

Development of Integrated Vehicle and Fuel Scenarios in a National Energy System Model for Low Carbon U.S. Transportation Futures

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A Research Report from the National Center
for Sustainable Transportation

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EXECUTIVE SUMMARY

Transportation is a major emitter of greenhouse gas (GHG) emissions in the United States accounting for 27% of the country's emissions, second only to the electricity sector (EPA, 2018). As a result, reducing GHG emissions are essential for mitigating some of the most damaging potential impacts associated with climate change and because of the importance and relative size of the transportation sector, it would need to contribute a significant amount of emissions reduction.

This report describes the development and use of an U.S. energy system optimization model (US-TIMES) in order to analyze the reductions in GHG emissions that can come about through policy targets. These policy targets induce technology investments and operation in order to satisfy the demand for energy services and environmental policy constraints (notably GHG emission targets).

The model development focused on two key areas within the transportation sector, light-duty vehicles and heavy-duty vehicles. In the light-duty space, we incorporated consumer choice elements into the energy system optimization framework through increasing consumer heterogeneity and adding non-monetary decision factors such as risk and fueling inconvenience. For heavy-duty vehicles, we adopt a segmentation approach and update vehicle cost and performance assumptions from our recent work.

The model is used to project scenarios for low carbon futures from a reference scenario all the way to an 80% GHG reduction target. Figure ES-1 shows the emissions and reductions by sector for each scenario. The figure shows that the electricity is the primary mechanism for reducing emissions at low target levels. The industrial sector makes very deep emissions reductions at moderate GHG targets while transportation (vehicles and fuel supply) makes reductions at the highest, most stringent reduction levels.

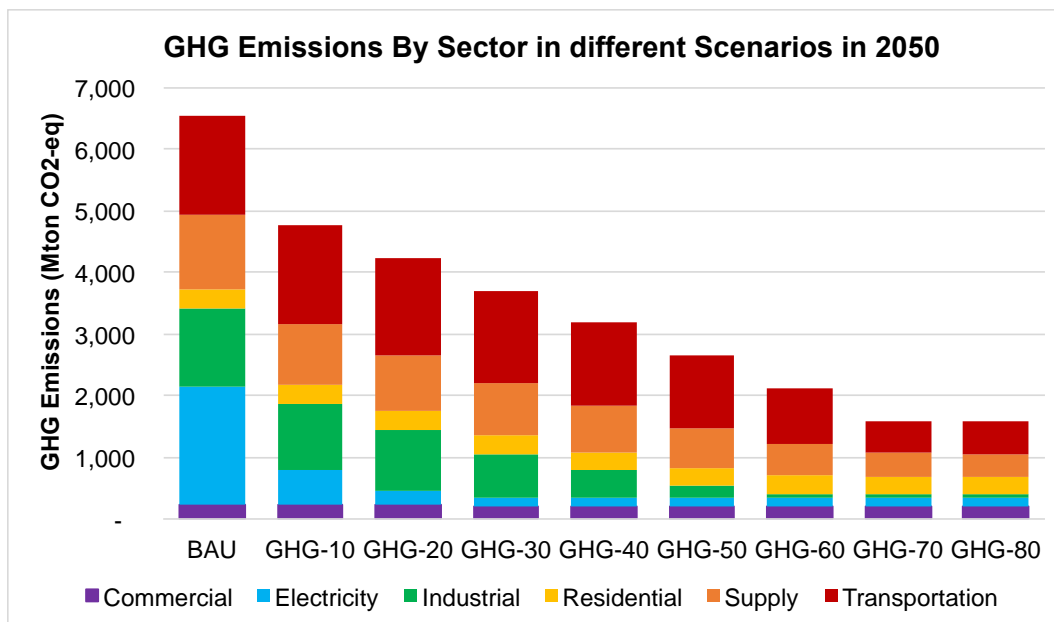


Figure ES-1. GHG emissions in 2050 by sector for different GHG reduction scenarios.

This result indicates the relative marginal cost of abatement is lowest in the electric sector and transportation has a fairly high cost of abatement, a result that is borne out by many other studies. This result is reinforced, somewhat, by the fact that incorporating other non-monetary factors into the choice calculus that the model uses for its system-side optimization (which already includes consumers' high discount rates for energy efficient purchases) tends to delay widespread adoption of advanced technology, alternatively-fueled vehicles. These retarding factors include technology risk and uncertainty, model availability, infrastructure availability and refueling inconvenience. Therefore, these factors tend to reinforce the relative ranking of transportation (especially passenger transportation purchases by consumers) as a mitigation option with relatively high abatement cost.

Figure ES-2 shows that the light-duty vehicle mix in each of the GHG reduction scenarios. As discussed previously, the changes to this sector occur only at more stringent GHG reduction levels (40% and up). This is because of the relatively high "cost" of abatement (i.e., purchases of electric and hydrogen vehicles), especially when including costs such as charging infrastructure availability, risk averseness within the largest consumer segments and limited model availability. Only when the GHG emission reduction targets are very stringent (50% reduction or greater) do we see substantial adoption of ZEV technologies. We do see some adoption of PHEVs in the business as usual (BAU) and other modest GHG reduction scenarios because of the presence of the ZEV mandate in many parts of the country. In the most stringent cases (70% reduction or greater, we have 100% adoption of ZEV or partial-ZEV technologies. In these stringent cases, we see substantial PHEV adoption because of home/work charging availability issues.

