ☐ ZNX: Zero NOx Appliance Standards
    - ☐ LIE: Low Income HH Electrification
    - ☐ BEP: Building Energy Performance Standards Expansion
    - ☐ AEC: All Electric Building Codes
    - ☐ VMR: VMT Reduction
    - ☐ ESX: Elect Storage Expansion
    - ☐ RSX: Rooftop Solar Expansion
    - ☐ RGZ: RGGI Net Zero Generation by 2040
    - ☐ NLX: Calvert Cliffs Life Extension
    - ☐ USX: Utility Solar Expansion
    - ☐ OWX: Offshore Wind Expansion

2.7 GHG Strategy Tool Implementation

CCS's Excel-based GHG Strategy Tool was used to reflect recent historical emissions and project future emissions from Maryland non-energy GHG sources. These sources are:

- **Industrial processes**, including:
    - Cement manufacturing, and specifically, the carbon dioxide released when limestone is heated to produce "clinker," the principal component of dry cement.
    - Other industrial uses of limestone (releasing CO_2).
    - Industrial (non-agricultural) uses of the chemical urea.[17]
    - Soda ash use (also releases CO_2).[18]
    - The use of substitutes for Ozone Depleting Substances (ODS) for industrial applications including refrigeration, air conditioning, and fire suppression. ODS substitutes are typically fluorine- and/or chlorine-containing chemicals with high global warming potentials.
    - Sulfur hexafluoride use in, and release from, electricity transmission and distribution systems.
- **Waste management** processes including:
    - Emissions of methane and CO_2 derived from wastes made of fossil carbon (mostly plastics) from landfills.
    - Emissions of methane from composting.
    - Emissions of methane and nitrous oxide (N2O) from wastewater treatment.
- **Forestry** and other land use emissions and sinks including:
    - Net sequestration of carbon in Maryland's forests (forest carbon flux).
    - Net emissions and sinks of carbon from mineral soils.
    - Emissions of methane and nitrous oxide from wildfires and prescribed burns.
- Emissions from the **agricultural sector** including:
    - Methane and nitrous oxide from management of livestock manures.
    - Methane from enteric fermentation in livestock.
    - Nitrous oxide from fertilizer application to agricultural soils.
    - Carbon dioxide from urea and lime applied to agricultural soils.
    - Methane and nitrous oxide emissions from agricultural burning.

In each of the above cases, the GHG Strategy Tool is used to estimate historical and future emissions of GHGs from non-energy sources based on key activities in the relevant sectors—such as acres of agricultural land cultivated, the extent of forests, volumes of waste treated, and use of industrial chemicals. The Tool is also used to estimate the impact in future years of several current policies and potential additional actions, as described below.

2.8 Modeling Considerations

Note that the modeling of Maryland's energy and non-energy GHG emissions described here has focused on transitions in the physical stocks, technologies, and usage of devices and processes, including devices such as residential appliances, commercial equipment, and vehicles, and processes such as industrial manufacturing and different types of electricity generation. This modeling, to date, has not tried to estimate the impact of primarily economic tools and polices, such as carbon dioxide cap-and-

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[17] Urea (CH_4N_2O) is widely used as a nitrogen fertilizer, but also as an industrial input.

[18] Soda ash is sodium carbonate (Na_2CO_3).

trade systems, carbon taxes, or other options that use economic levers to affect the behavior of individuals and organizations, and thus to reduce GHG emissions. These economic tools and policies could certainly be used to encourage the sorts of technological transitions included in the actions explored in the modeling described in this Report, but their estimated impacts are not modeled directly, as is done in other modeling approaches. However, economic variables are built into specific LEAP analysis expressions or assumptions, including prices, cost-benefit feedbacks, and macroeconomic influences. We have chosen to focus on modeling technological changes because those changes have a direct impact on energy use and non-energy emissions and can be more directly linked to required economic and financial costs and benefits required to bring about transitions in the stocks of energy-using and GHG-producing equipment. Econometric modeling, for example, of the response of consumer behavior to price change, is a useful complement to the accounting-based technological modeling we have undertaken in this study but has not been part of our focus.

Although electrification of demand sectors reduces direct emissions of GHG emissions from those sectors, the reductions in economy-wide emissions become greater as renewable energy sources are added to the electrical grid and reduce the carbon intensity of electricity generation. As a result, electrification-related emissions reductions achieved per unit of equipment replaced (for example, replacing gas-fired space heating systems with electrical heat pumps) are smaller in the near term than they are in the longer term.

3. Energy Demand Model Details

3.1 Buildings Sector: Residential and Commercial

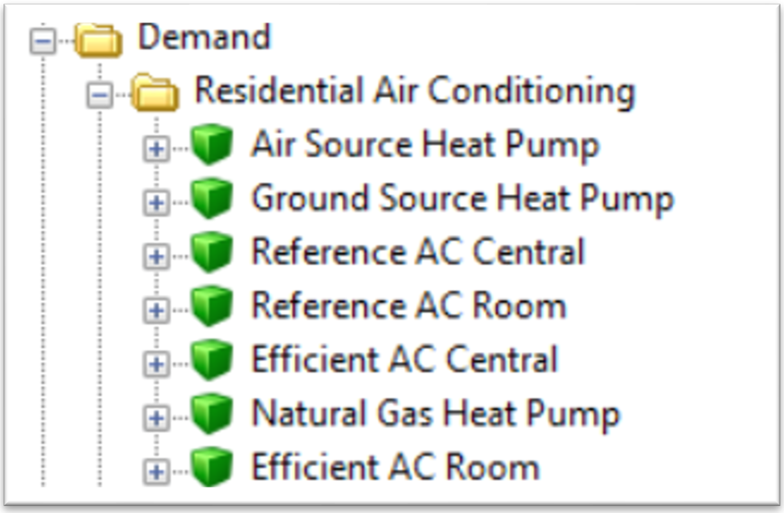
The Buildings, Facilities, and Industry sectors (also known as Demand in LEAP) are represented in the Maryland LEAP model by the following:

- 11 Residential end-use or related branches (such as Primary Space Heating, Lighting, and Other), each including an array of devices using different technologies and different fuels. Most of the Residential branches are modeled using a “stock modeling” approach in which sales of new devices are modeled to meet needs for new homes and to replace existing devices that have reached the end of their operating lives.
- Eight Commercial end-use or related branches, again each including an array of devices using different technologies and different fuels, again using stock models.
- Two branches (residential and commercial) to account for electricity savings provided through the Maryland utility-run EmPOWER energy efficiency programs, as described in sections 4 and 5 of the Technical Report.

Each of the end uses above is represented by a group of technologies. Technologies (or devices), include those currently used (for example, “Reference AC Room” in Figure A-6, which shows the detail of the Residential Air Conditioning branch) and those that could be used in the future (“Efficiency AC Room). For each residential end-use, the overall number of devices in Maryland is a function of the number of households in Maryland and the fractions of households with a given end use. For example, in 2021 an estimated 91 percent of Maryland households had air conditioning, 73.9 percent had dishwashers, and 34 percent had a second refrigerator. The growth assumed for the number of households in Maryland is the same in all scenarios, starting at about 2.25 million in 2021, and growing slowly to 2.63 million by 2050 (Figure A-7).[19]

The shares of each technology used, from the current stock of devices for each end use, are specified in the Maryland LEAP model, as well as the future sales shares, which can vary by scenario. Energy intensity is also specified—for example, the kWh used annually by room air conditioners for household with room air conditioners—and can also change over time. The future energy intensity improvements assumed for each type of technology/device vary by device and by end use, with, for example, residential refrigerators and freezers improving by 17 percent, air source heat pump space heating and water heating improving by 11 percent between 2021 and 2050, and resistance electric water heater improving by 6 percent over the same period. Figure A-8 shows an example of the estimated fractions of households using different types of primary space heat as of 2021.

Figure A-6: Technologies/Devices under Residential Air Conditioning in the Maryland LEAP Model



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[19] Uses composite MD Household projections for LEAP, based on household data and projections from [MD Dept. of Planning - MD State Data Center]() (through 2045). Assume linear trend in HH size to estimate for 2050 from population projection.

Figure A-7: Population and Household Growth Projections in the Maryland LEAP Model

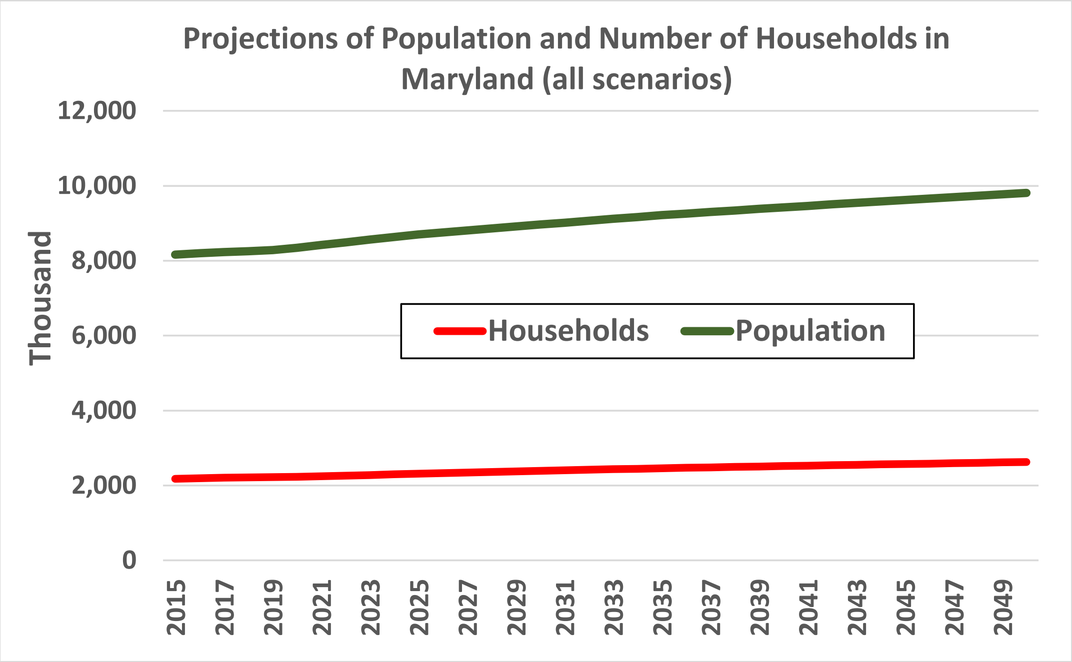
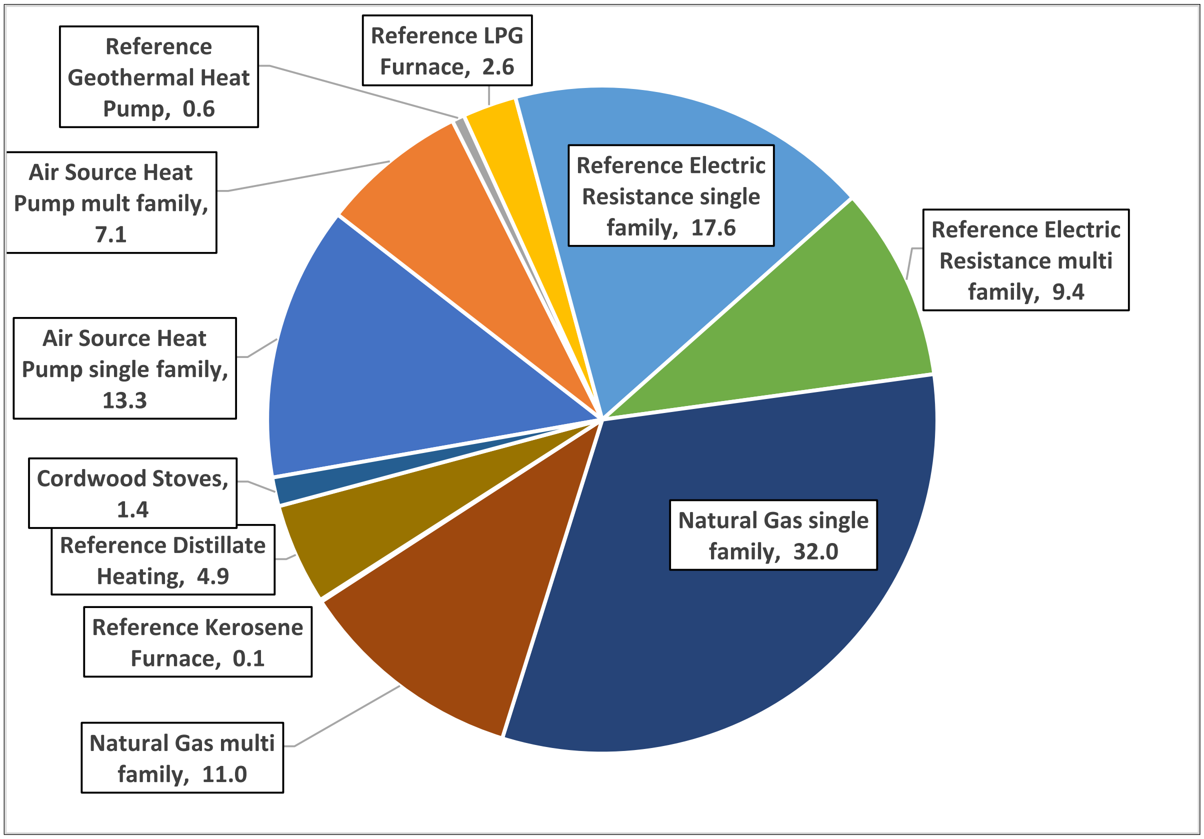
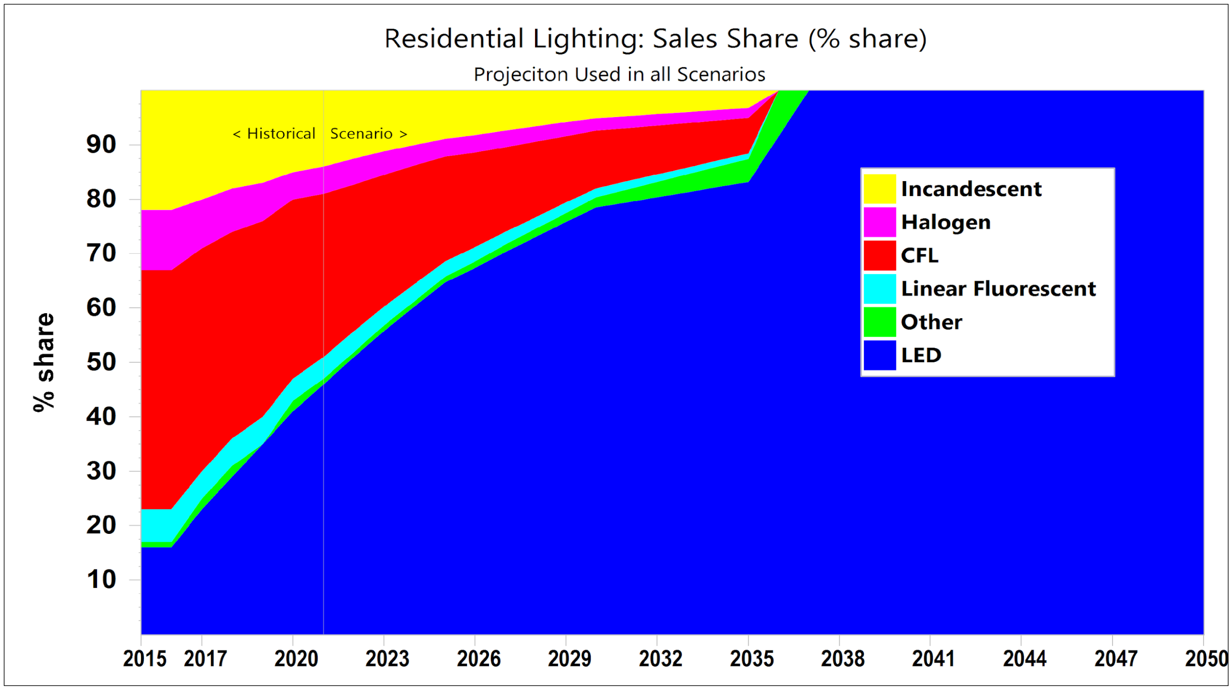


Figure A-8: Year 2021 Stock of Technologies/Devices under Residential Primary Space Heating in the Maryland LEAP Model (values shown are percent of households using each device)



Residential lighting has seen a vast change in technologies over the last two decades, with incandescent lamps largely replaced by compact fluorescent lamps, and both types replaced by lamps based on light-emitting diode (LED) technologies, which are continuing to evolve rapidly. The penetration of LEDs into the market has been responsible for a significant increase in energy efficiency in lighting in Maryland, driven in part by the EmPOWER utility energy efficiency programs. Within about a decade, the transition of the residential market to LED lighting is assumed to be essentially complete under all future scenarios, as shown in Figure A-9.

Figure A-9: Projection for Sales Shares of Lighting Technologies in the Residential Sector (all scenarios)



In the commercial sector, which includes most institutional and government buildings, overall activity is driven by growth in building floor area. Building floor area in Maryland is project to grow slowly, at the same rate as statewide population, increasing from 1.42 billion square feet in 2021 to 1.65 billion square feet in 2050 (Figure A-10). Other parameters, including energy intensity and costs, are thus expressed per unit of floor area, and sales shares refer to the share of floor area for each end use that particular technologies are used for.

The types of technologies included in commercial end-uses are in some cases somewhat more varied than in the residential sector, as they may depend on the types of businesses where they are installed. Commercial refrigeration, for example, includes the different types of cooling applications shown in Figure A-11, which presents the estimated share of device stocks per unit of overall commercial floorspace.

As in the residential sector, commercial lighting is in the process of becoming dominated by LED lighting technologies, as shown in Figure A-12.