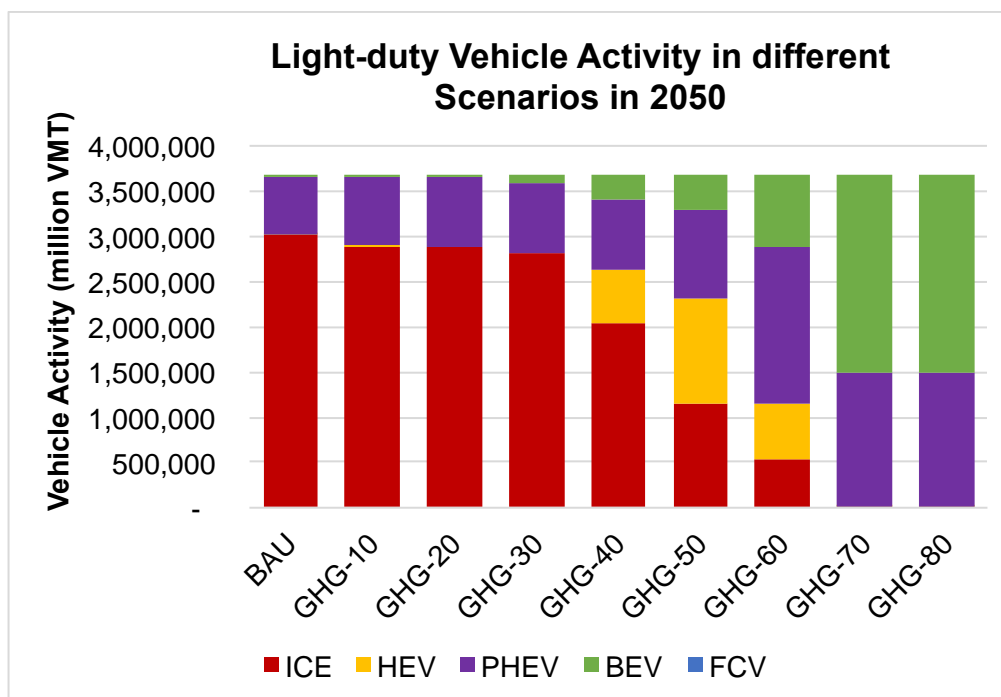


Figure ES-2. Share of light-duty fleet VMT by technology category.

We see similar results, though focused on hydrogen fuel cell vehicles, for medium and heavy-duty trucks (Figure ES-3). Transportation emissions are reduced because of a complementary reduction in emissions from the electric sector (for both EV charging and hydrogen production).

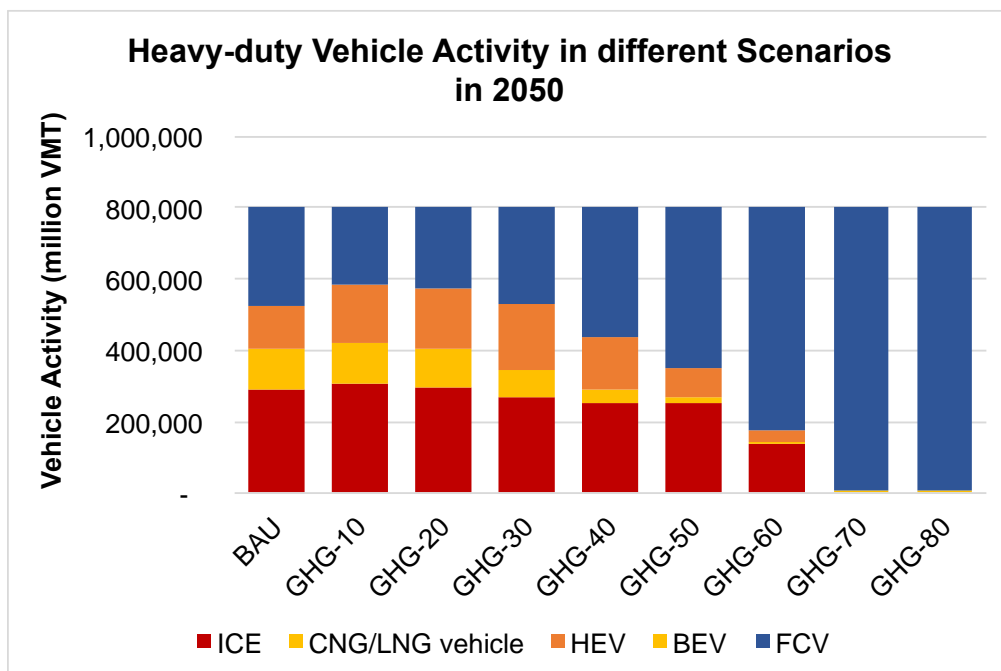


Figure ES-3. Vehicle activity of heavy-duty vehicles in different scenarios in 2050.

Overall, this initial analysis with the US-TIMES model shows how an energy system model can be used to analyze the role of vehicle technologies and fuels within a national energy system like that of the United States. These models are useful for analyzing cross-sectoral policies like carbon caps and cross-sectoral energy issues like resource competition (e.g., biomass) and synergies (e.g., charging of electric vehicles). Using a cost minimizing model, we find that emissions reductions at low cap levels focus primarily on decarbonizing electric sector emissions, and as you increase the stringency of the GHG cap, emissions reductions occur in additional sectors until the transportation sector is decarbonized at the most stringent levels (GHG-60 to GHG-80).

Introduction

Climate change is one of the critical important environmental issues of the 21st century, and has been linked to human activities that release emissions and increase the concentration of greenhouse gases (GHG) in the atmosphere. Limiting climate change impacts to 2°C would require a dramatic reduction in overall GHG emissions, estimated to be on the order of 80% or more by 2050 across developed nations (IPCC, 2014). Transportation is a major emitter of GHG emissions in the United States accounting for 27% of the country's emissions, second only to the electricity sector (EPA, 2018). As a result, reducing greenhouse gas (GHG) emissions are essential for mitigating some of the most damaging potential impacts associated with climate change and because of the importance and relative size of the transportation sector, it would need to contribute a significant amount of emissions reduction.

As part of a sustainable transportation system for the United States and a sustainable economy, reducing the GHG emissions from the transportation sector is critical. This report will detail ongoing analysis of vehicle technology, fuel pathway and resource options for reducing emissions from transportation to the year 2050. How these transportation mitigation options fit into the larger suite of economy-wide emissions is another important question to answer. The goal of this study is to help the visioning process for understanding how decarbonization of the transportation sector helps contribute to climate stabilization scenarios, through the development and use of a national level U.S. energy economic optimization mode, called US-TIMES. Through the use of scenarios and system optimization, we analyze the contribution of emissions reductions across transportation sectors as well as highlight the vehicle and fuel pathways that can help drive these reductions. The purpose is to help engage with government and policymakers to explore how a transition to low-carbon, alternative fuels and zero-emission vehicles could occur. An important secondary goal is to understand the critical linkages and synergies between the transport sector and other energy sectors.

Background and Motivation

Reductions in transportation emissions can be accomplished by looking at the primary factors of a decomposition analysis: activity reductions, modal shifts, higher efficiency, lower carbon intensity (Schipper et al., 2001; Yang et al., 2008). It is expected that these last two elements can and will make up the bulk of emissions reductions and as a result, the model and analysis described in this paper will focus the analysis on exploration of these resource and technology based factors. Understanding the role of the various transportation subsectors (light-duty vehicles, heavy-duty vehicles, rail, aviation and marine) in contributing to emissions as well as understanding the potential and challenges for technology based reductions in emissions is critical for analysis of this sector and its role in economy-wide GHG emissions.

National Transportation Analyses

Recent analyses of GHG mitigation options (e.g., (IPCC, 2014; Morrison et al., 2015; Yang et al., 2015)) all point to the importance of transportation to contribute significant reductions. A number of assessments have been performed to try to understand the potential for GHG reductions in the transportation sector, for both the U.S. (CARB, 2009; Greene and Plotkin, 2011; McCollum and Yang, 2009; Melaina and Webster, 2011; Wei et al., 2013; Yang et al., 2009; Yang et al., 2011) and for California (CARB, 2009; Yang et al., 2009; Yang et al., 2011). These studies point to the importance of low-carbon fuels (biofuels, hydrogen and electricity) and advanced, highly efficient vehicle technologies (especially electric-drive vehicles, batteries and hydrogen fuel cells) to achieving dramatic reductions in GHG emissions from the transport sector. However, they all have important limitations that this study hopes to overcome. See Table 1 for a list of current and past transportation GHG analyses and their limitations.

Table 1. Summary of current U.S. transportation/energy models and analyses and limitations.

Model	Authors	Model Type	Sectors	Limitations ^a
On Road in 2035 (2008) (Bandivadekar et al., 2008)	MIT	Assessment exercise, Spreadsheet scenario	LDV	1,3,5
McCollum and Yang (2009) (McCollum and Yang, 2009)	UC Davis	Spreadsheet scenario	All	2,3,4,5
VISION (2014) (ANL, 2014)	Argonne	Spreadsheet scenario	LDV, HDV	1,2,3,4,5
Greene and Plotkin (2011) (Greene and Plotkin, 2011)	DOE	Assessment exercise	All	2,3,5,6
Transportation Energy Futures (2013) (DOE, 2013)	DOE	Assessment exercise	All	2,3,4,5,6
LAVE-TRANS (2013) (NRC, 2013)	NRC	Spreadsheet, consumer choice	LDV	1,3,5
MA3T (2012) (Dong and Lin, 2012)	Oak Ridge	Spreadsheet, consumer choice	LDV	1,3,5
NEMS (2013) (NEMS, 2013)	DOE	Economic simulation model	All	6,7
U.S. MARKAL (2014) (Lenox et al., 2013)	EPA	Optimization Model	All	2,6
National U.S. TIMES Dataset (2013) (NUSTD, 2013)	NC State	Optimization Model	All	2,3,6,7
CA-TIMES (2015) (Yang et al., 2015)	UC Davis	Optimization Model	All	2,8

- ^a (1) Only includes a subset of transportation sectors
(2) Limited representation of some transportation sectors
(3) Limited representation of fuel production and infrastructure
(4) Lacking a full assessment of economic costs
(5) Ignores interactions with other key energy sectors
(6) Does not develop full scenarios of low-carbon transportation mix
(7) Limited representation of alternative technologies and fuels
(8) Limited geographic scope (California only)

While each of these analyses look at the future transportation picture in slightly different ways, none of them fully represent all of the critical elements to analyzing a transition to a low GHG transportation sector in a complete and integrated manner. One of the key limitations of several transportation GHG analyses is their focus on only a subset of transportation subsectors (typically light-duty vehicles, LDVs). Another limitation is their oversimplified representation of important transportation subsectors such as heavy-duty, rail, air and marine. For example, many analyses represent heavy-duty vehicles as a single monolithic category, instead of distinguishing between various types of heavy vehicles, like long-haul vs port vs delivery trucks. Another key gap in many current models is their limited representation of fuel production and infrastructure. The development and commercialization of alternative fuel supply chains is similarly, or even more challenging than development and commercialization of vehicle

technologies (e.g., hydrogen). Another limitation is that these studies often do not include an assessment of the cost of vehicle technologies and fuel infrastructure, only looking at the mix of technologies necessary to achieve a particular emissions goal. Assessment of incremental costs of vehicles and fuels is essential for understanding the likelihood and also the key barriers for these futures to be realized. A final limitation of many transportation models is that they often ignore interactions with other sectors of the energy system (such as electricity generation, resource and energy supply, and other end use sectors).

Many of these analyses are spreadsheet scenario tools such as the VISION spreadsheet model (ANL, 2014), which do provide policy-makers and interested stakeholders the ability to vary assumptions and understand the impacts of these changes. However, current versions of these models suffer from many of the limitations described in the last section. Among the main issues are lack of representation of fuel production and infrastructure, and interactions with other energy sectors. Integrated optimization models such as MARKAL/TIMES provide a minimum cost solution to lowering GHG emissions and the ability to identify and analyze the policies, technologies and resource that can be used to meet substantial GHG reduction targets. Specifically, they are useful for understanding the tradeoffs between emissions reductions between different sectors in order to meet policy targets at lowest overall costs. We focus on development of a new energy/economic model US-TIMES, to assess the costs of a low-carbon vehicle and fuel transition in the U.S. transportation sector and enable us to understand its potential role in a comprehensive, national GHG reduction approach. US-TIMES will build on existing work notably CA-TIMES (a California energy/economic model developed at UC Davis) (Yang et al., 2015) and existing National level MARKAL/TIMES models (including the EPA 9R MARKAL model (Lenox et al., 2013)).

Energy System Economic Optimization Models

Energy systems models have been used to understand the interactions between supply and demand, the role of new technologies, and the impacts of policies under various *long-term* scenarios. The model paradigm incorporates features from several areas such as energy, economics, engineering, and environment. Since the 1970s, several kinds of energy systems models have been developed that employ different types of mathematical methods such as linear programming (MARKAL, (Loulou et al., 2004) TIMES, (Loulou et al., 2005)) accounting (LEAP, (Heaps, 2012)), and simulation (WEM, (IEA, 2016)).

Models based on a linear programming framework identify the least-cost investment pathways in order to build, maintain and operate the energy system (often from resource extraction to energy end-use) under different long-term scenarios. Optimal solutions to these models are obtained by minimizing an objective function consisting of the discounted total system cost of the energy system over the entire model horizon. For example, MARKAL and TIMES developed by the International Energy Agency and Energy Technology Systems Analysis Programme (Loulou et al., 2004; Loulou et al., 2005) have been used widely to conduct in-depth analyses of energy pathways for long-term scenarios (UK- MARKAL, (Kannan et al., 2007); CA-TIMES, (Yang et al., 2015); US-TIMES, (Babaee et al., 2014)).