Figure A-10: Projection of Maryland Commercial Building Area (all scenarios)

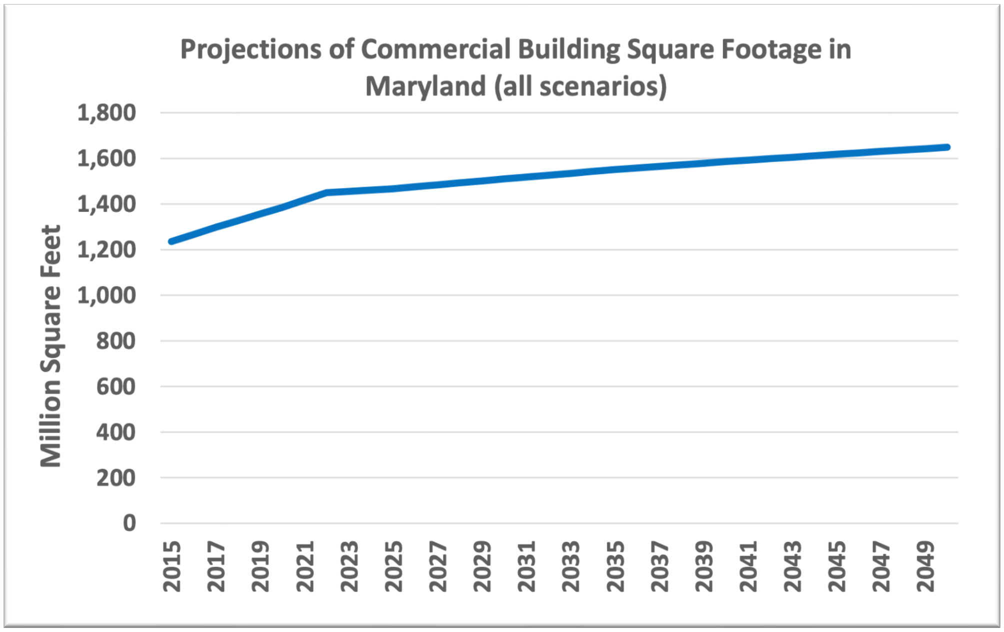


Figure A-11: Year 2021 Stock of Technologies/Devices under Commercial Refrigeration Heating in the Maryland LEAP Model (values shown are percent of refrigeration use by technology)

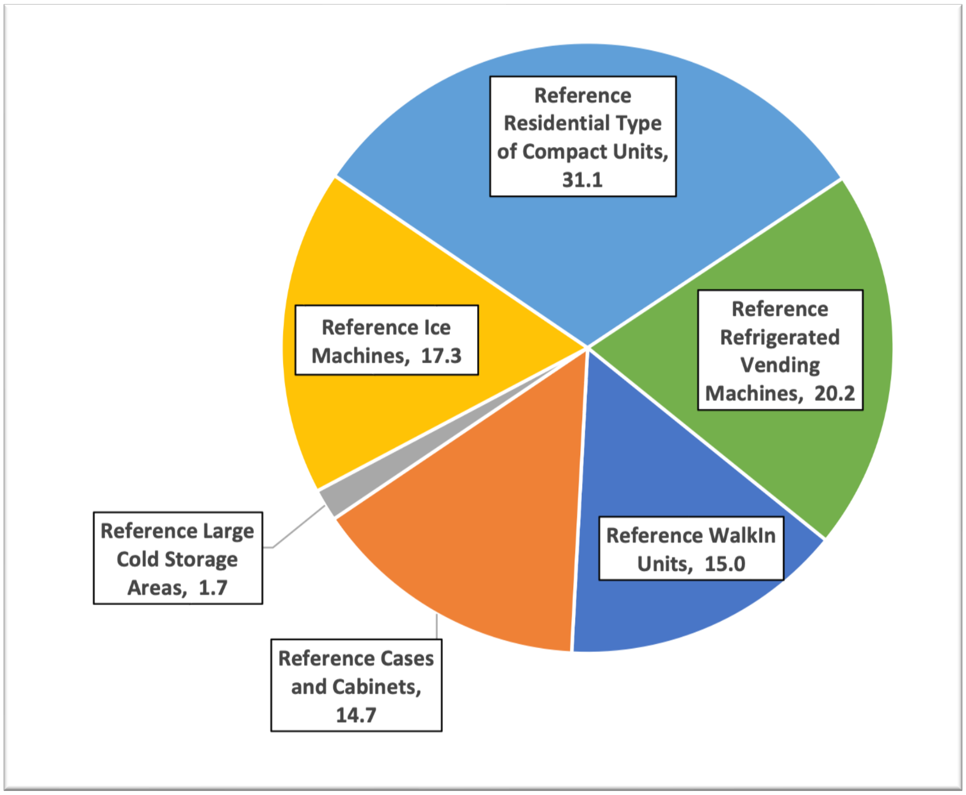
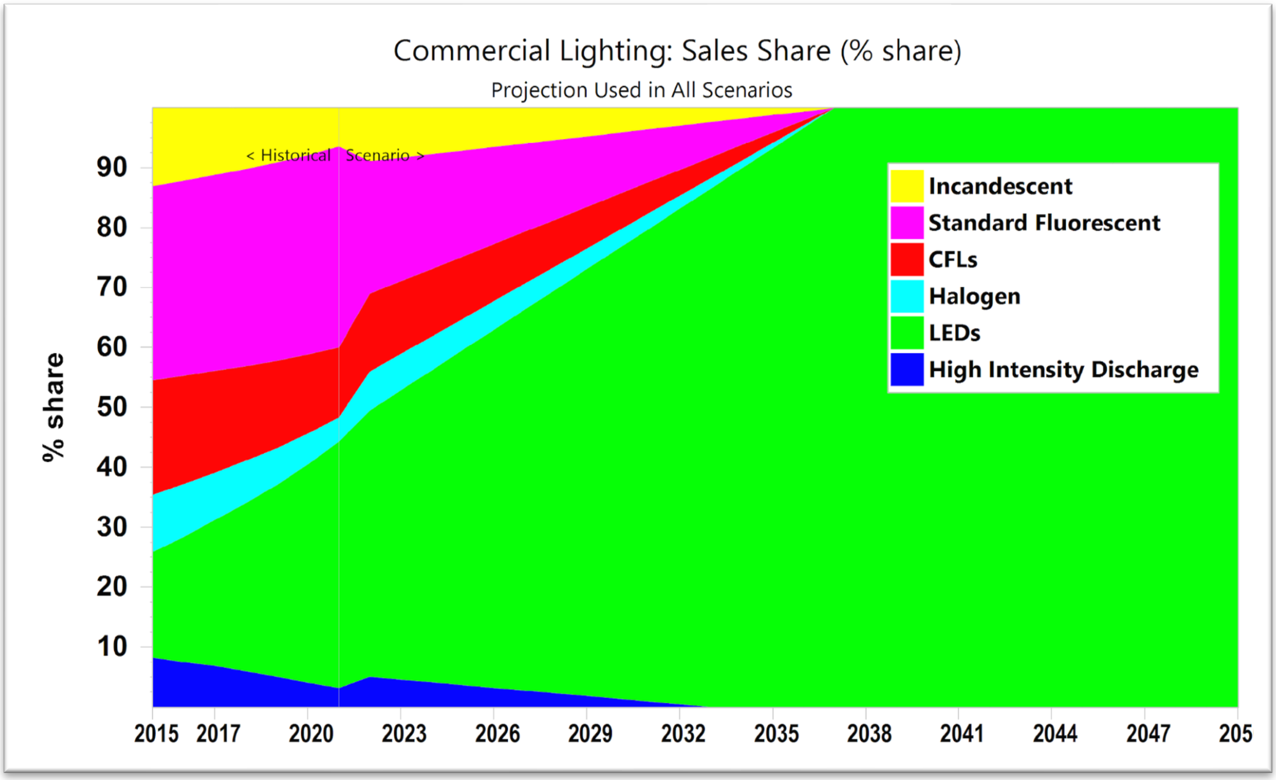


Figure A-12: Projection for Sales Shares of Lighting Technologies in the Commercial Sector (all scenarios)



3.2 Transportation sector

The Transportation sector in the Maryland LEAP model includes “branches” for Light Duty Autos, Light Duty Trucks (together, light duty vehicles, or LDV), Heavy Duty Vehicles (HDV), school buses, and transit and other buses, each of which is modeled on a stock turnover basis. The Transportation sector also includes a category called “Other,” which includes motorcycles and e-bikes, aviation, rail freight transport, shipping (vessel bunkering, which includes fuel transferred to ships, mostly in the Port of Baltimore), outdoor (lawn and garden) equipment, recreational equipment, the under-implementation Purple Line (connecting with the Metro system centered in the District of Columbia), other passenger rail in Maryland (Amtrak and MARC, or Maryland Area Rail Commuter), and a category covering equipment for electric vehicle charging and light duty vehicle fueling (gasoline and diesel vehicles).[20] The Maryland LEAP model categories for transportation-sector energy use are shown in Figure A-13. Most of these categories, as shown in the light duty autos example in Figure A-14, include multiple types of technologies, such as conventional gasoline or diesel vehicles or devices, battery electric, and plug-in hybrid vehicles, each of which can have multiple input fuels.

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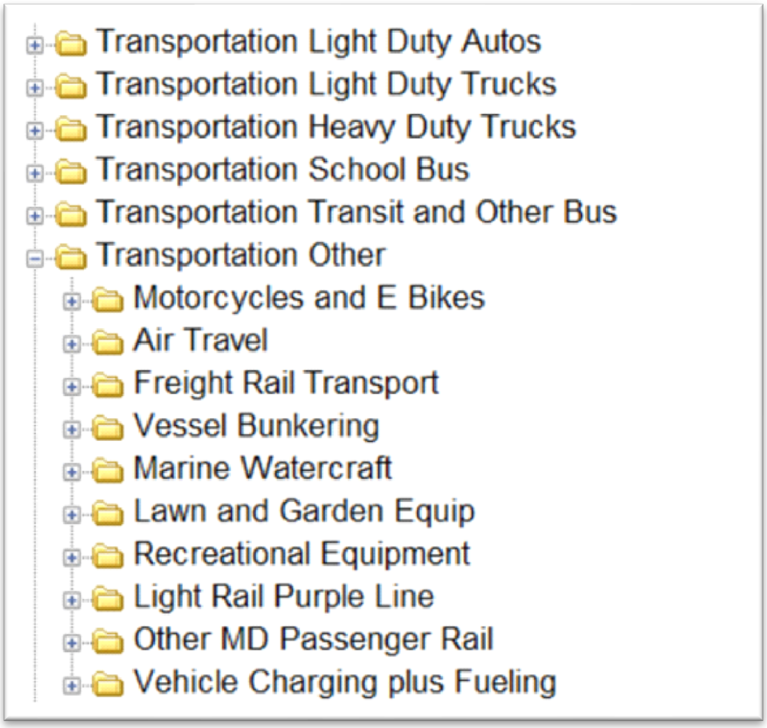
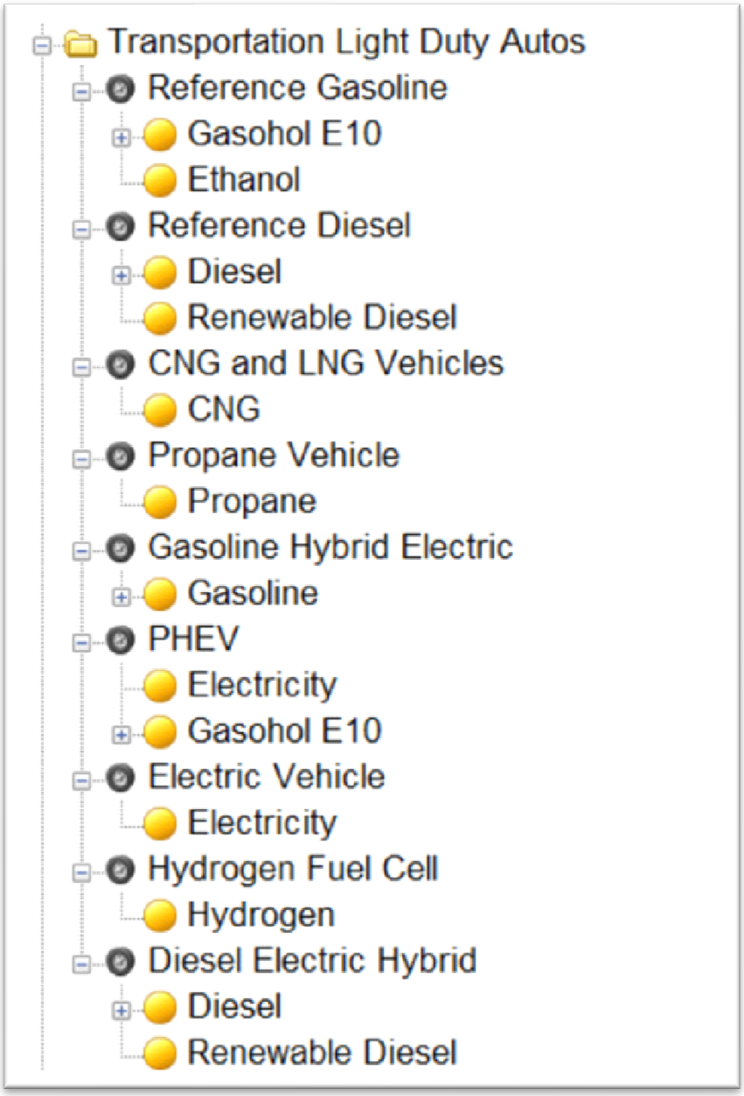
[20] Note that the vehicle changing plus fueling branch in the Maryland LEAP dataset is inserted to track the costs of fueling and charging equipment but does not model energy use (or losses) by charging equipment. Losses in the charging process for electric vehicles are typically built into estimates of vehicle fuel economy/energy intensity, expressed as kWh per mile or miles per gallon of gasoline equivalent, for example.

Figure A-13: Transportation Sector "Branches" in Maryland LEAP Model



- Transportation Light Duty Autos
- Transportation Light Duty Trucks
- Transportation Heavy Duty Trucks
- Transportation School Bus
- Transportation Transit and Other Bus
- Transportation Other
  - Motorcycles and E Bikes
  - Air Travel
  - Freight Rail Transport
  - Vessel Bunkering
  - Marine Watercraft
  - Lawn and Garden Equip
  - Recreational Equipment
  - Light Rail Purple Line
  - Other MD Passenger Rail
  - Vehicle Charging plus Fueling

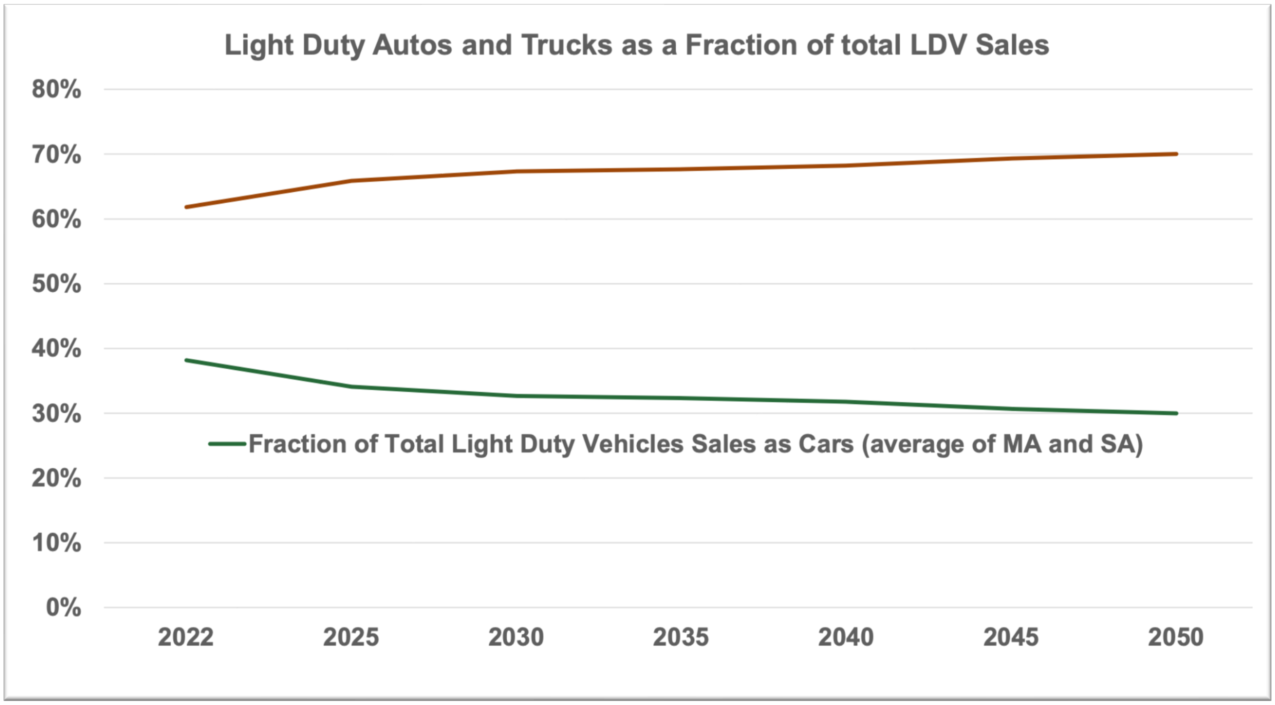
Figure A-14: Examples of Individual Technologies Included in Transportation Sector "Branches" in Maryland LEAP Model



- Transportation Light Duty Autos
  - Reference Gasoline
    - Gasohol E10
    - Ethanol
  - Reference Diesel
    - Diesel
    - Renewable Diesel
  - CNG and LNG Vehicles
    - CNG
  - Propane Vehicle
    - Propane
  - Gasoline Hybrid Electric
    - Gasoline
  - PHEV
    - Electricity
    - Gasohol E10
  - Electric Vehicle
    - Electricity
  - Hydrogen Fuel Cell
    - Hydrogen
  - Diesel Electric Hybrid
    - Diesel
    - Renewable Diesel

Except for the different branches of the "Other Transportation" category, the Maryland LEAP model tracks current and future stocks and sales of vehicles of different types. Starting with base-year stocks of vehicles, including the total number of vehicles of different types (light duty autos, or LDA, and light duty trucks plus SUVs, or LDT, for example) and the fraction of vehicle stocks that use different technologies and/or fuels, sales fractions for the different vehicle technologies, which can change over time, are used to drive changes in vehicle stocks. As vehicles age, they are replaced by new vehicles in proportions dictated by sales fractions, by technology. Additional growth in new (as opposed to replacement) light duty vehicles sales is assumed to occur as a function of population growth in Maryland. Overall stocks of LDVs are assumed in all scenarios to grow with Maryland's population, at a constant rate of 776 LDVs per 1000 people in the state through 2050, and the fraction of LDVs made up of LDTs (including the SUV class of vehicles) is assumed to rise from 62 to 70 percent of sales by 2050, based on the average of sales fractions for the Mid Atlantic and South Atlantic regions for the AEO2023 reference case. The trend in the fraction of LDVs accounted for by LDAs and LDTs as used in the Maryland LEAP model is shown in Figure A-15.

Figure A-15: Fraction of Light Duty Vehicles as Autos and Trucks/SUVs



Energy use by the different types of vehicles included in the Maryland LEAP model, and by vehicles using different types of technologies within each vehicle class, is modeled as the product of the number of vehicles in the fleet in any given year, the fuel economy of each type of vehicle, which varies by year, and the number of miles traveled by each type of vehicle (VMT). The VMT assumptions for vehicles were assumed to be the same across each vehicle class, such that, for example, electric LDAs were assumed to, on average, travel the same distance each year as gasoline fueled LDAs. Although LDV annual vehicle miles traveled were assumed to start from historical 2021 values derived from Maryland-specific data, growth in VMT in the model was assumed to follow the same rate as in the national AEO2023 Reference case projections, resulting in 9.5 percent overall growth in VMT per LDV between 2022 and 2050.[21] The fuel economy assumptions used for LDAs and LDTs in all scenarios, as derived from AEO2023 Reference case data, are presented in Figure A-16 and Figure A-17.[22]

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[21] Trends in annual LDV VMT are modified slightly in the Current Policies case through reductions due to use of e-bikes, as the e-bike fleet grows, and of the Purple Line, once it has been completed (see section 4 of the Technical Report), and much more significantly in the Additional Actions case through a set of measures designed for VMT reduction, as described in section 5.

[22] Note that one possible action not modeled in the scenarios presented below would be to raise fuel economy requirements for Maryland beyond those projected in the AEO2023 Reference case. As Maryland is a small part of the national, and indeed global, market for light-duty vehicles, this type of action might prove difficult to implement, but could be investigated.