These models can be useful because in optimizing the entire energy system, it allows for a means to begin to answer one of the most challenging questions in decarbonizing a large and complex energy system: What is the best combination of cost-effective emissions reduction strategies across sectors when there are important synergies between sectors?

Some of the primary limitations of this approach are that these models assume a single, social decision maker whose decisions are based solely on cost minimization. Because linear programming leads to corner solutions, this yields all or nothing outcomes on technology investments. Specifically, solving the model often yields a decision to invest in a single technology in a given year (rather than a mix of technologies), but may switch to an entirely different technology in the next year. This so-called “knife-edge” behavior results as small changes in costs can lead to a complete shift from one technology to another.

These models have been criticized for producing results that are an unrealistic representation of market behavior (Schafer, 2012). This problem of a highly simplified representation of consumer behavior in long-term integrated assessment energy models has been long recognized (Wilson and Swisher, 1993). Many identify this lack of a realistic depiction of consumer behavior as one of the major challenges that ESOM must address to build a complete climate policy analysis framework, as concerns about achieving climate goals increase over time (Brosch et al., 2016; DeCarolis et al., 2017; Pfenninger et al., 2014).

These limitations will be addressed via the addition of our consumer choice module for the light-duty sector described in the next section.

Modeling Methodology

This approach for this project is to develop a national energy economic optimization model that address each of these key limitations of the models described in Table 1. The key improvements include (1) incorporating consumer choice elements into our modeling of the light-duty vehicle choice module, (2) providing assessments of transportation subsectors at a disaggregated level including light duty vehicles, heavy duty vehicles, rail, aviation and marine, (3) developing models that focus on both vehicle technologies and fuel infrastructure from production to refueling, and (5) modeling the integrated energy system to understand important linkages/synergies between the transport sector and other energy sectors. This model can then be used to analyze scenarios of GHG emissions reductions at a national level and assess the role of the transportation sector in achieving these reductions.

TIMES Modeling Framework

This research project develops our model using the TIMES framework, a widely utilized energy modeling platform throughout the world. The TIMES framework, developed by ETSAP (in conjunction with the International Energy Agency) is used by dozens of academic and governmental institutions across the world to develop energy system models for states/provinces, countries and larger regions.

TIMES (a variant/evolution of the MARKAL framework) enables the characterization of the energy system (via investments in technologies and processes) that can meet projections for future energy services in a least cost manner. This is accomplished via a bottom-up, technologically-rich, integrated economic (linear) optimization modeling approach (Loulou et al., 2005).

The model represents all of the main sectors of the energy system including energy supply (energy resources, fuel production, conversion and delivery, and electricity production) and energy demands (residential, commercial, transportation, and industrial end-use sectors). In each of these parts of the energy system, the demand for end-use energy services must be supplied by flows of energy and energy commodities that are mediated and/or transformed by various technologies, such as vehicles, appliances, transmission and distribution systems, power plants, fuel production facilities and resource extraction. The model chooses the appropriate mix of these technologies in order to ultimately meet the demand for energy services that also yield the lowest discounted system cost, and subject to any specific system constraints such as limits on resource availability, technology growth limits and/or policy constraints (e.g., limits on emissions).

The structure of the US-TIMES model is laid out across numerous energy sectors across the nine U.S. Census regions and is built upon the EPA's 9 region MARKAL/TIMES model. Energy service demands are specified for end-use sectors for each region and drive the operation of existing energy supply and end-use technologies and required investments in new energy supply and

end-use technologies to cover shortfalls caused by growing demands and retiring energy infrastructure and appliances.

Figure 1 shows the structure of the U.S. TIMES model as broken into various stages of the energy system. On the left side of the figure shows the demands for energy services that drive the need for energy production/conversion/delivery processes. Everything to the right of the energy service demands in the diagram must be present (as part of the existing energy system or built as part of the evolving energy system) in order to supply the energy services specified in the model inputs.

Projected service demands to 2050 are described exogenously as input assumptions for the residential, commercial, industrial and transport sectors. The specification of energy service demands (e.g., heating, cooling, lighting, water heating, etc., in the residential and commercial sectors, boilers, process heat, machine drive in the industrial sector and vehicle miles traveled (VMT) across different transportation sectors (light-duty, heavy-duty, aviation, marine, off-highway, etc.)) means that the model has the flexibility to meet these demands from a set of technologies (appliances and vehicles) that can differ in the fuel type, energy efficiency and capital and operating costs. The model minimizes the cost of supplying these energy service demands by choosing the appropriate technologies as a function of their costs, efficiency and upstream fuel costs.

Given policy constraints like a carbon cap, the model has the flexibility to trade off higher costs for these technologies for greater emissions reductions and choose the appropriate mix of these technologies.