Figure A-16: Fuel Economy Assumptions for Light Duty Autos by Type, 2022-2050

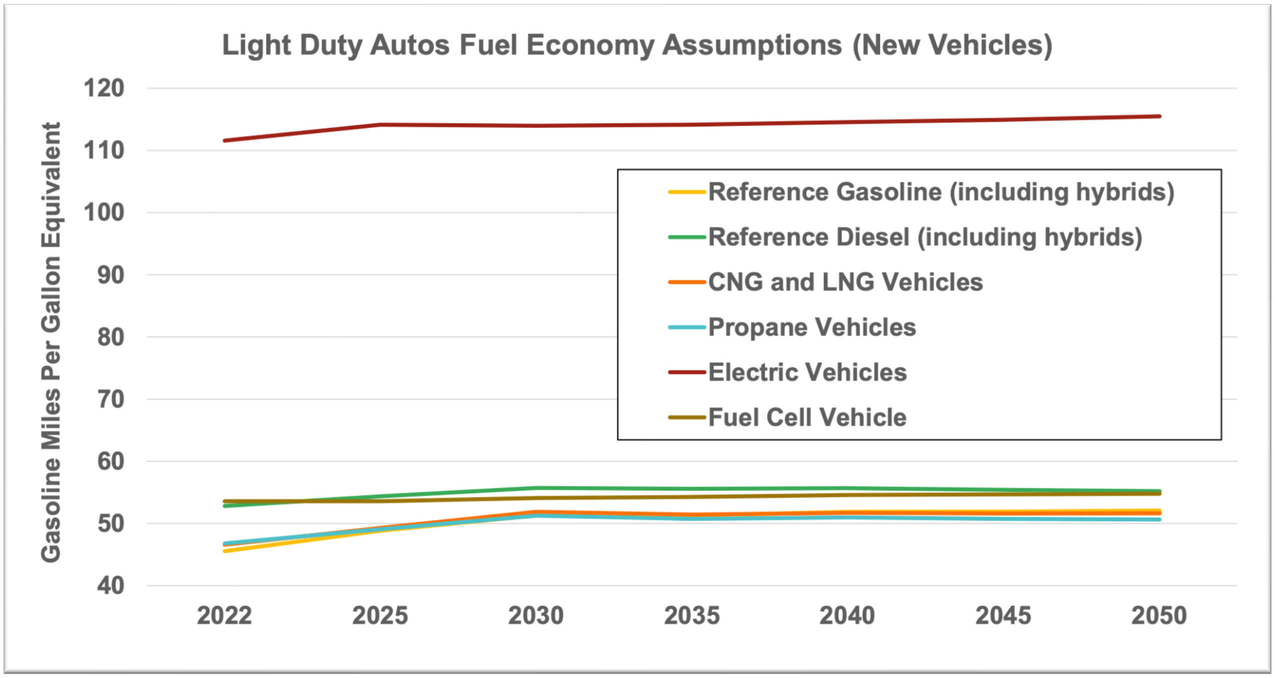
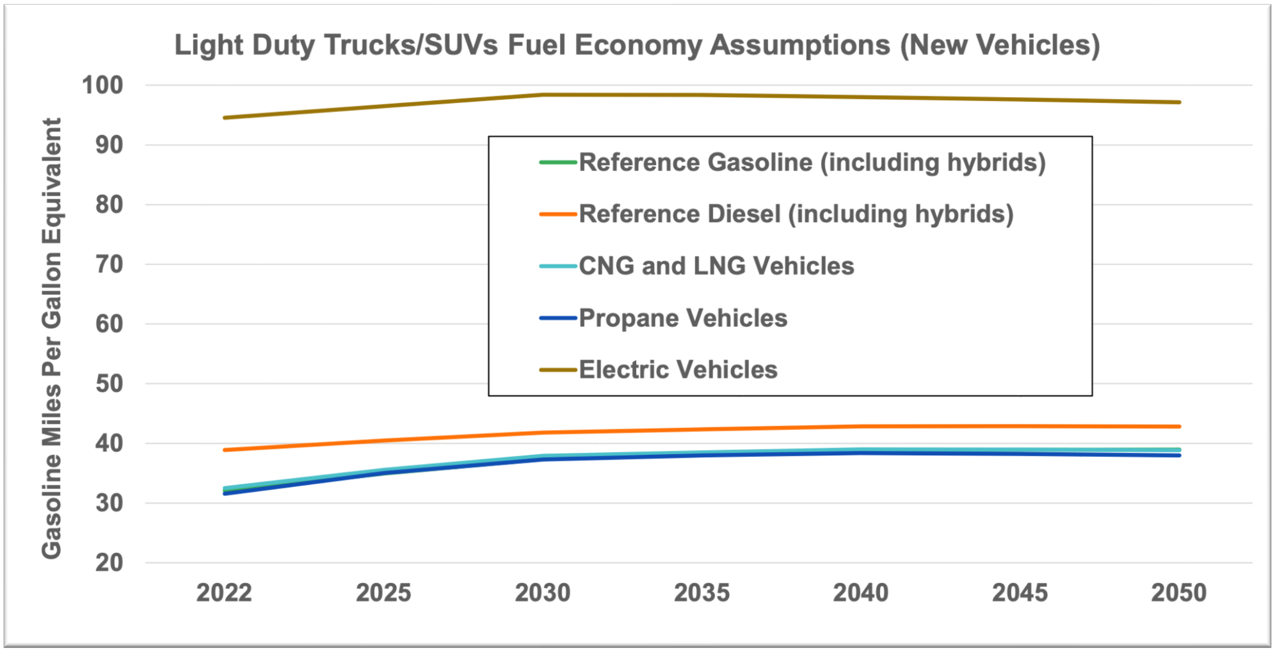


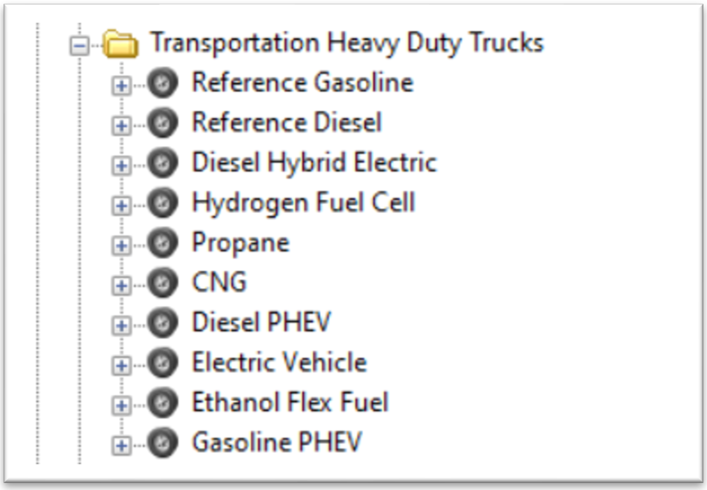
Figure A-17: Fuel Economy Assumptions for Light Duty Autos by Type, 2022-2050



For **heavy duty trucks**,[23] underlying assumptions include:

- Annual VMT per vehicle decreases from an average of over 26,000 miles in 2022, to just under 22,000 miles in 2050. This trend is modified in the Additional Actions scenario, as described in section 5 of the Technical Report.
- Overall fuel economy for most types of heavy trucks is assumed to improve by about 17 percent between 2025 and 2050, based on AEO2023 reference case results.
- Fuel economy for electric heavy trucks was estimated based on an average ratio of diesel to electric fuel economy of 3.5, although as the electric truck industry continues to mature, this value may rise. A California Air Resources Board document suggests that the ratio between the efficiencies of electric and diesel trucks, based on road tests, falls in the range between about 5 for lower-average-speed operation, and about 3.3 for higher average speed operation.[24] Thus, in practice, the relative efficiency of diesel and electric trucks will vary based on the type of trucks considered and how they are used.
- Hydrogen-, propane (or liquefied petroleum gas, LPG)-,[25] and compressed natural gas (CNG)-fueled trucks make up, at maximum, just over 1 percent of truck sales in all scenarios. Figure A-18 shows the types of heavy trucks included in the model.

Figure A-18: Types of Heavy-Duty Trucks Included in the Maryland LEAP Model



- Transportation Heavy Duty Trucks
  - Reference Gasoline
  - Reference Diesel
  - Diesel Hybrid Electric
  - Hydrogen Fuel Cell
  - Propane
  - CNG
  - Diesel PHEV
  - Electric Vehicle
  - Ethanol Flex Fuel
  - Gasoline PHEV

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[23] "Heavy duty trucks" in the LEAP model encompass all trucks that are not light-duty trucks, and thus span, for example, the AEO2023 categories "Light Medium," "Medium," and "Heavy" trucks. Of those three, heavy duty trucks consume on the order of 80 percent of the fuel used by the sum of the three sub-classes. See, for example, AEO2023 results, Table 7: "Transportation Sector Key Indicators and Delivered Energy Consumption".

[24] California Air Resources Board (CARB, 2018), *Battery Electric Truck and Bus Energy Efficiency Compared to Conventional Diesel Vehicles*, dated May 2018. CCS initially calculated estimates for reference fuel economy values for electric heavy trucks based on weighted average new vehicle fuel economy for 2022 and on from AEO2023, but those values ultimately looked very low both in the near and further term relative to diesel fuel economy, with electric fuel economy about 1.5 times diesel fuel economy.

[25] LPG, or liquefied petroleum gas, is a mixture of mainly the light hydrocarbons propane and butane, with small fractions of other hydrocarbons. In practice, although not quite accurately, the terms "LPG" and "propane" are used interchangeably to refer to the same petroleum product.

The Maryland LEAP model includes categories for **two types of bus transport**: school bus transport and transportation on transit and other buses. Categories for electric, CNG, hydrogen, gasoline, and diesel buses are included for both types of buses. The estimated number of school buses in the state, which was 7,200 as of 2021,[26] is assumed to increase at the rate of population growth in Maryland; thus, slow growth. School bus VMT per year is assumed to stay constant through the modeling period, at about 13,000 per vehicle per year.[27] An average operating life of 12 years is assumed for school buses.[28] For transit and other buses, the total fleet number was estimated by subtracting the number of school buses from the overall bus fleet totals in Maryland, as reported by the USDOT Federal Highway Administration, yielding just over 15,000 transit and other buses in the state.[29] The annual VMT traveled by other buses is also assumed to stay the same in all scenarios, at about 21,000 miles per vehicle per year.

The "Transportation Other" category in the Maryland LEAP model includes a variety of transportation modes beyond the vehicle categories described above. These transportation modes and related end-uses (Figure A-19), most currently supplied by fossil fuels, are not modeled based on vehicle sales and turnover similar to cars, trucks, and buses, but as overall categories of energy use by fuel, in which activities and fuel shares change over time. These categories include:

- **Motorcycles and e-bikes** include gasoline and electric motorcycles, and battery-electric bicycles. The total number of motorcycles registered in Maryland fell somewhat between 2015 and 2021, and the total reported vehicle miles traveled on motorcycles fell dramatically over the same period, for unclear reasons. We assume a slow increase in the total motorcycle VMT through 2050 in all scenarios, and a significant (about 30%) improvement in fuel economy, following AEO2023 trends. The energy intensity of e-bikes is set at a constant 0.0136 kWh per vehicle mile in all scenarios, although, in practice, there are many different e-bike models with different specifications.

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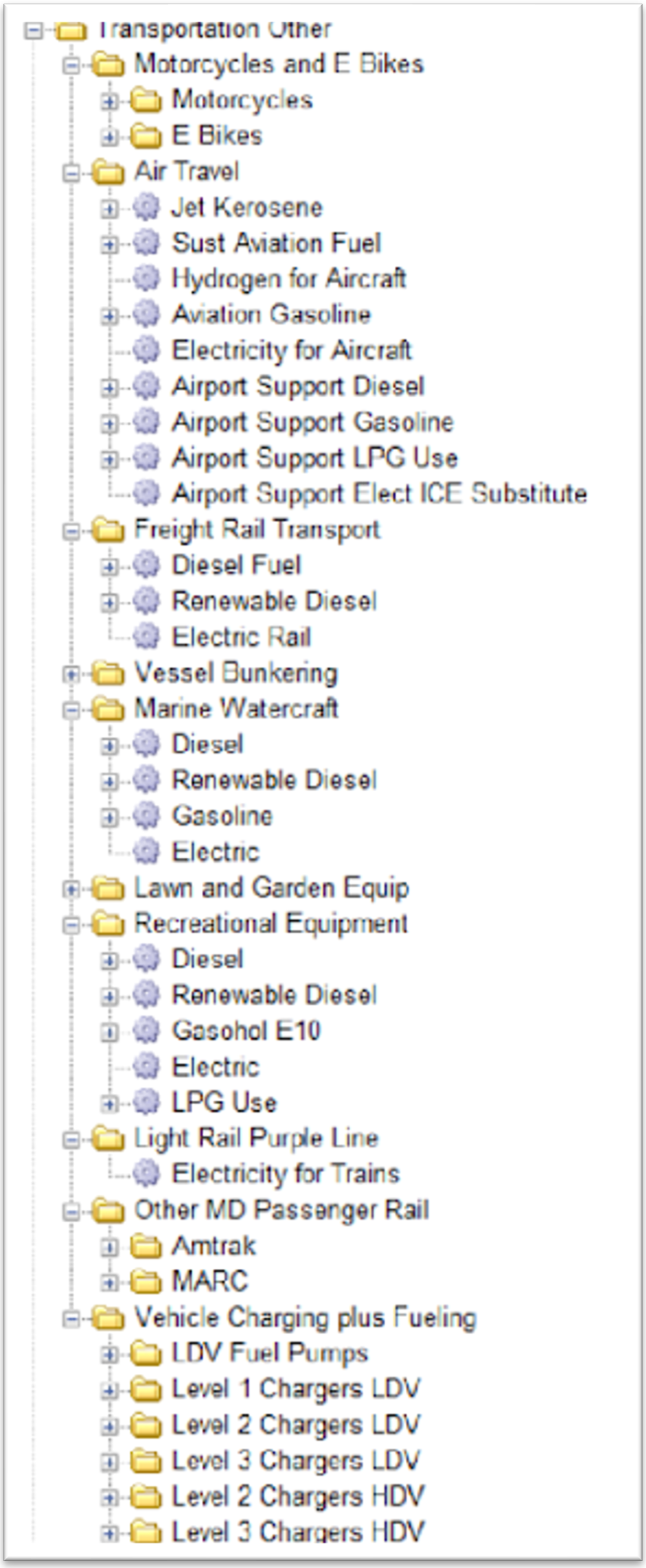
[26] See Maryland Matters (2023), "Opinion: Time for Maryland kids to get on the electric school bus," April 4, 2023.

[27] We assume, based on a national NREL study, that the average school bus in MD travels 73.46 miles per (operating) day (based on Adam Duran and Kevin Walkowicz (2013), "A Statistical Characterization of School Bus Drive Cycles Collected via Onboard Logging Systems," SAE 2013 Commercial Vehicle Engineering Congress). Assuming an average school year of 180 days (MD Public School Opening and Closing Dates) and a Maryland school bus population of 7200, implied total MD school bus vehicle miles are about 95.20 million annually, and 13,223 miles per bus per year, which further implies that 20% of total 2019 (or 2021/2022) bus VMT as used in LEAP. We assume that 2020 school bus use was about 33% of this total due to COVID closures, or 4,364 miles per year, based on school closures (see, for example, MD State Dept of Education (2020), "Maryland Local Education Agencies (LEA) Reopening Plans Archive"). All of these figures are rough estimates and should at some point be revisited in consultation with Maryland transportation authorities.

[28] In general, in the Maryland LEAP model, stock modeling of vehicles applies a "survival profile" that indicates what fraction of vehicles of a given vintage are still on the road after a certain number of years. As a consequence, for example, not all school buses put into service in 2030 will be retired at once in 2042; some will be retired earlier, and some later.

[29] See, for example, US DOT Federal Highway Administration (2021), "Highway Statistics Series, Highway Statistics 2020, State Motor-Vehicle Registrations – 2020." Note that these "other" buses doubtless encompass a range of types of uses, from, for example, transit buses plying regular routes through Maryland cities and counties to coaches used on a for-hire basis. Additional information from the MD DOT and/or other agencies on bus fleets and how they are used would be helpful in improving the existing model of bus use in Maryland.

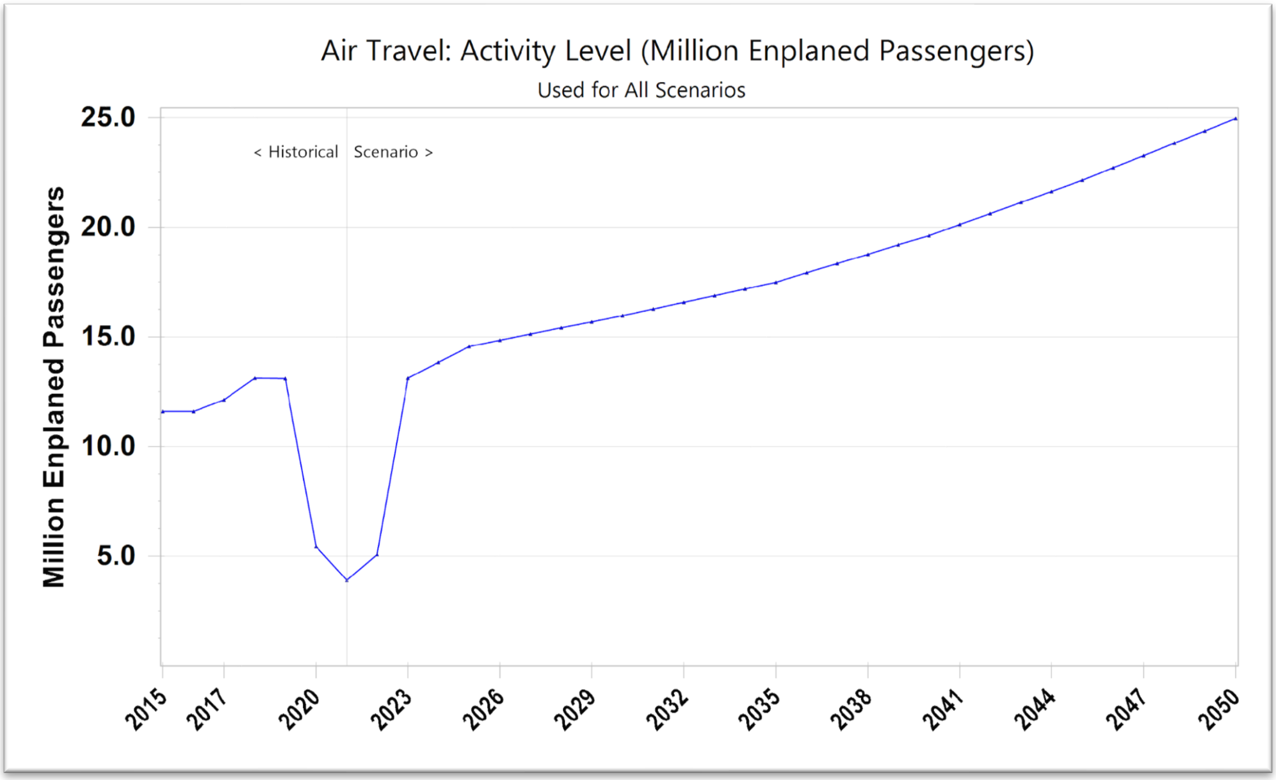
Figure A-19: Other Transportation and Related Branches in the Maryland LEAP Model



- Transportation Other
  - Motorcycles and E Bikes
    - Motorcycles
    - E Bikes
  - Air Travel
    - Jet Kerosene
    - Sust Aviation Fuel
    - Hydrogen for Aircraft
    - Aviation Gasoline
    - Electricity for Aircraft
    - Airport Support Diesel
    - Airport Support Gasoline
    - Airport Support LPG Use
    - Airport Support Elect ICE Substitute
  - Freight Rail Transport
    - Diesel Fuel
    - Renewable Diesel
    - Electric Rail
  - Vessel Bunkering
  - Marine Watercraft
    - Diesel
    - Renewable Diesel
    - Gasoline
    - Electric
  - Lawn and Garden Equip
  - Recreational Equipment
    - Diesel
    - Renewable Diesel
    - Gasohol E10
    - Electric
    - LPG Use
  - Light Rail Purple Line
    - Electricity for Trains
  - Other MD Passenger Rail
    - Amtrak
    - MARC
  - Vehicle Charging plus Fueling
    - LDV Fuel Pumps
    - Level 1 Chargers LDV
    - Level 2 Chargers LDV
    - Level 3 Chargers LDV
    - Level 2 Chargers HDV
    - Level 3 Chargers HDV

- **Air travel energy use**, most of which, in Maryland, takes place at the Baltimore Washington International Airport (BWI). Air travel energy use includes jet kerosene (standard and "sustainable aviation fuel"), aviation gasoline, and, in the future, hydrogen and electricity for planes, as well as fuels used for ground support activities. All these fuel uses are expressed in units of enplaned passenger, that is, per passenger arriving or departing. The use of fuel for airplanes at Maryland airports is derived from the amount of fuel reported to be used at those airports. As such, the amount of fuel used may differ from the fuel actually consumed by the aircraft landing at and departing from Maryland and is certainly different from the amount of fuel consumed on the ground in Maryland and in Maryland airspace. However, the fuel disbursed at Maryland airports contributes to the Maryland economy and is thus the measure used here. The number of enplaned passengers traveling from Maryland airports is assumed to grow at approximately the rate of overall US air travel growth included in the AEO2023 Reference case, with an increase of about 70 percent between 2023 and 2050 (Figure A-20), following the recovery of the airline industry from the sizable decrease in traffic during the COVID-19 pandemic. All types of air travel-related fuel use are assumed to scale with the increase in the number of enplaned passengers.

Figure A-20: Air Travel Activity in the Maryland LEAP Model



- Rail freight energy use is estimated based on rail freight activity denominated by tons of freight shipped into, out of, and within Maryland, as estimated using the national Freight Analysis

Framework (FAF).[30] These values were used with USDOE EIA data on "Maryland Total Distillate Sales/Deliveries to Railroad Consumers" to estimate Maryland-specific energy intensities.[31] FAF modeling results project an increase in rail freight transport in Maryland of somewhat less than 10 percent by 2050, with most of that increase occurring after 2045. The energy intensity of freight rail diesel use was projected based on national trends included in the AEO2023 Reference case, improving (energy intensity declining) by about three percent from 2022 to 2050.