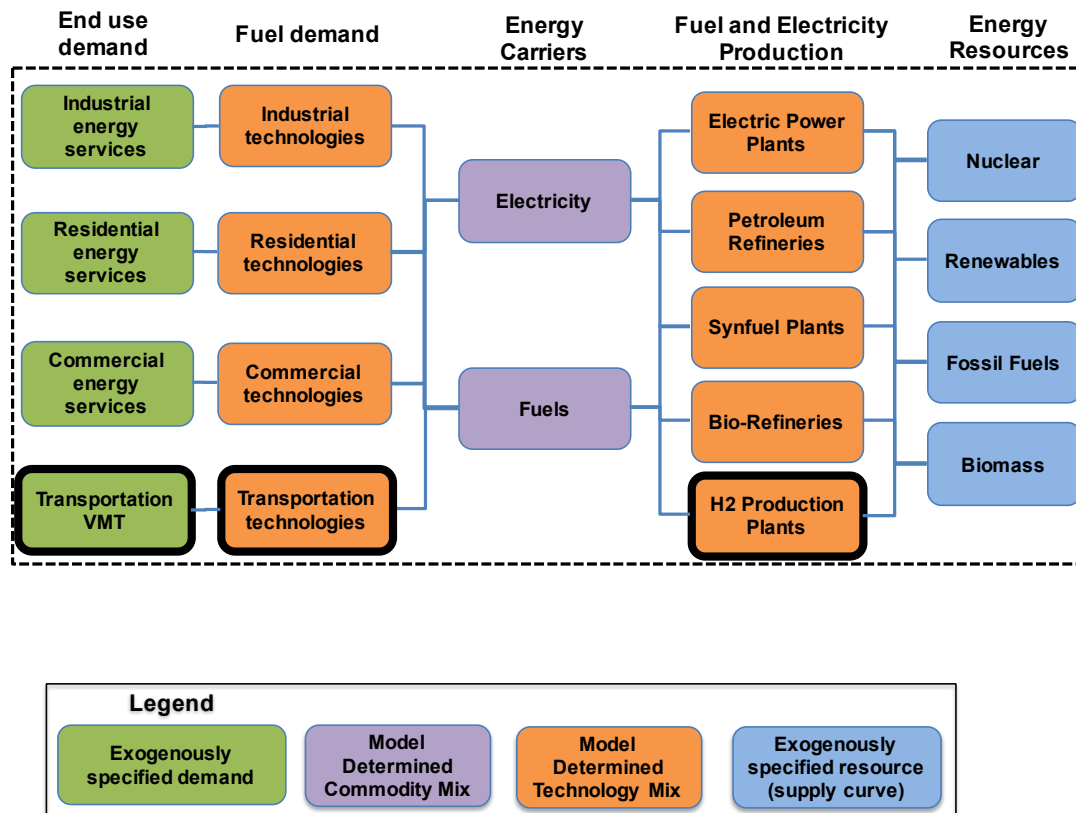


Figure 1. High-level structure of the full US-TIMES Energy System Model showing end use service demands and the fuels and energy conversion technologies and energy resources that will supply these service demands.

The choice of technologies and fuels that are used to supply these sectoral demands need to be supplied requires the existence of an energy supply infrastructure to provide these energy flows. The US-TIMES model must invest in technologies to extract and transport primary energy resources to the United States and plants and facilities that convert these primary energy resources into electricity and the finished fuels that are demanded. Each of these choices has a direct economic cost, related to the investment, installation and operation of the supply infrastructure and demand technologies. Because US-TIMES is an optimization model, all of the economic costs of these choices are summed and discounted to present value in order to find the mix of resource usage and technologies that meet the energy demands while minimizing the overall system cost. The same process can be used to analyze scenarios for meeting GHG emissions targets; the model will find the exact mix of technologies and resource utilization that minimizes the combined economic costs of all parts of the energy system that both meets the specified energy demands and GHG targets.

EPA Energy System Database

The U.S. Environmental Protection Agency (EPA) developed a National Energy System model based upon the MARKAL/TIMES framework. The model was originally developed as a MARKAL model but was recently updated to fit the newer TIMES framework in 2017. The US-TIMES model developed and used by the authors in this report draw very heavily on the original nine-region EPA MARKAL/TIMES model (called the EPA9R model) in order to draw from the best available data and model inputs while updating and expanding specific sections that we have particular expertise in.

The EPAUS9r was developed around the nine U.S. Census divisions and covers a modeling horizon from 2005 to 2055. The nine divisions, considered regions in the database, were chosen to follow the same divisions as the U.S. Energy Information Administration (EIA) Annual Energy Outlook (AEO) (AEO, 2013).

The technologies included in the database are commercially available technologies with historical data for investment costs, efficiencies, and operating and maintenance costs. Most of these technologies were drawn from the AEO, while other technologies are constructed from widely recognized authoritative sources.

Each of the nine-regions in the database has its own conventional reference energy system (RES), i.e., the linkages between energy processes and commodity flows. The nine RES structures are then interconnected through a series of trade technology links, so that for inter-regional energy or energy carrier imports/exports (e.g., petroleum and finished fuels, natural gas, coal, and electricity). The regions are shown in the **Figure 2**:

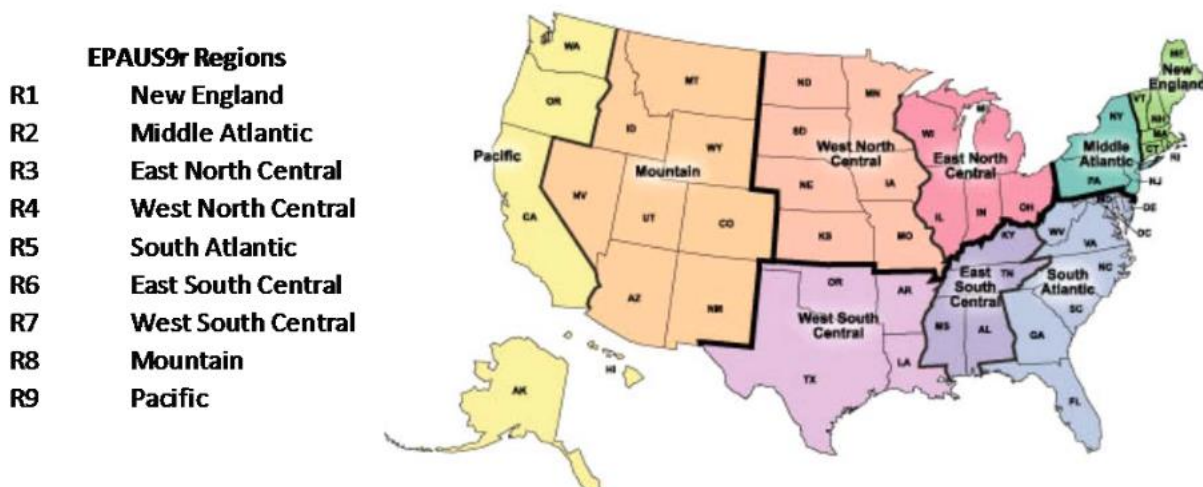


Figure 2. Regional breakdown (based upon U.S. Census regions) used in the EPA9R model and the US-TIMES model.

For more information about the EPA9R model and database see EPA 2013 (Lenox et al., 2013).

Consumer Choice Integration

This is one of the most critical new additions to the US-TIMES modeling. As described in the background, most TIMES models and other energy system models are not equipped to represent how consumer markets might actually respond to policy or technology changes. This is critical because much of the effect of climate policies will be borne by consumers decisions about investments in appliances/vehicles and energy choices.

The default decisions of optimization model often yield unrealistic, ‘all-or-nothing’ technology choices, because heterogeneity of decision-maker preferences and motivations are not represented. Often models such as these invoke ad-hoc approaches to model more “real-world” behavior, such as constraints on the share of specific technologies, on rates of growth and adoption and high discount rates to represent non-monetary factors that may affect utility for some technologies. Representing consumer behavior realistically becomes particularly important when it comes to light-duty vehicles in the transportation sector: they are the source of a substantial percentage of emissions that are difficult to reduce, and consumer perceptions play an important role in their adoption. An alternative methodology that incorporates theory-based behavioral factors directly into a frequently used energy systems modeling framework called COCHIN-TIMES (COnsumer CHoice INtegration in TIMES) is developed. (Ramea et al., 2018)

This modification incorporates multiple types of factors related to consumer utility/preference for vehicles, namely the inclusion of non-monetary factors that influence consumer utility for vehicles and also inclusion of consumer segmentation. The version incorporated into the US-TIMES model uses the approach and data from the MA3T vehicle choice model developed by Oak Ridge National Laboratory as the primary data source (Lin and Greene, 2010). The end-use demands of light-duty cars and light-duty trucks are divided into diverse set of consumer segments differentiated by driving profiles (annual VMT), and attitude toward risk. For each consumer segment, disutility costs are included based on their perception towards various vehicle technologies, such as, the range limitation cost to represent the limited vehicle range of battery electric vehicles, refueling inconvenience cost to capture the coverage of fueling infrastructure, risk premium and so on. These “additional costs” influence the optimal technology for each consumer segment in a given model year, in the framework of a cost-minimization model. The technology investment results are then aggregated for all the consumer groups.

The model represents these additional disutility costs for a number of key consumer groups that are built from segmenting consumers across 3 different dimensions:

- 1) three different annual VMT levels (low, medium and high)
- 2) three different risk categories (early adopter, early majority and late majority)
- 3) two different charging availabilities (home/work available, home/work not available)

Heterogeneity in consumer segments will allow different vehicles to be adopted by different consumer groups.

The main disutility costs that are considered in the model are:

- 1) Refueling inconvenience –additional time (and cost) required to find fuel stations and refueling a vehicle with low station availability (e.g., hydrogen and natural gas)
- 2) Risk premium – Cost associated with the newness and uncertainty associated with advanced technology vehicles (declines as technology becomes more common).
- 3) Model availability – cost associated with the number of makes and models for a given vehicle technology (high cost means fewer makes/models available)

Typically, these costs depend on which risk category a consumer belongs to. An early adopter is more likely to discount these costs relative to a consumer in the late majority category. This structure and parameters are described in much more detail in (Lin and Greene, 2010; Ramea et al., 2018). The introduction of consumer heterogeneity and non-monetary factors that influence a consumer's perception of vehicle technologies will increase the realism of modeling results and improve representation of the important effects of policies on energy system model outcomes.

Heavy-Duty Vehicle Segmentation

Among of the largest users of fuel in the transportation sector are medium-duty and heavy-duty trucks. This is a challenging sector to model because of the wide variety of uses, technologies and business models of those operating what are typically commercial vehicles. There is a distinct lack of comprehensive data on these sectors, though there are some important steps in the right direction (NREL Fleet DNA, VIUS). This methodology aims to improve the representation of these vehicles that have been poorly modeled.

Using data from other studies done at UC Davis (Miller et al., 2017), we have disaggregated the medium-duty and heavy-duty vehicles into 8 distinct truck categories that encompass specific vehicle types and use patterns:

- Long haul
- Short haul
- Heavy-duty vocational
- Medium-duty vocational
- Medium-duty urban
- Urban bus
- Other bus
- Heavy-duty pickups and vans

That study also projected future estimated truck vehicle fuel economy based on the vehicle type. Diesel, gasoline, and natural gas vehicle fuel economies were estimated using present values from EMFAC 2014 (CARB, 2014) and information from available literature to project future fuel economies. Fuel cell, battery electric, and hybrid vehicle fuel economies were estimated using dynamic vehicle simulations and tying the results to present EMFAC values for diesel vehicles. Vehicle costs were calculated by considering the total cost as a sum of component costs (glider, engine, transmission, engine after treatment system (EATS), fuel storage, fuel cell, battery, and/or motor/controller).

The vehicle engine technologies that were considered for each of these truck/bus categories include gasoline, diesel, diesel hybrid, natural gas (CNG and/or LNG), battery electric and hydrogen fuel cell.

These updates on vehicle technology performance and cost as well as specific application use cycles and annual mileage lead to a much more detailed and improved representation of this sector. This is especially important for understanding the role of alternative fuel technologies (like electric and hydrogen) in specific medium and heavy-duty niches (like urban delivery or buses) relative to other categories like class 8, large tractor trailers in long-haul operation.

For more information on this truck segmentation approach and cost and performance database see (Miller et al., 2017).

H2 Infrastructure

Another key area that was updated is the representation of hydrogen infrastructure. Based on extensive work on representing hydrogen infrastructure within the TIMES framework. While this approach does not take into account critical elements of economies of scale seen in some energy system models with hydrogen representation (e.g., (Yang and Ogden, 2013)) it does take into account the same important elements of hydrogen production, delivery and refueling infrastructure from many UC Davis studies (Yang and Ogden, 2007; Yang et al., 2015). Importantly, it also includes hydrogen electrolysis that can be made with electricity in a flexible manner to help deal with high-renewable penetration grid systems (McDonald, 2018).

Policies and Scenarios

This analysis focuses on greenhouse gas emissions policies as drivers for changes to the national energy system, specifically an economy-wide carbon target. The approach of the US-TIMES modeling is to minimize the cost of meeting the emissions targets, while still providing the specified energy services across the residential, commercial, industrial, and transportation sectors.

In this report, we model several scenarios focused on greenhouse gas emissions targets:

- **Reference scenario (BAU)** – one in which greenhouse gas emissions are not constrained
- **Greenhouse gas emission reduction scenarios (GHG-X)** – 2050 emissions are reduced relative to a 2010 baseline emissions at different levels with a linear emissions reduction trajectory from 2015 to 2050:
 - 10%, 20%, 30%, 40%, 50%, 60%, 70% and 80% below 1990 emissions levels

The 80% emissions reduction target for the United States is a widely acknowledge as necessary contribution of the U.S. to keeping global temperature rise to around 2 degrees Celcius from pre-industrial levels (IPCC, 2014). Because of the current uncertainty around U.S. policy action towards GHG emissions mitigation, it does not currently seem likely that the U.S. will target or achieve an 80% reduction target by 2050. However, we model this target as well as other levels of GHG emissions reduction to understand the expected changes in the energy system (particularly in terms of the fuels and vehicles) that would result from these policies.