- Emissions from **vessel bunkering** for distillate (diesel) fuel and residual oil are based on the quantities of general cargo shipped, based on Maryland Port Authority statistics, and the quantities of fuel delivered for bunkering (for supply to ships).
- The **marine watercraft** category echoes a similar category in the MDE GHG Inventory. It is not clear to us whether this category includes both smaller commercial vessels and recreational watercraft, but we assume it includes both. Energy use in the category is derived from MDE inventory data, and future activity is scaled to the growth in Maryland's population. The efficiency of marine watercraft is assumed to improve following AEO2023 trends for "Recreational Boats," resulting in an improvement of about 21 percent between 2022 and 2050.
- Similarly, historical energy use in the **lawn and garden equipment** and **recreational equipment** branches are based on data found in the MDE GHG Inventory. Energy use by fuel in both branches is assumed to grow with Maryland's population, and accounts for use of diesel, gasoline, and LPG, with "Electricity Replacing Gasoline" added to model the transition. This transition is already well underway for lawn and garden equipment, and beginning for recreational equipment, from mostly gasoline-powered to battery electric equipment. We assume that the efficiency of gasoline-powered equipment improves at the same rate as marine watercraft, above.
- The **light rail Purple Line** is modeled as an all-electric addition to transportation energy use, with a rough estimate of the total annual vehicle miles traveled by purple line trains derived based on public information. See the descriptions of Purple Line activity in the descriptions of the Current Policies and Additional Actions scenario provided in sections 4 and 5 of the Technical Report. Purple Line energy intensity is assumed to be about 5.9 kWh per vehicle mile, based on a Siemens study of a light rail installation in Switzerland, adjusted for the relative capacity of the example and Purple Line trains.[32]
- **Other Maryland passenger rail** includes categories for the US passenger rail system, Amtrak, and for MARC, the Maryland Area Rail Commuter. Amtrak is currently all-electric in its routes in Maryland, while MARC runs a combination of electric (on the "Penn Line") and diesel trains. In

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[30] Maryland results from FAF downloaded from ORNL (2023), "Freight Analysis Framework Version 5.".

[31] Given the substantial variation in distillate sales in MD for rail use from year to year reported in the last several years by USDOE EIA, it seems likely that the variation is less due to changes in activity and more due to changes in stocks, as these volumes of fuel use may not represent very many annual deliveries to rail fuel storage yards, particularly if shipments are received by sea to locations like the oil storage terminal on Baltimore's waterfront.

[32] Estimate energy use per vehicle-mile based on the following: "A Siemens study of Combino light rail vehicles in service in Basel, Switzerland over 56 days showed net consumption of 1.53 kWh/vehicle-km, or 5.51 MJ/vehicle-km. Average passenger load was estimated to be 65 people, resulting in average energy efficiency of 0.085 MJ/passenger-km. The Combino in this configuration can carry as many as 180 with standees. 41.6% of the total energy consumed was recovered through regenerative braking," from ChemEurope (undated), "Fuel efficiency in transportation". Assuming that kWh/vehicle-km scales with capacity, we estimate the energy use of Purple Line light rail as 5.869 kWh/vehicle-mile. This assumption should be confirmed/updated through consultations with Purple Line planners.

both cases, train energy efficiency, measured in energy use per vehicle mile, is assumed to decline slowly (at 0.25 percent per year) over the modeling period.

- The **vehicle charging plus fueling** branch includes sub-branches for fuel pumps in conventional gas stations for (mostly) light duty vehicles, plus branches for level 1 (110 volt) residential chargers, level 2 (240 volt) residential and commercial chargers, level 3 (480-volt direct current, or DC) commercial chargers, each for LDVs, and level 2 and level 3 charger branches for heavy duty vehicles. Energy losses in the charging process are not tracked in the model, as they are typically included in electric vehicle efficiency estimates. These branches are therefore used to track the requirements and costs for fueling and charging infrastructure, with the number of fuel pumps and chargers scaling with the number of gasoline/diesel and electric vehicles in the LDV fleet, and the number of electric vehicles in the HDV fleet, respectively. We assume that the Maryland LDV electric vehicle fleet is serviced by 0.7 home chargers per vehicle (25% level 1, with the rest level 2) and 0.1 commercial chargers (public or in apartment parking garages, for example) per LDV electric vehicle, of which 90 percent are level 2 and 10 percent level 3.[33] For each electric HDV truck and bus, we assume 0.2 chargers, of which half of the chargers for trucks are level 2, with the rest level 3, and 90 percent of the chargers for buses are level 2 (overnight), with the rest level 3.

3.3 Industrial sector

As Maryland has a relatively limited heavy industrial sector, with, for example, no remaining primary steel production plants, the industrial sector is not a major GHG emitter in Maryland, accounting for less than 3 $MTCO_2e$ of GHG emissions from energy use in 2021. Energy use and associated emissions in the sector are modeled in LEAP as two subsectors, the cement sector, and all other industrial energy use, described as “Other Manufacturing,” The branch structure for the industrial sector in the LEAP model is shown in Figure A-21.

There are two active cement plants in Maryland, Lehigh and Holcim, jointly producing on the order of 3 million tons of cement annually. The modeling of cement production emissions from energy use is further split into thermal energy use, largely for use in kilns converting limestone into “clinker,” the main active compound in cement. Cement energy use is driven by assumed growth in cement production. Cement production in Maryland is assumed to grow modestly over the modeling period, reaching over 3.3 million tons per year by 2050.[34] Thermal fuels for cement include coal, natural gas, and some waste-derived fuels, such as biosolids (a byproduct of sewage treatment processes) and used tires, although the use of waste fuels has been substantially phased out in recent years. Non-thermal energy use categories used in cement industry modeling include electricity for cement processing and other end-uses, mostly electric motors, and electricity for powering of carbon capture and storage systems, which are included in the Additional Actions case.

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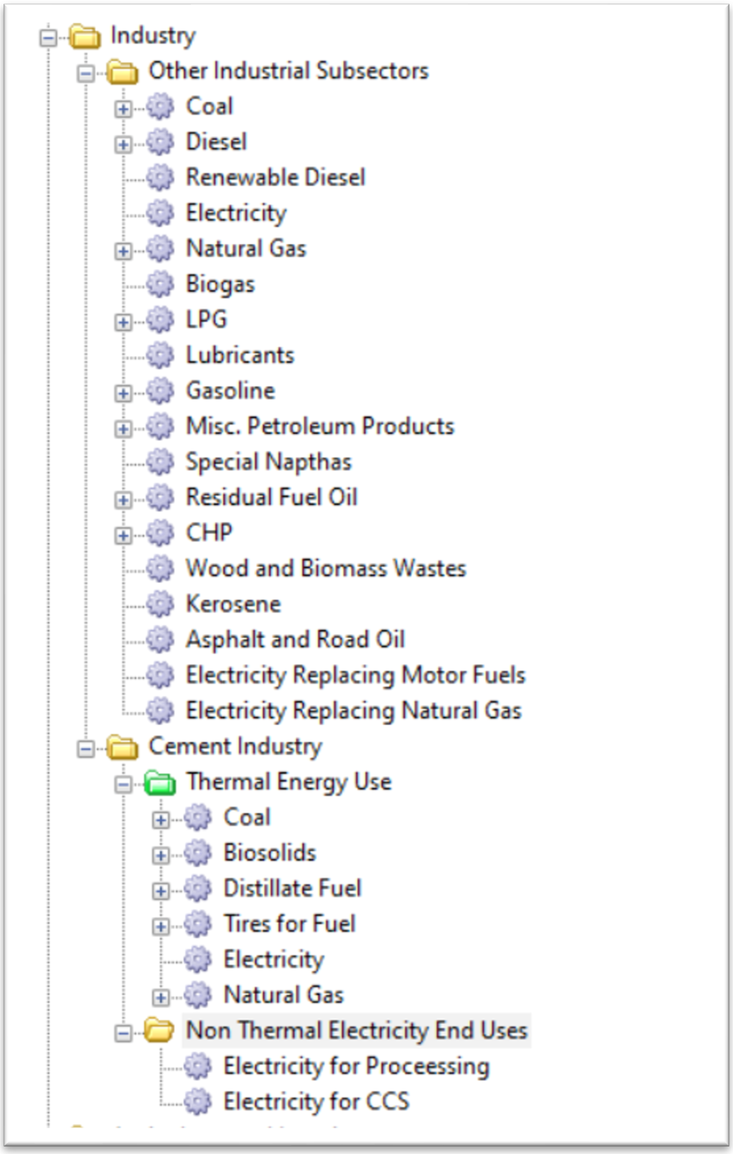
[33] Assumptions for public chargers from Following from Electrek (2023), "Here’s how many EV chargers the US has – and how many it needs,” by Michelle Lewis, dated Jan 9 2023

[34] This cement output trend is based on growth from 2021 historical output implied in Slide 21 of the University of Maryland Center for Global Sustainability (UMD CGS) Presentation, "Emissions Reductions and the Economic Impacts on Maryland’s Manufacturing Sector,” dated Aug 23th, 2022.

Figure A-21: Structure of the Industrial Sector Branches in the Maryland LEAP Model



- Industry
  - Other Industrial Subsectors
    - Coal
    - Diesel
    - Renewable Diesel
    - Electricity
    - Natural Gas
    - Biogas
    - LPG
    - Lubricants
    - Gasoline
    - Misc. Petroleum Products
    - Special Napthas
    - Residual Fuel Oil
    - CHP
    - Wood and Biomass Wastes
    - Kerosene
    - Asphalt and Road Oil
    - Electricity Replacing Motor Fuels
    - Electricity Replacing Natural Gas
  - Cement Industry
    - Thermal Energy Use
      - Coal
      - Biosolids
      - Distillate Fuel
      - Tires for Fuel
      - Electricity
      - Natural Gas
    - Non Thermal Electricity End Uses
      - Electricity for Processing
      - Electricity for CCS

Other Manufacturing includes the full list of fuels reportedly used in industry, but as of 2021 natural gas supplied about two thirds of the needs for combustible fuels in non-cement industries. Energy growth in other industries is driven by growth in industrial GDP in Maryland. Industrial GDP growth is assumed to track overall GDP growth in Maryland, which is projected to increase by about 39 percent in real terms between 2021 and 2050.[35] Branches included for “electricity replacing motor fuels” and “electricity replacing natural gas” are used in the Additional Actions case. Energy intensity trends are estimated for each fuel based on national Reference case results from AEO2023, which show decreases in industrial

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[35] Overall state GDP growth forecast taken from MD Department of Planning - MD State Data Center through 2040, and assumes 1% annual growth from 2040-2050. Available, for example, from Dept of Planning, “Maryland State Data Center, Projections by Topics.”

energy intensity (energy use per unit of GDP) for most fuels, with, for example, the energy intensity of natural gas use declining by 15 percent between 2022 and 2050.[36]

3.4 Other sectors

In the **Agriculture and Logging sector**, in which about 90 percent of fuel use is for agriculture, the driving activity is the state's agricultural land. Agricultural land is projected to decline slowly due to urbanization and other factors, following recent trends, from just under 2 million acres in 2022 to just under 1.9 million acres in 2050. Energy use in the agriculture and logging sector is derived from data in the MDE GHG Inventories, and is dominated by diesel use, but also includes use of CNG, LPG, and gasoline. Energy intensities in the sector are assumed to decrease consistent with national trends indicated in the AEO2023 Reference case, with a decline (improvement in efficiency) of about 14 percent between 2022 and 2050. Similar to the approach with other industries, branches are included for "electricity replacing diesel" and "electricity replacing gasoline" in the agricultural sector and are used in the Additional Actions case to model the implementation of additional battery-electric agricultural equipment.

In the **Construction and Mining sector**, which is dominated by construction energy use and the use of diesel fuel for construction and mining equipment, overall activity grows with construction GDP. Construction GDP is assumed to grow at a rate consistent with national construction "value of shipments" from the AEO2023 Reference case, and thus increase by somewhat over 25 percent between 2022 and 2050.[37] Historical energy data for the sector were derived from MDE GHG Inventory results. The intensity of diesel use, again based on AEO2023 trends, declines in the sector over time, falling by 17.6 percent between 2022 and 2050. As in agriculture and logging, branches are included here for "electricity replacing diesel" and "electricity replacing gasoline" and are used in the Additional Actions case to model the implementation of additional battery-electric construction and mining equipment.

A final sector in the LEAP Demand dataset for Maryland covers "**District Heat Use**". This branch is used to estimate the heat used in the Baltimore Steam Loop, to model the impacts of closing down the Baltimore waste-to-energy plant in the Additional Actions case, replacing the plant with heat from an electric heat pump system. The heat required in the Baltimore Steam Loop is estimated very roughly based on available sources and is assumed to stay constant over the modeling period.[38] Future expansion of district heat use in Maryland is a possible avenue for GHG emissions reduction but has not yet been explored in the modeling effort described in this Report.

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[36] Derived from data in AEO2023 Reference case results in EIA (2023), "Table 6. Industrial Sector Key Indicators and Consumption," downloaded May, 2023.

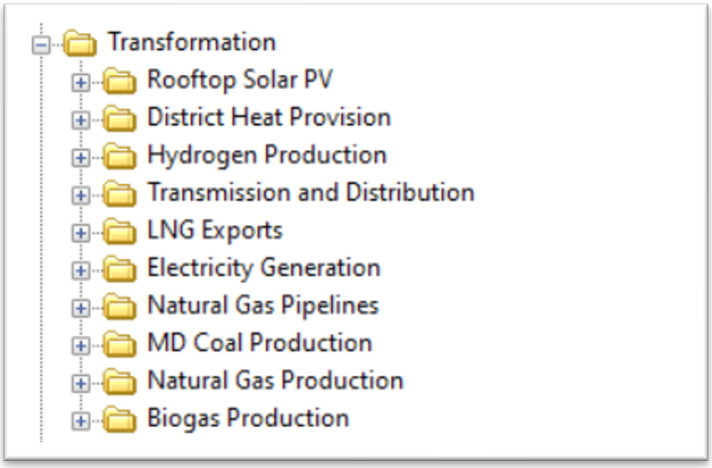
[37] Derived from data in AEO2023 Reference case results in EIA (2023), "Table 34. Nonmanufacturing Sector Energy Consumption," downloaded April, 2023.

[38] Assuming that Wheelabrator Baltimore provides 45% of the 635 metric tons of steam per hour that Vicinity (the current operator of the Baltimore Steam Loop, previously Veolia) distributes to the Steam Loop, the implied heat output of the Wheelabrator plant (used fraction) would have been about 5,500 GBtu of energy per year. In 2015, that heat output would have been the equivalent of 77% of the energy content of the fuel input to the Wheelabrator plant. This is a rough estimate based in part on information from WTE International (2014), "Veolia Extends Contract for Steam from Wheelabrator's Baltimore Waste to Energy Plant," *Waste to Energy International*, dated March 17, 2014. This estimate would benefit from additional input from stakeholders.

4.Energy Supply Model Details

As noted above, the Energy Supply (or energy "Transformation," in LEAP terms) portion of the Maryland LEAP model moves fuels and resources from where they are produced or imported to processing facilities, and ultimately to end-users. Energy supply elements of the model also convert resources into the fuels and other energy forms (for example, electricity and heat) used in the energy demand sectors (buildings, transportation, industry, and district heat). Each of the transformation elements (in LEAP terms, "modules") used in the model are described below and are shown in Figure A-22.

Figure A-22: Structure of the Energy Supply Branches in the Maryland LEAP Model



Transformation
- Rooftop Solar PV
- District Heat Provision
- Hydrogen Production
- Transmission and Distribution
- LNG Exports
- Electricity Generation
- Natural Gas Pipelines
- MD Coal Production
- Natural Gas Production
- Biogas Production

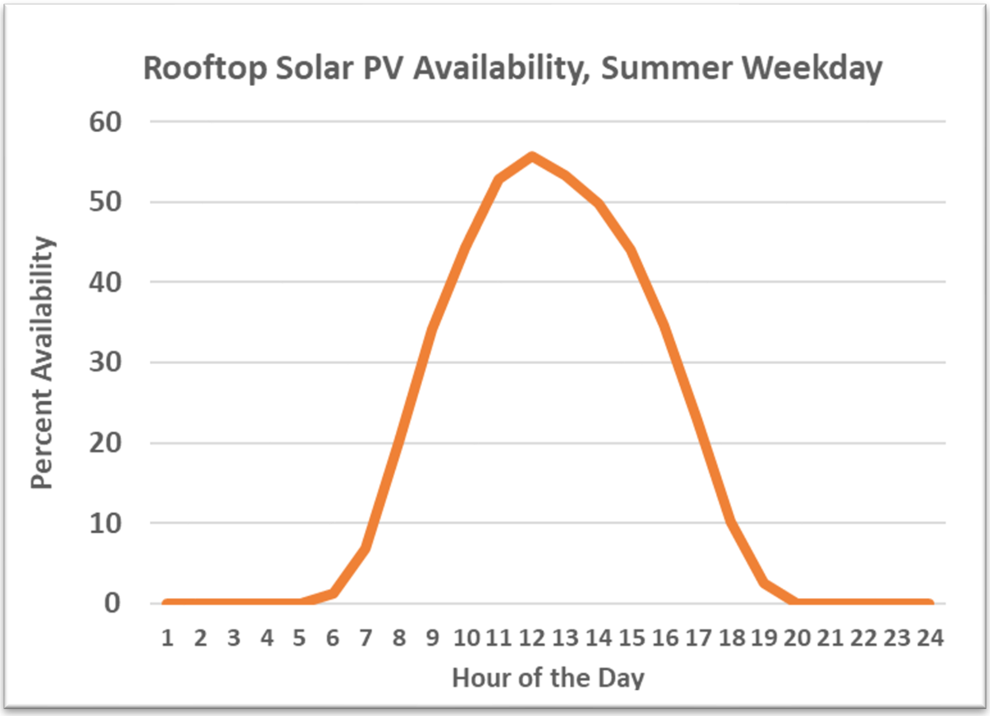
Note that in Figure A-22 the ordering of the energy supply branches is important, as lower branches can be used to provide fuels for branches above. Thus, for example, natural gas production provides some of the gas for natural gas pipelines, which provides gas for electricity generation and LNG Exports. In addition, for example, the position of Rooftop Solar PV above Transmission and Distribution indicates that the output of rooftop solar PV does not (for the most part) pass through the transmission and distribution system, and thus does not incur transmission and distribution losses.

4.1 Rooftop solar PV (distributed solar generation)

The "Rooftop Solar PV" energy supply branch produces distributed electricity. Four types of solar PV are included: residential, commercial (including institutional), industrial, and community solar. Industrial solar PV capacity is relatively limited in all scenarios, relative to the other categories. Community solar PV systems may not be located on rooftops, are typically larger than residential installations, and may not be located adjacent to some, or all, of the users sharing the power from the systems. CAPEX and OPEX costs for commercial, industrial, and community rooftop PV systems (see below) are assumed to be the same, with residential costs higher due to economies of scale (residential systems are smaller) and the need for custom installation. Additional data used to describe rooftop PV systems include capacity by type, and input "feedstock" fuel (solar). The "efficiency" of solar PV systems is set at 100%, as there are no impacts associated with using more or less of the solar resource, although in practice the efficiency of PV panels in converting incident sunlight to electricity is typically around 20 percent. This value has been rising in recent years and varies by technology and type of installation.

Rooftop solar PV is modeled as meeting a portion of demand for electricity based on a set of annual “availability shapes” indicating the average output of a PV system in each hour of the day. Different availability shapes are used for each of the four seasons; Figure A-23 shows an example for a summer weekday (although for solar availability, weekdays and weekends are the same in each season).

Figure A-23: Example Availability Shape for Rooftop Solar PV



Because of the position of the rooftop solar PV module in the overall list of transformation (energy supply) modules in the Maryland LEAP model, output from rooftop solar PV does not incur transmission and distribution losses. This means that the net electricity required from the transmission and distribution systems is equal to electricity demand (from the demand sectors) minus the output of rooftop solar PV, plus any electricity needed for district heat and hydrogen production.

4.2 District Heat Provision

The district heat provision module is used only in the Additional Actions case, as an element related to the retirement of Maryland’s waste-to-energy plants, to provide heat to the Baltimore Steam Loop after the Baltimore WTE plant has been shut down. An electric heat pump system is used to provide steam for the Steam Loop, and the module includes data on the system’s capacity, cost, efficiency, and other attributes. Electricity is the input energy form, and heat is the output.

4.3 Hydrogen Production

A process for hydrogen production by water electrolysis, using electricity as an input, is included to provide fuel for the relatively limited stock of future hydrogen-powered vehicles included in the Maryland LEAP model. This module can be scaled up to provide fuel for expanded vehicle fleets or industrial processes, if needed, but at present the overall use of hydrogen in the model is limited. The hydrogen “module” in the LEAP dataset sources electric power from the transmission and distribution grid.

4.4 Transmission and distribution

The transmission and distribution (T&D) portion of the model is used to account for the losses incurred in moving electricity from non-distributed generators to electricity end-users, and the transmission of natural gas from sources (mostly, for Maryland, out-of-state sources) through transmission and distribution piping to end-users. Electricity losses are projected to be more or less constant at just over 5 percent of grid generation through 2050. Historical values were calculated based on data from EIA.[39] Although national loss rates declined by 0.14%/yr. during the 2010s, future trends for PJM East in AEO2023 results show very little change over time.[40]

Estimates of natural gas T&D losses and methane emission factors are based on calculations in MDE GHG Inventory for 2020 ("Natural Gas and Oil" worksheet) and imply a loss rate that is about 0.66 percent of throughput. Reference case projections assume a reduction in losses at 0.25 percent (of losses) annually, yielding a 2050 loss rate of 0.61 percent of gas throughput. This decline in losses is a rough estimate assuming the ongoing replacement of metal pipelines and service lines with plastic piping and is currently assumed to hold for all scenarios.[41]

4.5 Central station electricity generation

Central station electricity generation is simulated in the Maryland LEAP model in the “Electricity Generation” energy supply module. This module produces electricity, with heat as a co-product from one generator (the Baltimore Waste-to-Energy plant), to meet the needs of the transmission and distribution grid. As such, electricity generation is equal to the generation needs, after factoring in electricity generation from distributed solar PV and losses from electricity transmission and distribution systems. Central station generation in Maryland includes generation from in-state plants and imports from the rest of the PJM grid. No specific targets for imports or exports are included in the modeling, but imports are generally modeled to make up the difference between net electricity demand and in-state electricity generation and peak power needs.

All the significant types of generation present in Maryland are described as “processes” in the Electricity Generation module, as shown in Figure A-24. For the most part, these processes list types of generation, although in three cases, the two WtE plants (MSW Baltimore and MSW Montgomery County) and the Calvert Cliffs nuclear station, specific generators are listed.[42]

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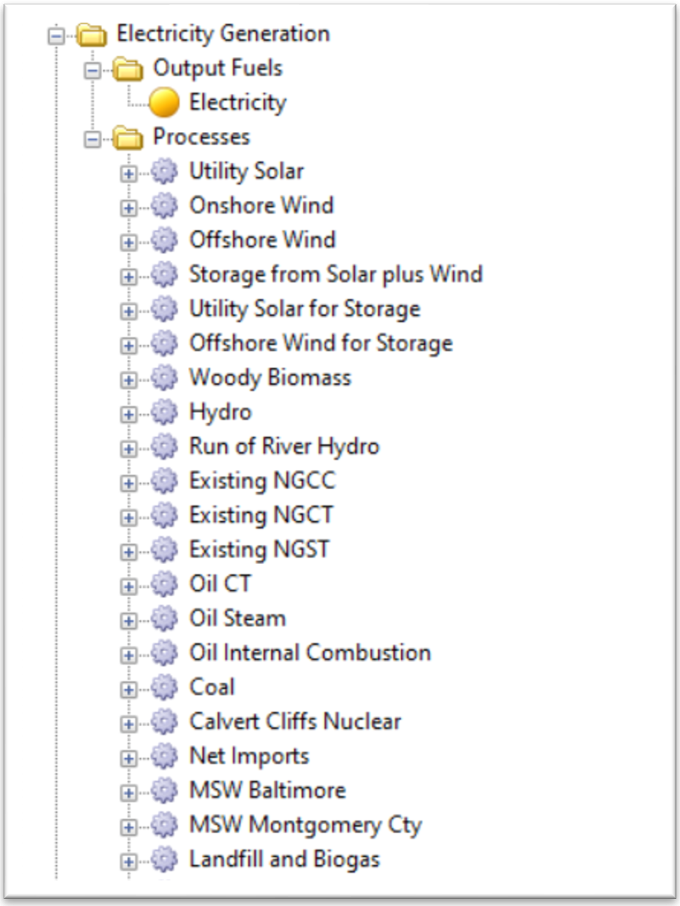
[39] Maryland Electricity Profile, EIA.

[40] Historical Maryland electricity T&D loss data from USDOE EIA state statistics were trended based on implied loss rates from USDOE EIA AEO 2023, ”Table 54.10. Electric Power Projections by Electricity Market Module Region [Reference Case], for PJM / East”.

[41] Methane is the primary constituent of natural gas, thus leakage from T&D pipelines is a major source of methane emissions, and the estimated impact of those emissions are amplified if, as in this study and the MDE GHG inventories, 20-year GWP factors are used. For future work, it will likely be worth consulting with gas companies and other stakeholders to identify better assumptions as to future leakage rates, and any difference in leakage rates that might come about though different scenarios in which natural gas use is phased out.

[42] Note that in this listing the term “utility solar” is used to differentiate central-station solar PV systems from rooftop and other distributed generation. In fact, relatively little solar generation, or, for that matter, generation of any type in Maryland, is actually owned by distribution utilities, rather, generation is owned by independent power producers, and sometimes by municipalities and other government agencies.

Figure A-24: Listing of Types of Electricity Generation Used in the Maryland LEAP Model



- Electricity Generation
  - Output Fuels
    - Electricity
  - Processes
    - Utility Solar
    - Onshore Wind
    - Offshore Wind
    - Storage from Solar plus Wind
    - Utility Solar for Storage
    - Offshore Wind for Storage
    - Woody Biomass
    - Hydro
    - Run of River Hydro
    - Existing NGCC
    - Existing NGCT
    - Existing NGST
    - Oil CT
    - Oil Steam
    - Oil Internal Combustion
    - Coal
    - Calvert Cliffs Nuclear
    - Net Imports
    - MSW Baltimore
    - MSW Montgomery Cty
    - Landfill and Biogas

A number of parameters are specified for each type of generation (for each “process”):

- The “**dispatch rule**” describes assumptions about how LEAP models the output of a given generator. In most cases, Maryland model renewable generation (except for hydro) and electricity storage facilities are assumed to be powered by renewable generation and are set to run to full capacity, while other generation uses “merit order dispatch”. The related “**merit order**” parameter sets hydro at 1, gas combined cycle and steam plants, along with imports from PJM, at 2, and gas combustion turbines and all oil-fired plants (many of which have been phased out recently) as 3, with the merit order number indicating in what order LEAP will dispatch the plants when more power is needed.
- **Historical production** indicates output from each type of plant in years 2015 through 2021.
- **Exogeneous capacity** indicates how capacity of a given plant is assumed to grow over time, with capacity trends varying substantially by plant type and scenario. See the scenario results in sections 4 and 5 of the Technical Report.
- **Capital costs**, **Fixed O&M costs**, and **Variable O&M costs** are specified for the types of generation whose output varies between scenarios (see below).

- The **heat rate** specifies the efficiency of those generators that produce power by combusting fuels. Renewable generators and the Calvert Cliffs nuclear units have heat rates set at the equivalent of 100% efficiency. Electricity storage use has an effective efficiency of 85 percent.[43] Heat rates for fuel-fired generators are derived from historical fuel use and output data for Maryland power plants and are assumed to remain mostly stable in the future, with some (natural gas combined cycle, for example) declining slightly over time, consistent with AEO2022 Reference case results for the PJM East region. For the Baltimore WtE plants, a **coproduct efficiency** of 50 percent was used, meaning that half of the input energy in the fuel used in the plant is available as heat energy for the Baltimore Steam Loop.
- For most types of generation, the **maximum availability**—a measure of how much a given generator runs over the course of the year, and in some cases, at what time it is available, is specified by "yearly shapes" for hydro, solar, wind, battery energy storage, gas-fired generation, and others. The yearly shapes specify output on a 24-hour basis for weekdays and weekend days in each of the four seasons. For some fuel-fired generation, particularly gas combined-cycle, maximum availability falls over time.
- Each type of generator is assigned one or more types of **feedstock fuels or resources**. For generators burning fuel, **emission factors** specify how much carbon dioxide, methane, nitrogen oxides, and other emissions are produced per unit of fuel consumed.

LEAP matches generation needs for electrical power based on the yearly shapes/maximum availability and dispatch rule/merit order parameters entered as above, and on a load curve that specifies the variation of electricity demand over time. To match the yearly output shapes, the load curve specifies demand for grid electricity, which is calculated net of output from distributed PV generation and T&D losses, on a 24-hour basis for weekdays and weekend days in each of the four seasons. Figure A-25 and Figure A-26 show, respectively, the daily load curves for summer and winter weekdays in Maryland. In the summer, peak electricity demand is in the evening, when it is still hot, and residents are coming home and turning on air conditioning and other appliances. In the winter, there are two peaks, one in the morning as residents are using space heat and appliances as they prepare for their days, and the other in the evening when they return home.[44]

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[43] From NREL (2023), "Annual Technology Baseline (ATB)," workbook downloaded as "2023_v2_Workbook_Corrected_07_20_23.xlsx," worksheet downloaded from "Utility-Scale Battery Storage." Efficiency values for Commercial and Residential battery storage from this source are the same as for Utility-scale storage.

[44] These load curves were derived from the 8760 hours per year load curves in the original older LEAP dataset provided to CCS by E3, and as used by E3 in an earlier project for MDE. Because the load curves used currently are divided into 192 annual "time slices,," representing 24 hours per day x 2 types of days (weekend/weekday) x 4 seasons, the vertical axis values on Figure A-25 and Figure A-26 represent the total percent of annual load summed over, for example, the electricity used in the 17th hour of the day in all of the summer weekdays during a year. It is the relative height of the curve at any given hour, however, that is important in understanding these curves.

Figure A-25: Load Shape Used for Summer Weekdays in the Maryland LEAP Model

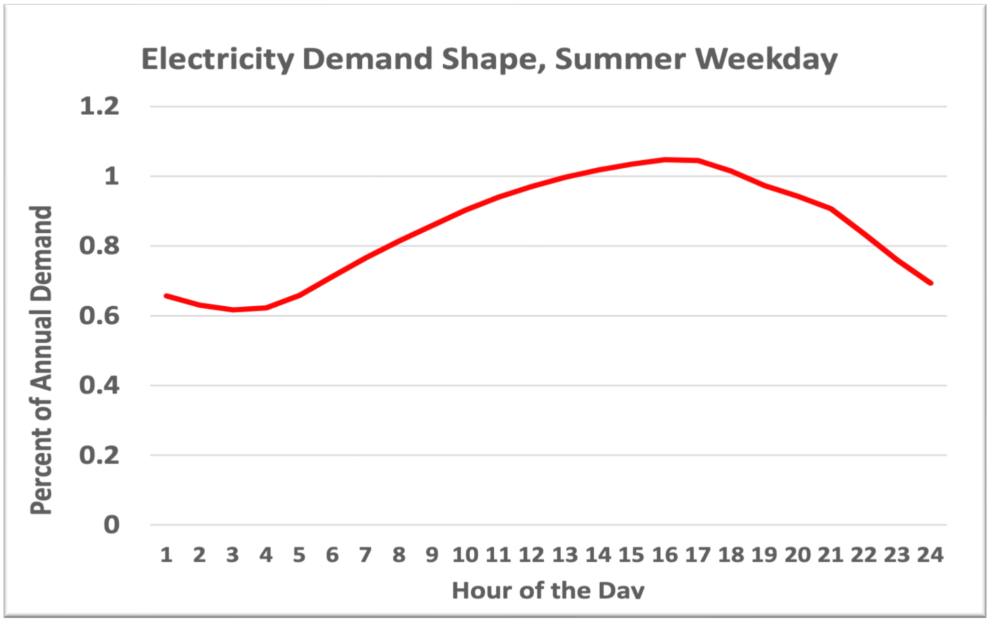
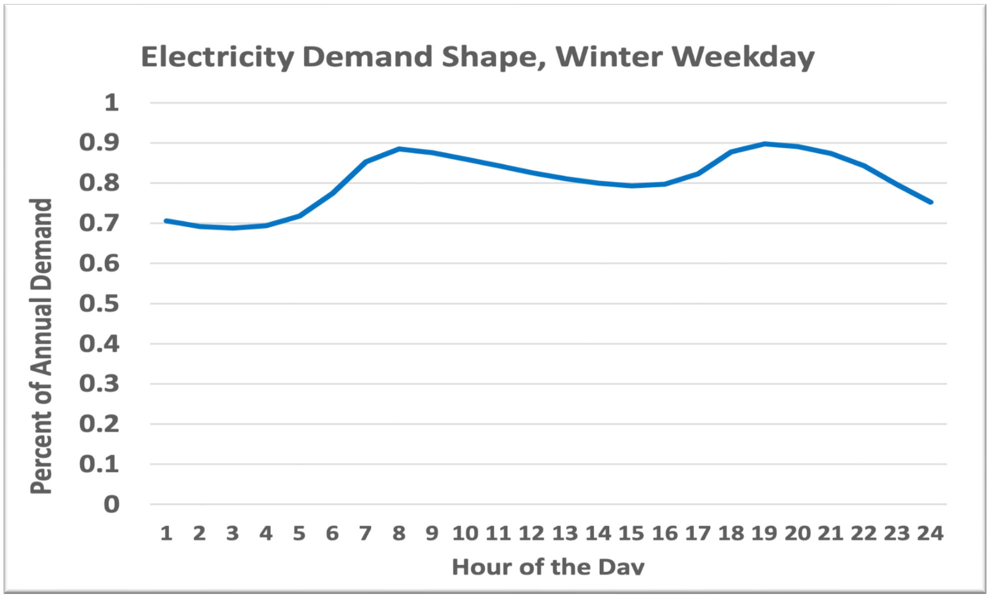


Figure A-26: Load Shape Used for Winter Weekdays in the Maryland LEAP Model



Note that for future analysis it will likely be useful to A) update these curves using more recent load data, likely derived from utility records, and B) consider how these load curves may change over the course of the years in Maryland under different scenarios. This may allow the modeler to factor in, for example, the impacts and timing of electric vehicle battery charging (or discharge into the grid) or the use of residential and commercial battery storage systems, as well as changes in the patterns of electricity use due to other forms of energy demand electrification.

4.6 Natural gas pipelines

The natural gas pipelines module models the use of natural gas in pipeline compressor stations. Pipeline compressor stations use compressors to maintain and increase the pressure in natural gas pipelines. There are four compressor stations in Maryland.[45] Emissions from these compressor stations occur when natural gas is burned in combustion turbines or reciprocating engines to drive natural gas compressors. This “auxiliary fuel use” in compressor stations is one source of emissions; another is fugitive emissions of (mostly) methane from leaks in compressor stations, but this source is not currently tracked in the LEAP model. Based on data in the MDE GHG Inventory, we assume that about 0.033 units of natural gas are used as compressor station fuel for each unit of natural gas entering the gas transmission and distribution system, including gas for LNG exports.

4.7 Coal production

The “MD Coal Production” module model emission of methane from the relatively few remaining underground and surface mines in Maryland. Current mine capacity is estimated at about 2 million tons of coal equivalent (TCE) per year. The operating mines are in Western Maryland; Figure A-27 shows a map of Maryland’s coal seams.[46] We assume that Maryland coal production trends down to zero by 2036 in all scenarios. The coal phase out is driven by a combination of the reduction in coal use in the US over that period and progressively more unfavorable mining economics in Maryland versus larger producers (companies and states), and the depletion of the most valuable coal in the mine (at least for the coal reported above as "deep mined,” underground mined, which by 2019 was almost all from the Casselman Mine in Upper Freeport, MD, estimated at 2.6 million tons of metallurgical coal by the current mine owner,[47] and "15 million tons of recoverable coal,” type unspecified).[48] Just under half of production came from underground mines in 2022, with the rest from surface mines. Methane emissions factors for the two types of mines are derived from those used in the MDE GHG emissions inventories and are 2.6 kg of methane per TCE coal produced in underground mines, and 0.847 kg of methane per TCE coal produced in surface mines.

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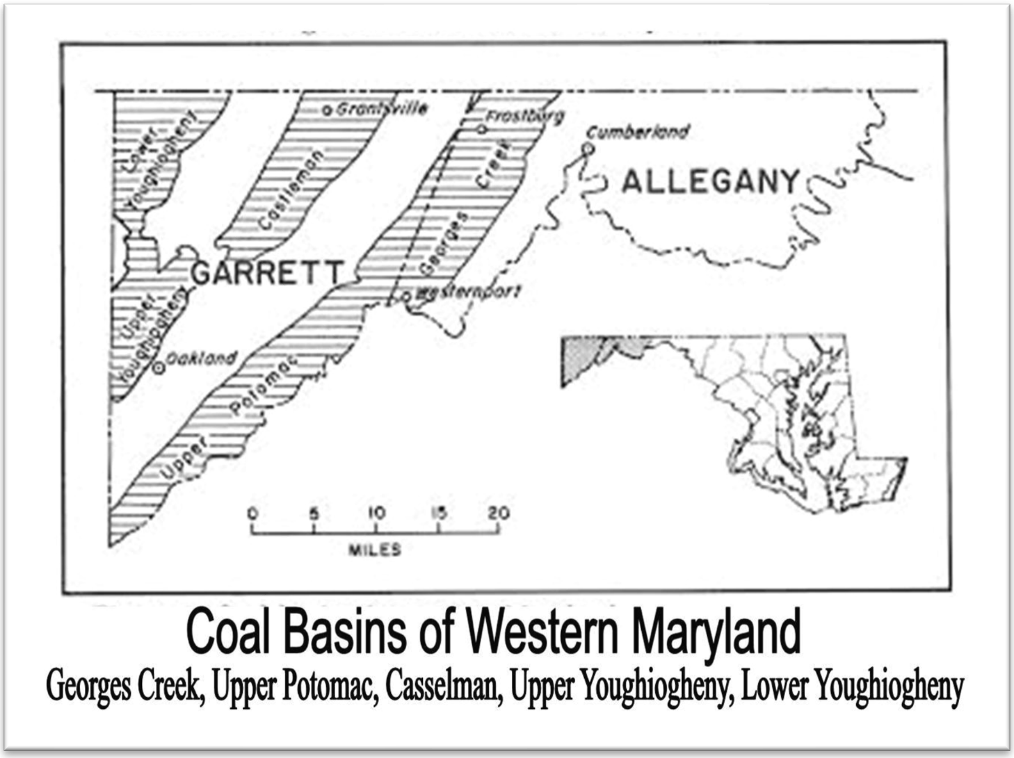
[45] The four stations and their owners/operators are Myersville, run by Dominion, Accident (not a misprint], run by Texas Eastern, Rutledge, run by TransCanada, and Ellicott City, run by Transco. See Tad Aburn and Joshua Shodeind, MDE (2019), “‘Minimizing Methane Emissions from Natural Gas Compressor Stations and other Related Equipment,” presentation for Stakeholder Meeting # 3 - March 6, 2019.

[46] Image from MDE (undated), “Maryland Bureau of Mines Coal Division.”

[47] Corsa coal company (2021), “*Corsa Coal Corp. Annual Information Form For the Year Ended December 31, 2020*”, dated March 3, 2021.

[48] Global Energy Monitor (2022), “Casselman Mine,” last edited on 14 June 2022.

Figure A-27: Coal Seams in Western Maryland



4.8 Natural gas production

There are also relatively few operating natural gas wells in Maryland. In-state production of natural gas accounts for well under a tenth of a percent of natural gas use in Maryland. In all the scenarios modeled, Maryland's gas production capacity falls to zero by 2035, consistent with (perhaps even understating) recent trends, which saw a nearly eight-fold decline in production between 2015 and 2021. Based on data from the MDE GHG Inventory for Maryland, we assume that emissions are 789 kg of methane per year per Billion Btu of gas output, although this may be an under-estimate as gas production decreases, as MDE's emission factor is specified per well, not per unit of output. Methane emissions from gas wells are difficult to estimate, due to lack of data and varying conditions in different wells.

4.9 Biogas production

A biogas production module was added to model the production of biogas, a mixture of mostly methane and carbon dioxide, from biogenic feedstocks via anaerobic (oxygen-excluding) fermentation. Two types of biogas "digesters" are modeled, one using animal wastes (manures), and one using solids from wastewater treatment processes. Biogas production is used in the Additional Actions case. Capacities of the two types of digesters are modeled as increasing to accommodate and provide treatment for the waste available. The energy efficiency of both types of digesters is assumed to be 50 percent.