In addition to the national carbon targets, we also look at the presence of regional policies in specific sectors, including zero-emission vehicle (ZEV) mandates which have been enacted in California and several other Northeastern states. A national fuel economy (CAFE) standards is included, which governs the fuel economy of the fleet of new vehicles. And state-level renewable portfolio standard (RPS) policies are also included, which govern the electricity generation from renewable energy sources.

The model will then optimize the energy system at lowest-cost while simultaneously meeting all of these assorted policy constraints (if possible). The policy constraints help us to understand how targets may be achieved, i.e., which technologies and resources could be deployed in order to meet the targets.

The proposed work will enable the development of robust full transport sector scenarios for 2030 and 2050, estimations of GHG reductions, costs, and policy pathways to achieving them.

Modeling Results

Overall scenario emissions

The results shown in this section represent a set of modeling results from US-TIMES. Set of different scenarios including Reference scenario (BAU) and carbon emissions cap with different levels of stringency (GHG-10 to GHG-80).

GHG emissions in the U.S. for the Reference (BAU) scenario are plotted across the different sectors in **Figure 3**. In this scenario, emissions are shown declining from the base year of 2010 to 2025 (from 6100 MMTCO₂e/yr to 5800 MMTCO₂e/yr) and then growing slightly from there (6500 MMTCO₂e per year) to 2050. This amounts to a 7% increase in emissions from 2010 to 2050 (0.17% annual rate), and slightly less than the rate of emissions growth from 1990 to 2010 (9% over 20 years or 0.43% annual rate). These numbers vary slightly from the U.S. EPA's official emissions inventory because the US-TIMES energy model does not include U.S. agricultural emissions or high global warming fluorinated gases which are both not a direct part of the U.S. energy system.

The largest source of emissions in 2010 is the electricity sector which contributes to 38% of total emissions followed by the transportation sector which contributes 30% of total emissions. Electricity and transportation emissions reduce to 30% and 25% of total emissions in 2050, respectively, while the energy supply sector and other end-use sectors (residential, commercial and industrial) increase their absolute amount and share of total emissions.

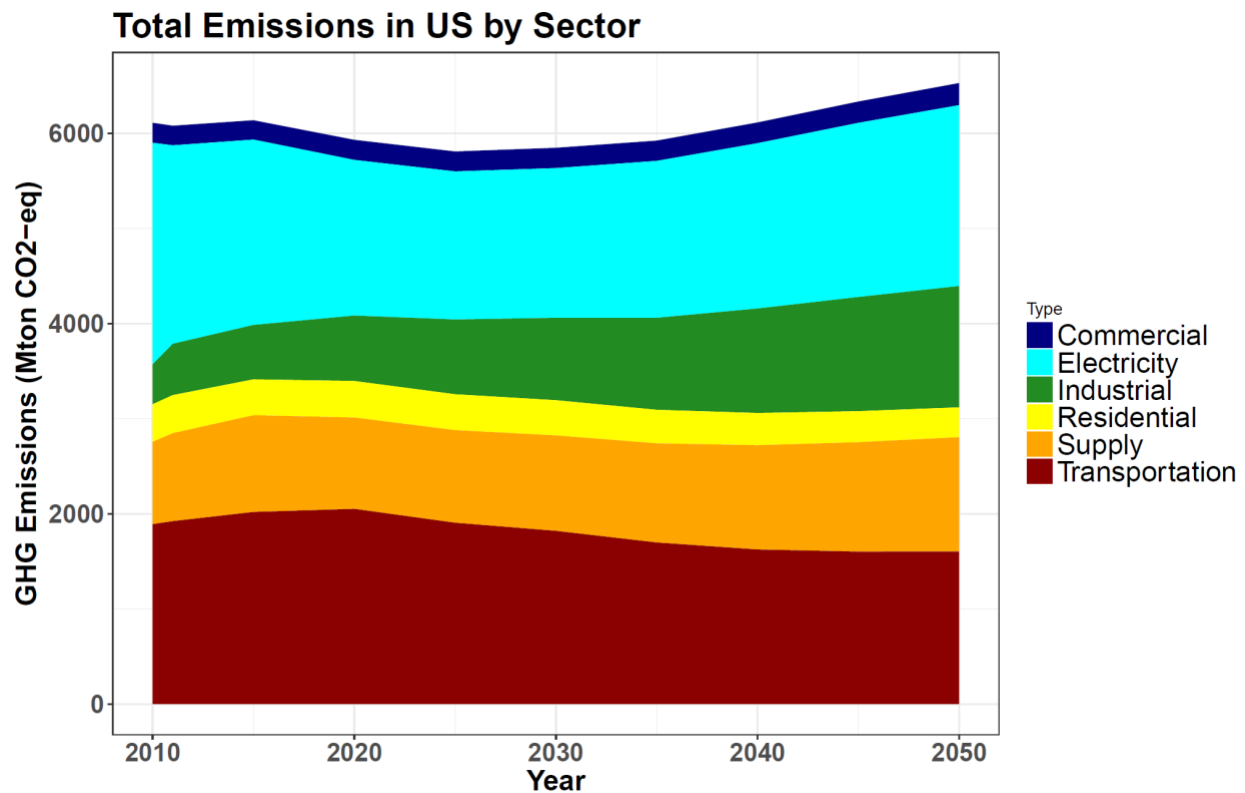


Figure 3. GHG emissions from 2010 to 2050 by sector for the Reference (BAU) scenario.

Running the model with an 80% cap requires annual GHG emissions to be reduced to approximately 1200 MMTCO₂e in 2050. The US-TIMES model is not able to solve this scenario of meeting an 80% GHG emissions reduction target in 2050, while still supplying all of the energy service demands required across all end-use sectors. This is due to a lack of viable technologies and resources available (to the model) to reduce emissions. This will be explored in a little more detail in later sections. However, we can analyze the 70% scenario to explore what changes occur within the energy system and to see which sectors emit the most GHGs within this still highly decarbonized energy future. Sectoral emissions within the 70% GHG emissions reduction constraint are shown in **Figure 4**. In this scenario, total emissions reduce from 6100 MMTCO₂e/yr in 2010 to 1800 MMTCO₂e/yr in 2050. Emissions from industrial, electricity and supply sector shrink dramatically while transportation provides the largest share of emissions (520 MMTCO₂e or 29% of remaining emissions) in 2050. Electricity sector emissions are reduced by 95% between 2010 and 2050, which is the largest emissions reduction among the different sectors.