5. Energy Resources Model Details

“Resources” in LEAP span a combination of natural resources and fuels (or other energy forms, such as heat and electricity) made directly or indirectly from natural resources. Resources in LEAP are divided into primary resources, which are typically those which come directly from natural or unprocessed wastes from various sectors or processes, and secondary resources, which are typically made directly or indirectly from primary resources. The various fuels and other forms of energy used in LEAP are included in the primary and secondary resources shown in Figure A-28. Some of these, like electricity, natural gas, diesel, and gasoline, are used extensively throughout the model, and others have more limited use.

The parameters associated with individual primary and secondary resources in the “Resources” part of the LEAP model, and used in the Maryland model, include the following:

- Base year reserves for fossil resources.[49]
- Annual yields for renewable resources.
- Import costs for those fuels and resources, such as natural gas, nuclear reactor fuel, motor fuels, and electricity from PJM, imported into Maryland.
- Export benefits for those fuels and resources exported from Maryland, including, perhaps, electricity exports. This feature is not used at present for the main fossil fuel exports from Maryland LNG and coal (via coal terminals at the Port of Baltimore), because these two export processes do not vary between the Current Policies and Additional Actions cases.

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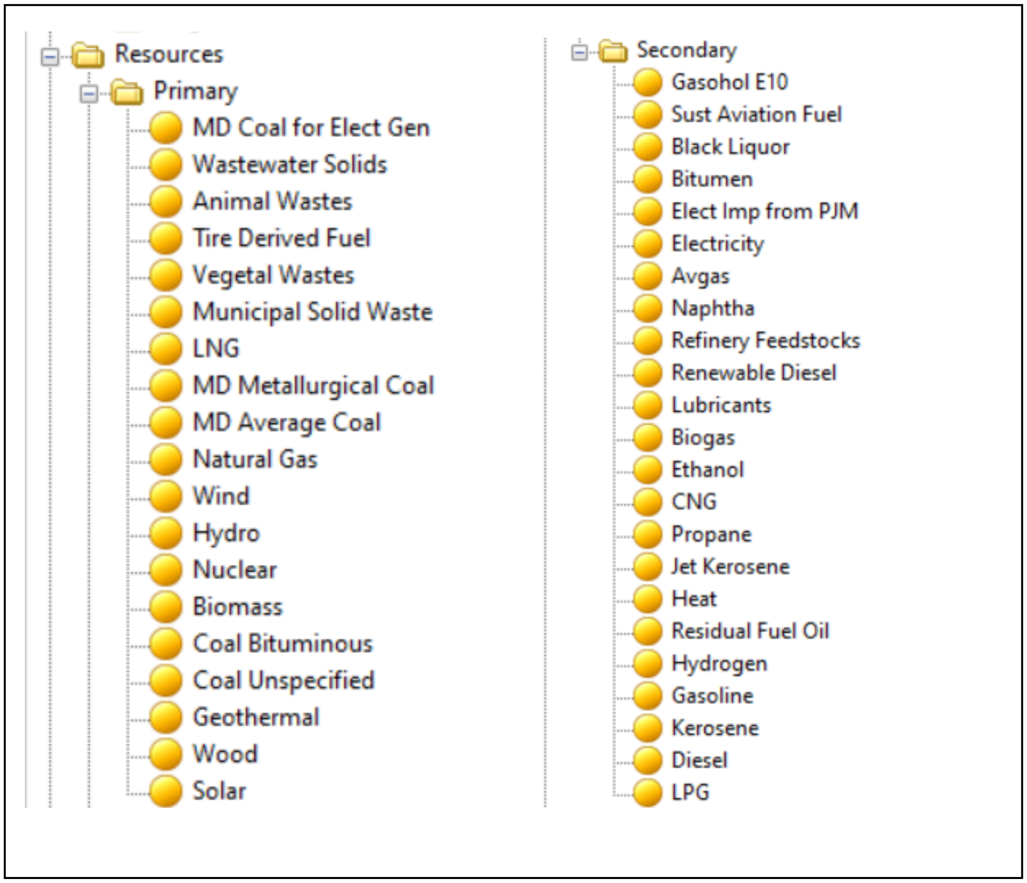
[49] Although a specific estimate of the extent of gas resources lying under Maryland was not immediately available, total estimates for the Marcellus shale, which underlies the western part of Maryland and parts of several other states in the region, has been estimated to be, variously, 50 and 141 trillion cubic feet of recoverable reserves. Source: article by: Hobart M. King (undated, but after 2015), "Marcellus Shale - Appalachian Basin Natural Gas Play, A resource that moved from "marginal" to "spectacular" as a result of new drilling technology,” Geology.com, available as https://geology.com/articles/marcellus-shale.shtml. Since Western MD constitutes only a small portion of the area underlain by the Marcellus Shale, we assume that Maryland's share of this gas would be on the order of 5 trillion cubic feet, pending receipt of better information.

Figure A-28: Primary and Secondary Resources in the Maryland LEAP Model



- Resources
  - Primary
    - MD Coal for Elect Gen
    - Wastewater Solids
    - Animal Wastes
    - Tire Derived Fuel
    - Vegetal Wastes
    - Municipal Solid Waste
    - LNG
    - MD Metallurgical Coal
    - MD Average Coal
    - Natural Gas
    - Wind
    - Hydro
    - Nuclear
    - Biomass
    - Coal Bituminous
    - Coal Unspecified
    - Geothermal
    - Wood
    - Solar
  - Secondary
    - Gasohol E10
    - Sust Aviation Fuel
    - Black Liquor
    - Bitumen
    - Elect Imp from PJM
    - Electricity
    - Avgas
    - Naphtha
    - Refinery Feedstocks
    - Renewable Diesel
    - Lubricants
    - Biogas
    - Ethanol
    - CNG
    - Propane
    - Jet Kerosene
    - Heat
    - Residual Fuel Oil
    - Hydrogen
    - Gasoline
    - Kerosene
    - Diesel
    - LPG

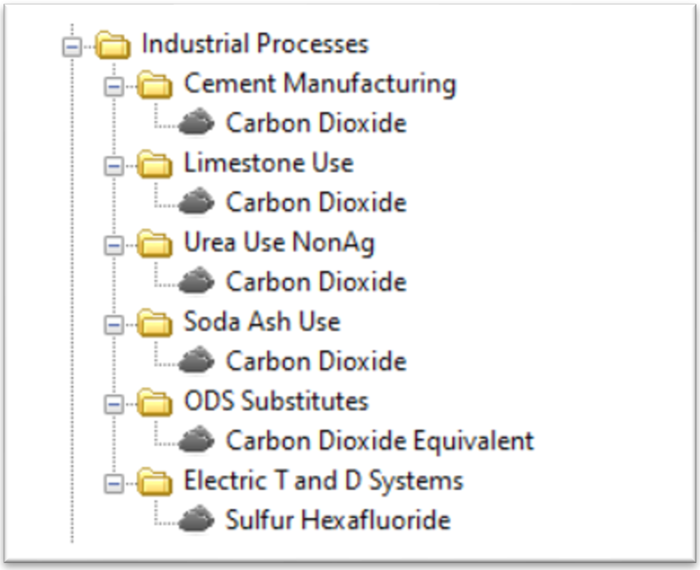
6. Non-Energy Model Details

6.1 Industrial Processes and Product Use

Non-energy emissions from the industrial processes and product use (IPPU) sector in 2021 account for more than double the industrial sector GHG emissions from energy. Of the non-energy GHG emissions sources shown in Figure A-29, ODS substitutes—high GWP gases used in various industrial applications—accounted for 5.7 $MMtCO_2e$ in 2021, with non-energy cement manufacturing emissions accounting for 1.8 $MMtCO_2e$. The other subsectors, which include industrial uses of limestone (other than cement manufacturing), urea, soda ash, and of SF_6 in electrical transmission and distribution systems, total 0.3 $MMtCO_2e$.

Estimates of emissions for IPPU were based on historical production and consumption data for each subsector and EPA emission factors obtained from the MDE GHG emission inventories, with intervening years interpolated. Future emissions for cement manufacturing were estimated within LEAP, so that it could be linked with the energy emissions for that sector, based on forecasted growth in cement output.[50] All other IPPU subsectors were assumed to remain at 2021 levels throughout the forecast period.

Figure A-29: Industrial Non-Energy GHG Emissions Sources



6.2 Fossil Fuel Industry

The only source covered in this sector is abandoned coal mines, as all active fossil fuel production sources are handled in the Transformation branch of the model. Emissions from abandoned coal mines were taken from MDE's inventory, estimated as 0.025 MMtCO$_2$e, and assumed to remain constant throughout the forecast period.

6.3 Waste Management

Waste management emissions account for 6.7 MMtCO$_2$e of gross emissions in 2021, with landfills accounting for 4.7 MMtCO$_2$e, wastewater for 1.8 MMtCO$_2$e, and composting at 0.1 MMtCO$_2$e. Within the landfill subsector, there is also a sink of -0.13 MMtCO$_2$e from long-term carbon storage in landfills.

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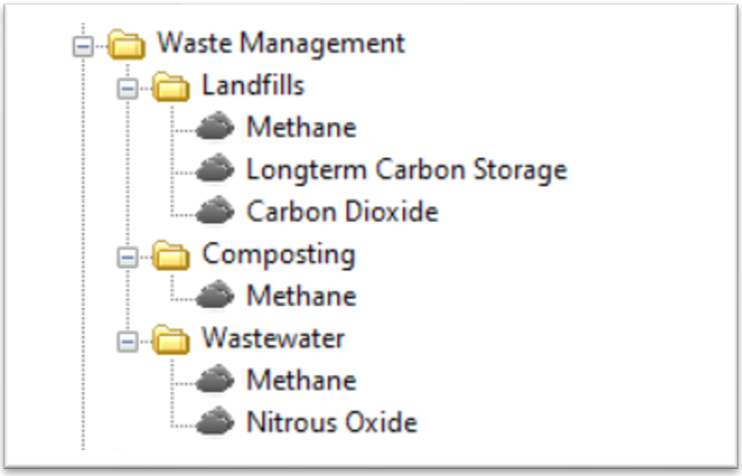
[50] As implied by Slide 21 of UMD CGS Presentation, "Emissions Reductions and the Economic Impacts on Maryland's Manufacturing Sector," dated Aug 23, 2022.

Figure A-30: Waste Management GHG Emissions Sources



- Waste Management
  - Landfills
    - Methane
    - Longterm Carbon Storage
    - Carbon Dioxide
  - Composting
    - Methane
  - Wastewater
    - Methane
    - Nitrous Oxide

Landfill emissions were estimated within the GHG Strategy Tool using a first-order decay equation from the IPCC guidelines[51] applied to the organic matter landfilled in the state each year. For historical years, the amount of organic waste was estimated based on data from the MD Solid Waste Management and Diversion Reports.[52] Emission factors used by the decay model equations, such as the fraction of degradable organic carbon that can decompose (DOC_f) and methane generation constant, were first set to values from the IPCC guidelines and then adjusted to reflect the level of historical reported landfill emissions in the MDE inventories. The amount of organic waste landfilled in future years was estimated by increasing the amount of total waste according to population forecasts, and increasing levels of composting through 2031, as described in the Current Policies Scenario section.

Composting emissions are estimated to be small but will grow as more organic waste is diverted from landfills. Emissions were estimated based on the amount of waste composted each year from the waste diversion reports and EPA emission factors for methane emissions, as well as the soil carbon storage sink that is reported under Agriculture below. This subsector is not included in the MDE inventories.

Wastewater emissions were estimated based on the state population, proportion of the population served with each type of wastewater treatment, and EPA emission factors, as obtained from the MDE state inventories.

6.4 Forestry and Other Land Use (FOLU)

The FOLU sector includes forest carbon flux, which includes emissions from deforestation and sequestration from forest growth and is estimated to be a net sink of 7.8 MMtCO2e in 2021. It also includes carbon loss from mineral soils and emissions of CH_4 and N_2O from wildfires and prescribed fires, totaling emissions of 0.14 $MMtCO_2e$.

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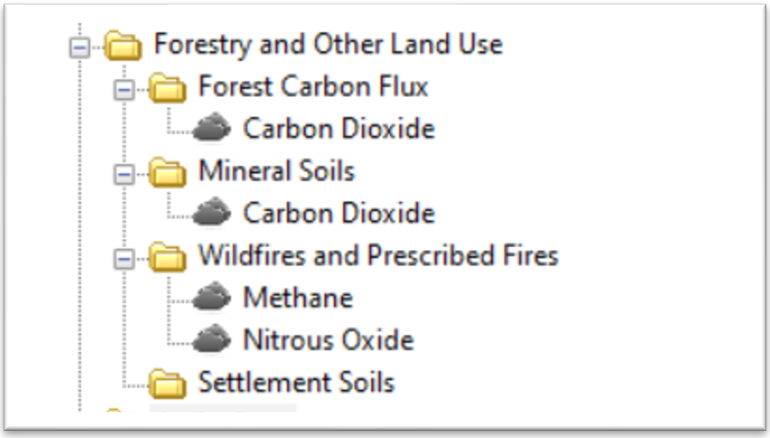
[51] IPCC (2019), "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 5: Waste".

[52] MDE, Annual Report on the Management of Solid Waste in Maryland, 2015-2021, Land Publications & Reports (maryland.gov)

Figure A-31: Forestry and Other Land Use Management GHG Emissions Sources



- Forestry and Other Land Use
  - Forest Carbon Flux
    - Carbon Dioxide
  - Mineral Soils
    - Carbon Dioxide
  - Wildfires and Prescribed Fires
    - Methane
    - Nitrous Oxide
  - Settlement Soils

Emissions from land use change and forest growth were estimated using land cover data from the National Land Cover Database (NLCD) for 2013, 2016, and 2019. For land use change emissions, the land cover map layers for each year were compared to each subsequent year within QGIS[53] to determine the amount of land being converted from one land cover category to another. Emissions were then estimated in the GHG Strategy tool based on estimates of average above-ground carbon stocks[54,55] for each land cover applied to these land area changes. For forest growth, the amount of land in the following land cover categories for each year were multiplied by annual average growth factors to estimate carbon sequestration:

- Deciduous forest
- Evergreen forest
- Mixed forest
- Shrub/Scrub
- Grassland/Herbaceous
- Emergent Herbaceous Wetlands

Emissions from fires were estimated based on the area of wildfires and prescribed burns reported in the annual Wildfire Summary Reports[56] and IPCC emission factors for CH_4 and N_2O. Estimates of emissions from mineral soils were taken directly from the MDE inventories.

6.5 Agriculture

The agriculture sector, estimated to be 3.0 $MMtCO_2e$ in 2021, includes emissions from livestock, such as enteric fermentation and manure management; emissions from agricultural soils, including those resulting from crop residues; inputs of synthetic and organic fertilizer; and emissions from agricultural burning. The largest source of emissions in the agriculture sector is enteric fermentation at 1.3 $MMtCO_2e$ in 2021, followed by manure management at 0.77 $MMtCO_2e$.

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[53] QGIS is an open-source geographic information system.

[54] IPCC (2019), "2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4: Agriculture, Forestry and Other Land Use".

[55] USFS, 2021. "Current aboveground live tree carbon stocks and annual net change in forests of conterminous United States".

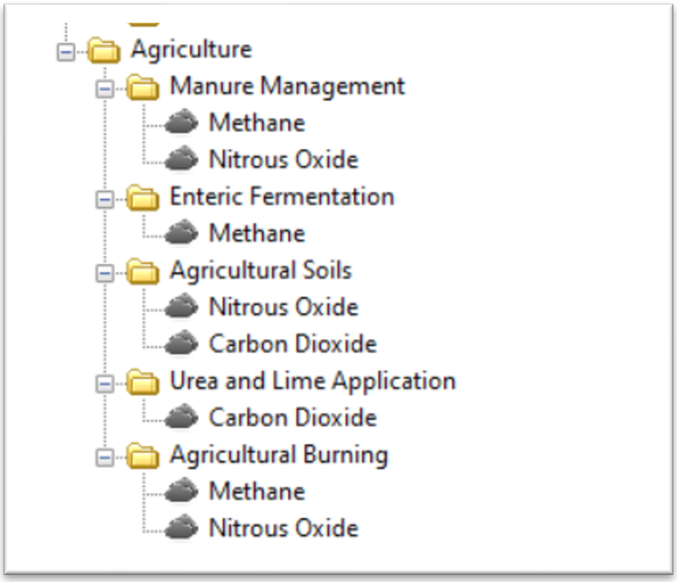
[56] MD DNR (2023), "MD Department of Natural Resources, Wildfire Summary Reports, 2015-2022".

Emissions in this sector were estimated in the GHG Strategy Tool based on the following data taken from the MDE GHG inventories:

- Livestock populations and EPA emission factors used to estimate emissions from livestock, including enteric fermentation and direct emissions from manure management.
- Crop production and nitrogen content of residue, amounts of fertilizer and manure applied to cropland soils, and emission factors used to estimate emissions of N_2O from agricultural soils from inputs of fertilizer, crop residue, and manure.
- Application rates and emission factors for emissions of CO_2 from urea and lime use on cropland soils.
- Estimates of CH_4 and N_2O emissions from agricultural burning.
- Agricultural soil carbon sequestration estimates were taken from the MDE inventories; however, additional sequestration estimated for use of compost on agricultural soils were added to this value, estimated as described in Waste Management above.

Except for the soil carbon emissions sink calculated under Waste Management, all agricultural emissions were kept constant at the 2021 level throughout the forecast period.

Figure A-32: Forestry and Other Land Use Management GHG Emissions Sources



7. Treatment of Costs in the LEAP Model

The treatment of costs in the Maryland LEAP model focuses on costs that will change between scenarios, and specifically, between the Current Policies and Additional Actions cases. The LEAP model therefore estimates the cost differences between the two cases with regard to:

- **Capital** (financial investment) costs required to purchase different (for example, electric versus fossil- fueled) **demand** devices, including residential appliances, commercial equipment, industrial equipment, and transportation vehicles.
- Non-fuel financial **operating expenses**, where they vary significantly between the **demand** devices in a given scenario. For example, the operating expenses for electric vehicles are typically less than those for vehicles using petroleum fuels.
- The differential between the scenarios regarding **investment costs** of **energy supply systems** and equipment, ranging, for example, from the cost of power plants to LNG terminal electrification investments to costs for systems to produce or harvest biogas.
- Fixed and variable operating costs for **energy supply systems**.
- The **costs or savings** from differences in **consumption of fuels or energy forms** between scenarios, typically costed at wholesale (not retail) prices. Wholesale prices are used because the focus in the cost analysis is on estimating the relative social costs of scenarios. Social costs typically include the cost to the state as a whole of increased (or decreased) fuel imports, but not, for example, dealer markups on fuels, which for commodities like gasoline can be on the order of a factor of two.[57]

Note that all the cost estimates above can, but do not always, vary through the modeling period.

The Maryland LEAP model was used to estimate two different measures of net cost to the state of moving from the Current Policies case to the Additional Actions case. The first measure is **social costs**. Social costs here are defined for most actions as the sum of the incremental **annualized** net costs of additional actions relative to costs of the activities in particular sectors that are included in the Current Policies case. So, for example, when the Additional Actions case calls for additional deployment of community solar in 2040, relative to the Current Policies case, the social cost difference shown will include an annualized cost (similar to a mortgage payment) for the additional megawatts of community solar deployed through 2040 in the Additional Actions case beyond those in the Current Policies case. These social costs include the capital (investment, or CAPEX costs) of the additional community solar deployed— financed at a specified interest rate, typically five percent per year on a real basis—plus the additional operations and maintenance costs for those additional community solar systems.

Social costs are computed for each year and separately for each type of device (for example residential heat pumps), vehicle (for example, electric autos), and process (for example, offshore wind power plants) for which the Additional Action scenario differs from the Current Policies case, meaning that both costs (for example, higher sales of electric trucks) and benefits (for example, reduction of purchases of diesel trucks) of the additional actions are counted. Social costs also include **savings in fuel costs**, such as for Current Policies purchases of gasoline, diesel, natural gas, and imported electricity avoided by the measures (shown as a reduction in cost of "Resources") in the Additional Actions Case.

The second cost metric showing the differences between the two scenarios is financial **investment costs**. Investment costs are generally higher than social costs in the years in which investments are made. For example, investments made in utility solar PV plants in 2031 continue to result in GHG savings for the life of the infrastructure purchased, often for 20 years or more, and are financed to spread payments (as in the accounting for social costs), but the investments themselves occur in lumps when a facility, an appliance, a piece of equipment, or a vehicle is purchased. In addition, total investment costs do not net out benefits such as fuel cost savings. The estimates of investment costs for some actions in

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[57] Dealer markups would not be a net social cost to Maryland, as they would be internal to the state.

the Additional Actions case are imperfect due to the way that certain actions are costed in LEAP but present an approximation of the annual lump-sum investments for equipment and installation costs (where applicable) that would need to be financed to implement the actions.[58]

As noted above, costs appear in the model in several places. Some of the major cost assumptions used in the model to compare the costs of the Current Policies and Additional Actions cases are presented below.

7.1 Energy demand sectors

In the **residential** sector, capital (initial) costs, and in some cases non-fuel O&M costs, were ascribed to individual devices, such as appliances, and used to calculate the social costs of emissions reduction actions relative to the Current Policies case. The Maryland LEAP model for the residential sector includes dozens of different devices. For most devices, costs were derived based on a USDOE EIA document used to inform the Annual Energy Outlook modeling process.[59] Examples of costs (in year 2022 dollars) and lifetimes for one end-use, Residential Primary Heating, are provided in Table A-1.

Table A-1: Cost Assumptions for Residential Heating Systems

Heating System	CAPEX, 2023	CAPEX, 2050	OPEX ($/yr)	Lifetime (Years)
Air Source Heat Pump, SF/MF	$6810	$7330	$75	15
Reference Geothermal Heat Pump	$23120	$23120	$90	25
Reference LPG Furnace	$4150	$4150	$130	20
Reference Electric Resistance SF/MF	$1480	$1480	$50	20
Natural Gas SF/MF	$4150	$4150	$130	20
Reference Kerosene Furnace	$5510	$5510	$80	20
Reference Distillate Heating	$5510	$5510	$80	20
Reference Natural Gas Heat Pump	$6500	$6500	$200	16
Cordwood Stoves	$7090	$7090	$190	25

Notes: SF = Single Family, MF = Multi-Family

Similar to the residential sector, estimates of costs and related parameters for devices used in **commercial end uses** are provided in the LEAP model for capital and O&M costs. Costs, in terms of $/kBtu/hr, were derived based on the same USDOE EIA document referenced above for residential equipment. As the key activity driving overall growth of energy use in the commercial sector is square feet of floor area, capital and O&M costs for devices and equipment are converted to a basis of cost per square foot of floor area using cost conversion factors that differ by end use. An example of costs for a

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[58] LEAP has the capability to report investment costs directly for some types of energy supply options, depending on how they are modeled (electricity generation is an example), but does not have that functionality at present for demand-side investments. As a consequence, CCS estimated the investment costs for demand-side actions by modeling those costs as capital outlays annualized over only one year, as opposed to over the economic lifetime of the device, vehicle, or equipment, as in the typical social cost calculation.

[59] USDOE EIA (2023), "Updated Buildings Sector Appliance and Equipment Costs and Efficiencies", dated March 2023.

commercial sector end use is provided in Table A-2. Costs for commercial refrigeration are converted to costs per square foot of floor area using a conversion factor of 0.0183 thousand Btus per hour (kBtu/hr).[60]

Table A-2: Cost Assumptions for Commercial Refrigeration Systems

Type of Refrigeration	**CAPEX ($/(kBtu/hr))**	**O&M ($/(kBtu-hr)-yr)**	**Lifetime (years)**
Reference Walk-in Units	$ 774.00	$ 25.00	12
Reference Cases and Cabinets	$ 970.00	$ 79.00	12
Reference Large Cold Storage Areas	$1,057.00	$ 31.00	12
Reference Ice Machines	$ 732.00	$ 175.00	12
Reference Residential Type of Compact Units	$1,551.00	$ 79.00	12
Reference Refrigerated Vending Machines	$1,928.00	$ 184.00	12

For the **transportation** subsectors that are modeled on a stock turnover basis, namely the light duty vehicles (cars and trucks), heavy duty trucks, and bus (school and transit/other) branches, vehicle purchase and O&M costs are included on a per-vehicle basis, in some cases varying over the modeling period. The cost assumptions used for light duty autos are shown in Table A-3. Cost assumptions for light duty trucks (and SUVs) are essentially the same for the most common vehicle types.[61]

Table A-3: Cost Assumptions for Light Duty Autos

Type of Light Duty Auto	**CAPEX ($/vehicle)**		**O&M ($/vehicle-yr)**		**Lifetime (years)**
	2023	**2035**	**2023**	**2035**	
Reference Gasoline	$ 32,500	$ 33,500	$ 800	$ 800	16
Reference Diesel	$ 32,500	$ 33,500	$ 800	$ 800	16
CNG and LNG Vehicles	$ 32,698	$ 34,033	$ 800	$ 800	16
Propane Vehicle	$ 36,099	$ 37,572	$ 800	$ 800	16
Gasoline Hybrid Electric	$ 33,228	$ 33,854	$ 800	$ 800	16
PHEV	$ 38,000	$ 36,700	$ 600	$ 600	16
Electric Vehicle	$ 38,000	$ 29,300	$ 400	$ 400	16
Hydrogen Fuel Cell	$ 35,804	$ 33,975	$ 800	$ 800	16
Diesel Electric Hybrid	$ 33,228	$ 33,854	$ 800	$ 800	16

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[60] This factor is based on a conversion factor from the original E3 model and an additional normalization factor to account for the fact that less than 100% of commercial space uses refrigeration, but the sales shares for each type of refrigeration sum to 100%.

[61] Costs estimated based on Oraan Marc (2023), "EVs Will Be More Affordable Than ICE Cars by 2032 in the U.S., Study Claims," *AutoEvolution*, dated 17 Feb 2023.

The assumptions for heavy duty truck purchase and O&M costs used in the Maryland LEAP model are provided in Table A-4 and Table A-5, respectively.[62]

Table A-4: Capital Cost Assumptions for Heavy Duty Trucks

	Weighted Average CAPEX	**CAPEX Projections based on LDV CAPEX Costs Trends**		
HDV Vehicle Classes in LEAP	**2023**	**2027**	**2032**	**2035**
Gasoline	$72,500	$73,615	$ 73,615	$75,880
Diesel	$120,833	$122,692	$122,692	$126,467
Electric	$247,246	$217,967	$172,079	$132,682
Gasoline PHEV	$100,500	$98,649	$95,274	$92,014
Diesel PHEV	$191,756	$188,223	$181,784	$175,565
Ethanol Flex Fuel	$72,500	$73,615	$73,615	$75,880
CNG	$120,833	$122,692	$122,692	$126,467
Hydrogen Fuel Cell	$196,949	$173,626	$137,073	$105,691

Table A-5: O&M Cost Assumptions for Heavy Duty Trucks

HDV Vehicle Classes in LEAP	**Weighted Average 0&M ($ per vehicle year)**
Gasoline	$2,600
Diesel	$4,550
Electric	$2,275
Gasoline PHEV	$1,950
Diesel PHEV	$3,413
Ethanol Flex Fuel	$2,600
CNG	$4,550
Hydrogen Fuel Cell	$2,275

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[62] Capital costs for heavy duty trucks from USDOE (2022), "*2022 Incremental Purchase Cost Methodology and Results for Clean Vehicles*", USDOE Vehicle Technologies Office, dated December 2022. O&M costs are estimated based on "An Analysis of the Operational Costs of Trucking: 2022 Update," dated August 2022, by Alex Leslie and Dan Murray of the American Transportation Research Institute, which suggests average costs of $0.175. We use the latter figures, and assume electric vehicles offer a 50% reduction, similar to other electric vehicle classes. We use approximately the LEAP 2022/2023 mileage figure of 26000 miles per year. For gasoline and similar trucks, which are typically smaller, we use a slightly lower figure of $0.100 per mile for non-electric vehicles to derive the values in Table A-5.

Capital (purchase) and O&M cost assumptions for electric and diesel transit and school buses are as shown in Table A-6. The costs of diesel school buses are expected to increase modestly, in real terms, while the cost of electric buses decrease dramatically through 2035.[63] Distance traveled per year is our Maryland-specific estimate, which should be refined through conversations with transit authorities in Maryland.

Table A-6: Capital and O&M Cost Assumptions for School Buses

	Estimated CAPEX cost per bus					Annual Maintenance Costs per Mile		Implied Annual Maintenance Costs per Bus (Historical, but used for all years)	
	Diesel, 2023	Diesel, 2035	Electric, 2023	Electric, 2035	Distance Traveled per bus per year	Diesel	Electric	Diesel	Electric
School Buses in MD	$ 100,000	$ 103,077	$ 220,000	$ 169,632	13,223	$ 0.631	$ 0.332	$ 8,344	$ 4,390
Transit Buses in MD	$ 350,000	$ 360,769	$ 650,000	$ 269,868	23,578	$ 0.631	$ 0.332	$ 14,878	$ 7,828

Key cost assumptions in the **Other Transportation** categories include:

- **E-bike** costs are assumed to average $2000 per bike, equating to a cost of $1.67 per annual mile (not lifetime mile) ridden, based on an e-bike lifetime of 10 years and an annual distance ridden of 1200 miles.[64]
- **Sustainable aviation fuel** (SAF) as of 2022 was reported to cost about twice as much per gallon as fossil-based jet fuel.[65] Several publications suggest that this price differential will decrease as the volumes of SAF produced rise to meet market demand, but information was not immediately available as to how much the SAF cost premium will decline over time (and when). We assume that the cost of SAF will fall to 50 percent more than the (wholesale) cost of standard jet fuel by 2050, but that should be considered only a placeholder assumption.
- We do not assume additional costs for **aircraft** improvements, aircraft electrification (which in any case is the same in the Current Policies and Additional Actions case), or electrification of airport ground operations equipment. Aircraft improvement costs will be borne by airline travelers nationwide and worldwide, to the extent that they prove to be significant, and as such it is very difficult to assess Maryland's portion of those costs. Electrification of ground transport equipment is likely to require a low or negative marginal investment and will result in significant O&M cost savings.
- Likewise, we assume no net capital costs for electrification of **rail freight**, as the required investments in electric locomotives will be made nationally, given that Maryland's part of the

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[63] Source of transit bus cost figures is Neil Quarles, Kara M. Kockelman, and Moataz Mohamed (2020), "Costs and Benefits of Electrifying and Automating Bus Transit Fleets," *Sustainability*, May 2020. School bus costs from NYC Clean School Bus Coalition (undated, but likely 2021 or 2022), "3 Types of Electric School Buses."

[64] This is a rough estimate, as e-bikes are available in the US as of 2023 at prices ranging from a few hundred dollars to $10,000 to 15,000. Prices can be expected to fall somewhat due to economies of scale. See, for example, David Smith (2023), "Will eBikes Get Cheaper? Analyzing the Market Trends and Future Possibilities" Eco Motion Central, dated June 2, 2023.

[65] See, for example, Thom Patterson (2022), "Could SAF Be a Cost-Effective Solution to Rising Aviation Fuel Prices?," *Flying*, dated May 5, 2022.

rail freight network is very small. Any net capital costs for electric locomotives relative to diesel locomotives will also A) likely fall over time, and B) be offset in part by savings in O&M costs.

- Similarly, we assume no net costs for electrification of **marine watercraft, lawn and garden equipment, or recreational equipment**, as we judge that purchase costs for electric vehicles/vessels/devices in all of these categories are likely to fall to the level of gasoline- and diesel-fired options in the near future, if they have not already, and savings in O&M costs for electric options will make those purchases even more cost-effective.
- A cost estimate for the new **Purple Line trains**, which will apparently be built by CAF, although which model is unclear, was not immediately available, but a recent contract from CAF to build trains for Montpelier, France that seem similar to Purple Line models, was quoted at 3.5 million Euros per train in 2022,[66] which would be just over 3.5 million USD. We add some costs for shipping from Europe, and for the smaller order to be placed by MTA and estimate a total capital cost of $5.00 million per train. Assuming that the first phase of the Purple Line will put 28 trains in service,[67] the average annual distance traveled per train per year would be about 23,000 miles. Assuming a train lifetime of 20 years and an interest rate of 5%/yr., this would be an ownership cost of about $490 per annual mile traveled. However, we model this as a set of total capital costs with a lump sum of $140.00 in 2025 for the trains delivered under the Current Polices scenario, and in the VMT reduction (and Additional Actions) scenarios. An additional seven trains at $35.00 million are delivered each year from 2027-2030, plus an average of 1.4 trains at $7.00 million per year are delivered each year thereafter through 2050.
- No additional costs are assumed to accrue to Maryland for any additions to **Amtrak** service, as Maryland is a small part of the national network. Costs to electrify the remainder of the MARC commuter rail service and expand **MARC** service are estimated as follows. MARC currently uses approximately 34 diesel-electric locomotives and six electric locomotives.[68] Electrification and expansion of MARC will require the purchase of approximately 14 electric locomotives by 2031, and 34 by 2050 to electrify existing trains, and 28 electric locomotives by 2031, and 102 by 2050 in the VMT Reduction (and All Actions) case. As there are presently about 160 passenger cars in service, expanding MARC service will require the purchase of additional cars as well. We assume a capital cost of about $6.00 million per locomotive[69] and $3.78 million per passenger car.[70] We assume a 20-year life for annualization of train purchases.
- Cost assumptions for charging stations used by light-duty vehicles and by heavy duty trucks are provided in Table A-7 and are based on USDOE figures.[71] The overall costs for charging stations are calculated based on the number of electric vehicles in the fleet and an assumed ratio of charging stations to vehicles. The costs of chargers for buses are assumed to be $50,000 each for overnight chargers, and $110,000 each for en-route fast chargers.[72] We also include in the model an avoided cost for gasoline (mostly) pumps not needed as the stock of fossil-fueled vehicles shrinks, at about $21,000 per pump and with an average of 230 light-duty vehicles per

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[66] See Urban Transport Magazine (2022(, "CAF delivers up to 77 low-floor trams to Montpellier," dated 7-13-2022.

[67] Wikipedia (2023), "Purple Line (Maryland)."

[68] See Wikipedia (2023), "MARC Train."

[69] See, for example, Train Conductor (2023), "How Much Do Locomotives Cost – Diesel-Electric, Steam, Used, GE."

[70] See, for example, SEPTA (2017), "SEPTA Board Approves Purchase of Multi-Level Coaches for Regional Rail," dated March 23, 2017.

[71] USDOE (2022), "Chapter 5: Infrastructure," dated 2022, apparently input to AEO2022.

[72] Neil Quarles, Kara M. Kockelman, and Moataz Mohamed (2020), "Costs and Benefits of Electrifying and Automating Bus Transit Fleets," *Sustainability*, May 2020.

pump.[73] These costs do not reflect the net cost of the Additional Actions case because the same number of electric LDVs are deployed in both the Current Policies case and the Additional Actions case.

Table A-7: Capital Cost Assumptions for Electric Vehicle Charging Stations

	Residential			Workplace / Commercial		
Year	**L1**	**L2**	**L3/DC**	**L1**	**L2**	**L3/DC**
2020	$600	$2,000	$44,500	$1,200	$6,100	$44,500
2025	$600	$1,800	$43,000	$1,200	$4,900	$43,000
2030	$500	$1,600	$41,600	$1,100	$4,800	$41,600
2035	$500	$1,400	$40,300	$1,000	$4,700	$40,300
2040	$400	$1,200	$39,000	$900	$4,600	$39,000
2045	$400	$1,000	$37,700	$800	$4,500	$37,700
2050	$300	$800	$36,600	$700	$4,400	$36,600
Note: L1 = Level 1 Charging (low power); L2 = Level 2 Charging (medium power); L3/DC = Direct Current Fast Charging (high power).						

In the **non-cement industrial subsector**, and for electricity savings in the **cement sector** related to existing electricity use (mostly for electric motors and drives), we assume that the cost of saved electricity will be similar to the industrial energy efficiency improvement programs in Maryland in the last decade. Based on the weighted average cost of lifetime energy savings, an interest rate of five percent per year, and an average assumed lifetime of 12 years for electricity energy efficiency investments, we use an effective capital cost of $238 per MWh/yr. for savings from electricity use efficiency improvements.[74] For non-cement industry fuel switching from natural gas and motor fuels to electricity, we assume that net capital costs for electrification are zero on average, based on the use of typically simpler electrified devices.

Unlike most other fossil fuel-to-electricity measures producing heat, **electrification of cement** kilns requires much higher temperature heat. Cement kilns are typically fired with coal or natural gas, sometimes with inputs of oil products or wastes such as tire-derived fuel, biomass, or biosolids from waste treatment. As such, special types of electrical heat sources are required to reach the temperatures needed for kilns. Technologies for this application have recently been developed and applied, but are not widespread.[75] As a result, no cost estimates for this application were immediately available, although a number of articles in the literature mention expected overall cost savings. Rather

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[73] Cost per pump based on the following from CommTank (undated), "How Much Does a Gas Station Fuel Pump Cost?" "The average cost of a gas station fuel pump ranges from $16 - $21K. It ranges because of many available options such as digital screens, the ability to dispense multiple fuels, secure credit card technology, etc. The average cost to install a gas pump ranges from $2,500 - $3,000 per dispenser.

[74] Derived from historical energy efficiency program data for Maryland from USDOE EIA (2022) workbook downloaded from "USDOE EIA Maryland Electricity Profile 2021,", Tables 13 and Table 8.

than use a zero cost for this important action, however, we made the following very rough estimate. To provide an order-of-magnitude "guess" for what a retrofit of a gas- or coal-fired kiln with an electric technology like the one above might cost, we start with an overall cement plant cost of $500 million for a plant about the size of the two MD plants combined.[76] Of that total, about 50 percent may be equipment. Kiln burners for this size of plant appear to cost on the order of $500,000 FOB China. We assume that converting MD cement production facilities to electrified kilns will require an investment of $10 million, as an order-of-magnitude guess. This would make for an investment of $3.31 per metric tonne of cement produced, based on 2021 estimated production in Maryland. For annualization of this cost, we assume a device lifetime of 15 years.

As with some of the Other Transportation subsectors, we assume no net costs for electrification of equipment for the **agriculture and logging** or **construction and mining** sectors. We judge that the initial costs of battery-electric equipment in these sectors are likely to fall to the level of gasoline- and diesel-fired equipment in the near future, as production of electric equipment ramps up, and savings in O&M costs for electric options will make those purchases even more cost-effective. This transition is assumed to happen at no net cost because electric equipment, at least exclusive of battery costs, is assumed to cost no more (and likely less) than diesel-powered equipment to produce, on an OEM (not retrofit) basis for units of similar sizes, and reduced maintenance costs are assumed to offset battery costs, which also have been declining rapidly.[77]

7.2 Energy supply

Costs for **distributed solar photovoltaic systems** include capital and fixed O&M costs. These costs, shown in Table A-8, were derived from the "Moderate" cost projection from the NREL 2023 *Annual Technology Baseline* (ATB), [78] and converted to u (alternating current) capacity. Distributed PV for industrial and community solar installations were assumed to have the same cost as shown for commercial systems in the table below, and an average lifetime of 30 years for all systems was assumed. Values in yellow highlights in the table are currently used for evaluation of the cost differences between the Additional Actions and Current Policies cases. The other values (high and low projections) are entered in the model and available for future sensitivity analyses.

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[76] Electrification of cement kilns requires higher-temperature heat than is typically possible to produce with resistance heating. One technology, called a RotoDynamic Heater (RDH), produces high temperatures: "RDH delivers aerodynamic action through a rotating blade flow. To provide sufficient process heat, the heater directly imparts mechanical energy of its shaft to the heated gas. Air, nitrogen or process gasses get heated to very high temperatures.". From "Kiln Electrification Takes a Step Forward," Specify Concrete, Posted on February 23, 2023, . This indicates efficiency of 90% for this process. Another technology under development is "heating gas in an electric arc reactor" to temperatures sufficient for calcining. "Cement's future could be a combination of Carbon Capture and Electrification," Industry Decarbonization Newsletter, dated June 15 2023, as well as other sources, point out that electrification of cement plants would make carbon capture and storage from cement kilns easier, as it would, at least for some technologies, allow the kiln to produce an exhaust gas that is near 100% CO_2.

[77] See, for example, James Jeff (2023), "Opinion: electric construction equipment will live or die on battery pricing," *International Rental News*, dated, 20 July 2023. This article provides a table showing that at battery costs under $200 per kWh capacity, construction equipment in a range of sizes will yield payback on additional initial investment on the order of five years or less. A USDOE publication, "FOTW #1272, January 9, 2023: Electric Vehicle Battery Pack Costs in 2022 Are Nearly 90% Lower than in 2008, according to DOE Estimates?," dated January 9, 2023, , indicates that average vehicle battery prices were already under $200 per kWh as of 2022.

[78] Costs derived from NREL ATB workbook downloaded as "2023_v2_Workbook_Corrected_07_20_23.xlsx," worksheet downloaded from "Solar - PV Dist. Res."

Table A-8: Cost Assumptions, Distributed Solar PV (2021 USD)

CAPEX, $/kW	**2022**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**
Residential PV Low CAPEX	$3,570	$3,058	$2,207	$1,355	$1,256	$1,156	$1,056
Residential PV High CAPEX	$3,570	$3,368	$3,034	$2,699	$2,436	$2,173	$1,910
Residential PV Mid CAPEX	**$3,570**	**$3,187**	**$2,548**	**$1,910**	**$1,725**	**$1,539**	**$1,355**
Commercial PV Low CAPEX	$2,309	$ 2,017	$ 1,530	$ 1,043	$985	$927	$868
Commercial PV High CAPEX	$2,309	$ 2,212	$ 2,049	$ 1,888	$1,722	$1,556	$1,391
Commercial PV Mid CAPEX	**$2,309**	**$ 2,097**	**$ 1,744**	**$ 1,391**	**$1,274**	**$1,158**	**$1,043**
OPEX, $/kW-yr							
Residential PV Low OPEX	$37.5	$32.7	$24.2	$17.0	$ 15.7	$ 14.5	$ 13.3
Residential PV High OPEX	$37.5	$36.3	$32.7	$29.1	$ 26.6	$ 24.2	$ 21.8
Residential PV Mid OPEX	**$37.5**	**$33.9**	**$27.9**	**$21.8**	**$ 20.6**	**$ 18.2**	**$ 17.0**
Commercial PV Low OPEX	$23.0	$20.6	$17.0	$12.1	$ 12.1	$ 10.9	$ 10.9
Commercial PV High OPEX	$23.0	$21.8	$18.2	$15.7	$ 14.5	$ 13.3	$ 12.1
Commercial PV Mid OPEX	**$23.0**	**$21.8**	**$20.6**	**$19.4**	**$ 18.2**	**$ 17.0**	**$ 15.7**

The **district heat** module is included to provide heat to the Baltimore Heating Loop in scenarios where the MSW-fueled portion of the Baltimore Waste-to-Energy Plant (the Wheelabrator Baltimore plant) is shut down to reduce emissions. We assume a capital cost for the plant of $200,000 per MW of heat production capacity, which is a rough estimate derived from a presentation at an ACEEE (American Council for an Energy-Efficiency Economy) Summer Study.[79] No estimate for the O&M costs of such plants was immediately available, although those costs will likely be more than offset by the reduction in O&M costs of the WtE plant.

For **hydrogen** production, we assume electrolyzer costs fall from $22.2 per gigajoule per year (GJ/yr) of hydrogen output capacity in 2020 to $6.34 GJ/yr in 2050.[80]

Costs for the improvements needed in electricity **transmission and distribution** in the Additional Actions case are based on a rough estimate of additional costs to accommodate a mostly renewable grid.[81] A Lawrence Berkely National Lab (LBNL) source document estimates the additional grid cost of each added MWh of renewable generation as within the wide range from $1 to $10 per MWh. We use $5/MWh as a

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[79] Cordin Arpagaus of the Institute for Energy Systems IES (2023), "Industrial Heat Pumps: Technology readiness, economic conditions, and sustainable refrigerants," Industrial Heat Pump Workshop at ACEEE Industrial Summer Study, 11 July 2023, Detroit, USA. Assumes low-end of investment costs for devices like the "Epcon MVR-HP" (listed in table on slide 14 of source, which is based on an international energy agency (IEA) document). Six or so of the largest units would be required. Assumes average COP of 4.00 (efficiency of 400%).

[80] CAPEX costs for hydrogen electrolyzers estimated based on data in the IRENA (2020) document "Green Hydrogen Cost Reduction: Scaling Up Electrolysers To Meet The 1.5°C Climate Goal".

[81] Costs are based on the article/report "Improving estimates of transmission capital costs for utility-scale wind and solar projects to inform renewable energy policy," by Will Gorman, Andrew Mills, Ryan Wiser of LBNL, dated October 2019, This article concludes "The average VRE LCOT range estimated in this study, $1–$10/MWh, represents a substantial expense in relation to the LCOEs of utility-scale wind ($29–$56/MWh) and solar ($36–$46/MWh)."

starting assumption and convert it to cost per kW added (about $225 per additional kW of renewable generation deployed). Once again this is based on a near-center point of a very wide range, and may overlap with allocations for electricity storage, which we account for separately. In addition, as network operators and regulators learn more about how to accommodate renewables on grids, it is not clear that the transmission and distribution upgrade costs of will actually be as significant as many observers believe.[82]

For **LNG exports**, in the LNG electrification scenario (a part of the Additional Actions case), our estimate of the cost of electrification is based on a document by the electricity sector infrastructure provider ABB describing the benefits of LNG electrification. This document implies that electric drives for a 6.25 Million TPA (metric tons of LNG per annum) plant would cost $30.00 million, which would scale up to $37.54 million if sized for the Cove Point facility, and is entered as a module cost for the LNE case.[83] Implied maintenance costs before conversion for the Cove Point plant, based on this source, would be $12.51 million/yr if sized for the Cove Point facility, with maintenance costs for the electrified plant decreasing by 50%. Note that the plant illustrated in the ABB source document assumes that an on-site, gas-fired generation plant will run the electric drives, whereas we are implicitly assuming that the electrified LNG plant will run on MD grid electricity that will be increasingly renewables-based over time. Scaled per unit of output, O&M costs would be $38,498.46 per million GJ/yr of capacity. We model the facility as decreasing its gas use, but not increasing its send-out (that is, despite the additional gas available via savings, we do not assume that exports will be increased) but send-out could alternatively (and probably would) be increased to take advantage of the gas savings.

Most capital and O&M (fixed and variable) costs for **electricity generation** plants, as shown in Table A-9, were derived from the 2023 NREL *Annual Technology Baseline*, Moderate scenario.[84]

Table A-9: Cost Assumptions, Central-station Electricity Generation (2021 USD)

Generation Type or Plant	Capital Costs ($/kW)			Fixed O&M Costs ($/kW-yr)			Variable O&M Costs ($/MWh)		
	2023	2035	2050	2023	2035	2050	2023	2035	2050
Utility Solar	$ 1,331	$ 829	$ 632	$ 21	$ 16	$ 13	-	-	-
Onshore Wind	$ 1,568	$ 1,145	$ 968	$ 28	$ 24	$ 21	-	-	-
Offshore Wind	$ 4,750	$ 3,705	$ 3,330	$ 108	$ 88	$ 76	-	-	-
Storage from Solar plus Wind	$ 2,756	$ 1,732	$ 1,270	$ 69	$ 43	$ 32	-	-	-
Hydro	$ 5,898	$ 3,113	$ 2,989	$ 87	$ 87	$ 83	$ 5.80	$ 5.80	$ 5.80
Existing NGCC	$ 1,237	$ 1,108	$ 971	$ 31	$ 27	$ 24	$ 1.94	$ 1.77	$ 1.62
Existing NGCT	$ 1,111	$ 1,005	$ 872	$ 24	$ 22	$ 20	$ 6.44	$ 6.44	$ 6.44
Existing NGST	$ 1,018	$ 1,018	$ 1,018	$ 30	$ 30	$ 30	$ 0.50	$ 0.50	$ 0.50
Coal	$ 4,212	$ 3,970	$ 3,703	$ 78	$ 73	$ 64	$ 8.43	$ 8.01	$ 7.60
Calvert Cliffs Nuclear	$ -	$ 1,200	$ 1,200	$ 152	$ 152	$ 152	$ 2.47	$ 2.47	$ 2.47
Net Imports	$ -	$ -	$ -	$ -	$ -	$ -	$ 85.27	$ 76.31	$ 74.21
MSW Baltimore	$ -	$ -	$ -	$ 157	$ 157	$ 157	$ 5.04	$ 5.04	$ 5.04
MSW Montgomery Cty	$ -	$ -	$ -	$ 157	$ 157	$ 157	$ 5.04	$ 5.04	$ 5.04
Landfill and Biogas	$ 2,803	$ 2,803	$ 2,803	$ -	$ -	$ -	$ 17.87	$ 17.87	$ 17.87

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[82] See, for example, Mike Parr (2015), "Network Costs & Renewables: A Euro View," *T&D World*, dated April 27, 2015. This article cites German and Italian experience of network costs declining or changing very little despite massive additions of renewable capacity.

[83] See ABB (2006), "All electric LNG plants Better, safer, more reliable - and profitable." Despite the age of this document, our guess is that the costs it is indicating are unlikely to be significantly higher today, given the continued improvement in related technologies.

[84] Following from workbook downloaded from NREL (2023), "2023_v2_Workbook_07_20_23.xlsx."

Exceptions to costs drawn from the NREL ATB include:

- Costs for **landfill gas and biogas** plants were derived from a USEPA document, *Landfill Gas Energy Cost Model, User's Manual*.[85]
- Capital costs for offshore wind plants include an adder for interconnection costs, also derived from the NREL ATB, that trends downward from about $900 per kW in 2023 to a bit less than $700/kW by 2050.
- Costs for life extension of the **Calvert Cliffs nuclear power** units were derived from the document *IPM Model – Nuclear Power Plant Costs, Nuclear Power Plant Life Extension Cost Development Methodology, Final*, and also from the USEPA.[86] Life extension costs are significant, at $1200 per kW, but still a factor of five to ten less than the costs of a new nuclear power plant of a similar size, based on recent trends virtually everywhere except China. For example, NREL ATB projections list the cost of nuclear power in 2035 as nearly $7500/kW in a Moderate case, and $8800/kW in a Conservative case, despite a downward trend in costs from current values.
- For **net imports** to Maryland over the PJM connections, estimated variable O&M costs (essentially, average wholesale imported electricity costs for MD) are estimated based on Reference Case "Generation" plus "Transmission" costs for PJM East from AEO2023 modeling. For scenarios with large, assumed penetration of renewables at lower renewables CAPEX, these wholesale costs may be slightly high.

Note that fuel costs for those generators that use fuel—principally natural gas-fired and nuclear generation--are not specified in the electricity generation module within the LEAP model (although it is possible to do so); rather, they are associated with primary or secondary resources as import costs (see below).

We do not include any variable O&M costs for **natural gas pipeline** compressor stations. Those costs, if available, could be added to the model, but are unlikely to be significant relative to the cost of natural gas consumed in the compressors.

For **Maryland coal production**, we assume variable O&M costs of $86 per ton of coal equivalent for underground mines, and $20 per TCE for surface mines. Both values should be considered rough approximations, as costs of mining vary substantially by mine. These costs have little impact, however, on net cost results in the model, as coal-fired power is phased out in the near term in both the Current Policies and Additional Actions cases.

We also include no costs for **natural gas production in Maryland**, as in-state gas production does not vary between the two cases compared and is very small relative to Maryland's natural gas consumption.

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[85] USEPA (2021), *Landfill Gas Energy Cost Model, User's Manual*. The capital cost formula from the source is: ($2,340 * kW capacity) – (0.103 * (kW capacity)^2 +250,000 for interconnection. We assume a typical addition size of 2000 kW. The use of the formula above yields a total capital cost of $4,518,000, or $2,259 per kW in 2008 dollars, which equals an estimated capital cost of $2,803.64 per kW in 2021 dollars. O&M costs listed by the source (sum of fixed and variable O&M costs) is 14.4 $/MWh in 2008 dollars, or 17.87 $/MWh in 2021 dollars. We use these values for both biogas and LFG.

[86] The USEPA-funded document "*IPM Model – Nuclear Power Plant Costs, Nuclear Power Plant Life Extension Cost Development Methodology, Final*", dated January 2018, Project 13527-001, Eastern Research Group, Inc., prepared by Sargent and Lundy, estimates the capital cost of nuclear plant extension after 50 years as $70 per kW-year in 2017 dollars. Assuming a discount rate of 5% and a loan period of 30 years, this equates to a capital cost of $1,200 in 2021 dollars. The same document lists an O&M cost after 50 years of 91 + 0.56 * (Plant Age) $/kW-yr, which would be equal to $168.41 $/kW-yr in 2034, and $186.25 $/kW-yr in 2050, both for the older of the two Calvert Cliffs units. We use these figures in the Calvert Cliffs life extension scenario (a part of the Additional Actions case).

For systems that produce **biogas from animal manures or wastewater solids**, we assume capital costs of $26 per annual GJ of gas output capacity, with fixed O&M costs of $0.64/yr. per annual GJ of gas output capacity.[87]

7.3 Resources

LEAP has the potential to use several types of cost for resources, including **primary resources**, such as coal and natural gas, and **secondary resources**, such as refined petroleum products. Costs can be ascribed to indigenous resources, resource imports, or resource exports, and unmet requirements can also be assigned a cost for use in social cost analysis. The Maryland LEAP model focuses on costs for imported fuels and resources. Most of the cost projections in Table A-10 are derived from historical fuel prices from USDOE EIA sources, extrapolated using regional or national price trends from AEO2023.[88] Note that, as mentioned above, most of the key costs for end-use fuels, such as for diesel, gasoline, and natural gas, are presented as wholesale costs, as wholesale costs are what the state (society) as a whole pays or saves when use of fuels rise or decline between scenarios. When considering costs perspectives other than societal costs (for example, that of consumers), using retail costs, which are higher, would be appropriate, but analyses from different cost perspectives have not been a part of our analyses of the Current Policies and Additional Actions cases to date.

Table A-10: Fuel Price Projections, Primary and Secondary Fuels/Resources (2021 USD)

Fuel	Units	2023	2030	2035	2040	2045	2050
Brent Spot Oil Price	2021 USD/BBL	$ 71.98	$ 70.89	$ 73.56	$ 75.79	$ 77.52	$ 79.68
Gasoline Wholesale Price	2021 USD/Gallon	$ 2.37	$ 1.99	$ 2.02	$ 2.07	$ 2.08	$ 2.15
Diesel Fuel Wholesale Price	2021 USD/Gallon	$ 2.46	$ 2.02	$ 2.06	$ 2.08	$ 2.10	$ 2.13
Jet Fuel Wholesale Price	2021 USD/Gallon	$ 2.38	$ 2.13	$ 2.20	$ 2.26	$ 2.31	$ 2.36
Sustainable Aviation Fuel	2021 USD/Gallon	$ 4.75	$ 4.01	$ 3.94	$ 3.82	$ 3.68	$ 3.54
Distillate Fuel Wholesale Price	2021 USD/Gallon	$ 2.30	$ 2.04	$ 2.09	$ 2.11	$ 2.13	$ 2.15
Propane Wholesale Price	2021 USD/Gallon	$ 0.65	$ 0.58	$ 0.63	$ 0.66	$ 0.68	$ 0.68
Natural Gas Henry Hub Spot	2021 USD/MMBtu	$ 2.19	$ 1.50	$ 1.61	$ 1.66	$ 1.63	$ 1.59
Coal Price in Maryland for	2021 USD/MMBtu	$ 3.95	$ 4.11	$ 4.00	$ 3.69	$ 3.73	$ 3.81
Residual OIl, trended by "All	2021 USD/Gallon	$ 1.77	$ 1.97	$ 2.03	$ 2.07	$ 2.10	$ 2.15
Compressed Natural Gas	2021 USD/MMBtu	$ 14.69	$ 14.00	$ 14.11	$ 14.16	$ 14.13	$ 14.09
Electricity Imports from (and Exports to) PJM	2021 USD/MWh	$ 78.58	$ 69.82	$ 70.32	$ 73.06	$ 72.45	$ 68.38
Nuclear Fuel Costs	2021 USD/MWh	$ 6.88	$ 6.87	$ 6.87	$ 6.87	$ 6.86	6.86

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[87] Based on data from Benefits, US EPA, "Costs and Operating Experience at Seven New Agricultural Anaerobic Digesters" and Duke University Nicholas Institute, "Biogas in the United States: An Assessment of Market Potential in a Carbon-Constrained Future".

[88] For petroleum products, data sources are "Petroleum & Other Liquids, Spot Prices, (Crude Oil in Dollars per Barrel, Products in Dollars per Gallon)". 2023 values were taken as averages of monthly values through August from EIA (2023) "Spot Prices, Crude Oil." Historical natural gas prices were from EIA (2023), "Natural Gas Spot and Futures Prices, NYMEX," historical coal prices for Maryland were from USDOE EIA, "Coal Data Browser," and compressed natural gas historical prices were from Mika, Shelley (2021), "Comparing Alt Fuel Costs for Vocational Fleets," *Worktruck Online*. Reference case projections for energy prices were taken from the USDOE EIA AEO2023, downloaded from "Table 3. Energy Prices by Sector and Source," and "Table 12. Petroleum and Other Liquids Prices." For imports of electricity from PJM, costs were projected based on data in "Table 54.10. Electric Power Projections by Electricity Market Module Region (PJM East)".

7.4 Social Cost of Carbon

Estimates of the social costs of carbon (SCC) are not used in the primary cost-effectiveness evaluation of the relative costs and benefits of the Current Policies and Additional Actions cases but are used in sensitivity analyses to see what the net benefits of the Additional Actions case would be if SCC is included.

SCC values continue to be widely debated throughout the climate policy communities, but two major recent sets of values stand out:

1. The current “Biden Administration” Social Cost of Carbon (SCC) is set at $51 per MTCO$_2$e, presumably in 2020 dollars.[89] Expressed in 2021 dollars, this would be $53.74 per MTCO$_2$e.
2. At a higher level, are a pair of studies with similar results, one published in Nature, and one in a recent USEPA document. A study reporting a value of $185 per tCO$_2$e, also in 2020 dollars, was quoted in a 2022 Resources for the Future press release.[90] The press release refers to a study published in Nature by multiple authors.[91] Expressed in 2021 dollars, the mean value above would be $194.94 per tCO2e. A SCC value from a 2022 USEPA study that would correspond to the $185 per tCO$_2$e value above is $190 per tCO$_2$e, also in 2020 dollars. Expressed in 2021 dollars, this would be $200.21 per tCO2e.[92] The latter document proposes a range of SCC values, as shown in table ES-1 in the sources document and summarized, for CO$_2$ only and through 2050 in Table A-11. These SCC estimates rise with the year of emissions and when lower discount rates (“Near-term Ramsey Discount Rate”) are used to value the economic impacts of climate damages. The implication is that the SCC used for modeling the benefits of reducing GHG emissions over multiple decades might in fact most appropriately use a series of costs rising over the years, as damages due to climate change become more severe, and thus the value of reducing emissions rises. Although we do not use SCC costs that rise over time in the work described in this Report, we note that it may be appropriate to do so in the future, and it would be straightforward to test the impacts of such rising SCC costs in sensitivity analyses using the Maryland LEAP model.

Table A-11: Stream of Increasing SCC Values based on USEPA Report Results

	2020	2030	2040	2050
SCC, 2021 dollars	$ 200.21	$ 242.36	$284.51	$326.65

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[89] See, for example, Jean Chemnick (2021), “Cost of Carbon Pollution Pegged at $51 a Ton, The Biden Administration raised the benchmark, and may do it again within a year,” *Scientific American*, March 1, 2021.

[90] “Social Cost of Carbon More Than Triple the Current Federal Estimate, New Study Finds,” dated Sept. 1, 2022,.

[91] Kevin Rennert, Frank Errickson, Brian C. Prest, Lisa Rennels, Richard G. Newell, William Pizer, Cora Kingdon, Jordan Wingenroth, Roger Cooke, Bryan Parthum, David Smith, Kevin Cromar, Delavane Diaz, Frances C. Moore, Ulrich K. Müller, Richard J. Plevin, Adrian E. Raftery, Hana Ševčíková, Hannah Sheets, James Stock, Tammy Tan, Mark Watson, Tony E. Wong, and David Anthoff (2022), "Comprehensive evidence implies a higher social cost of CO$_2$,” *Nature*, 610, pages 687–692 (2022). This article lists a range of "$44-413/t-CO$_2$: 5-95% [confidence interval] range, 2020 US dollars) at a near-term risk-free discount rate of 2 percent".

[92] USEPA (2022), “Supplementary Material for the Regulatory Impact Analysis for the Supplemental Proposed Rulemaking, “Standards of Performance for New, Reconstructed, and Modified Sources and Emissions Guidelines for Existing Sources: Oil and Natural Gas Sector Climate Review,” dated September, 2022.