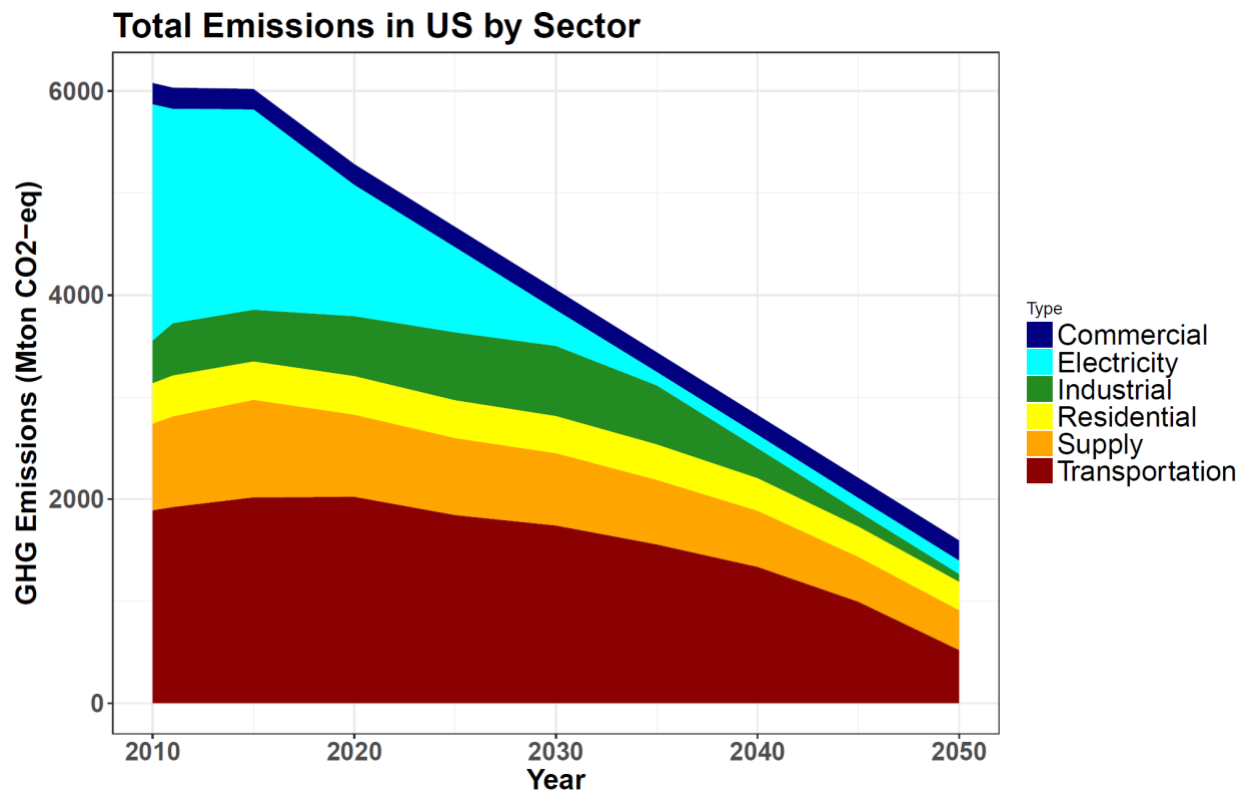


Figure 4. GHG emissions from 2010 to 2050 by sector for the 70% GHG emissions reduction scenario.

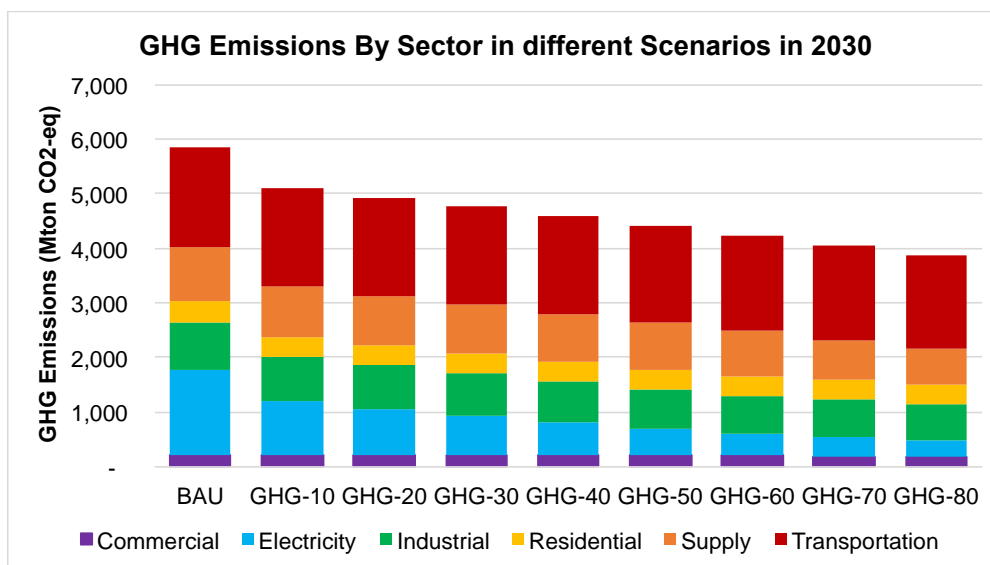


Figure 5. GHG emissions by sector in different scenarios in 2030.

Figure 5 shows GHG emissions disaggregated by sector across the different carbon cap scenarios in the year 2030. We see that the major reduction in emissions in the 2030

timeframe relative to the BAU scenario is primarily in the electricity sector across all of the carbon cap scenarios. Other end-use sectors show some slight-to-moderate reductions, especially as the cap gets more stringent.

Figure 6 shows the sectoral GHG emissions across the different carbon cap model scenarios in 2050. The electricity sector is the first sector that decarbonizes with the existence of carbon cap, even with 10% emissions reduction carbon cap electricity emissions reduces by 70% relative to the reference scenario in 2050. However, electricity sector reaches its maximum decarbonization potential in 30% carbon cap policy. Transportation emissions reduction is not significant up to 30% carbon cap reduction where electricity emissions reduction is sufficient to meet the cap while transportation emissions are the main source of decarbonization when there is a 40% or more stringent carbon cap. This indicates that transportation emissions reduction is more expensive than electric sector reductions, since the electric sector reduces emissions first. This optimization across sectors is a feature of energy system models to produce emissions reductions at the lowest cost and simulates efficient trading of emissions across sectors from something like a cap and trade program.

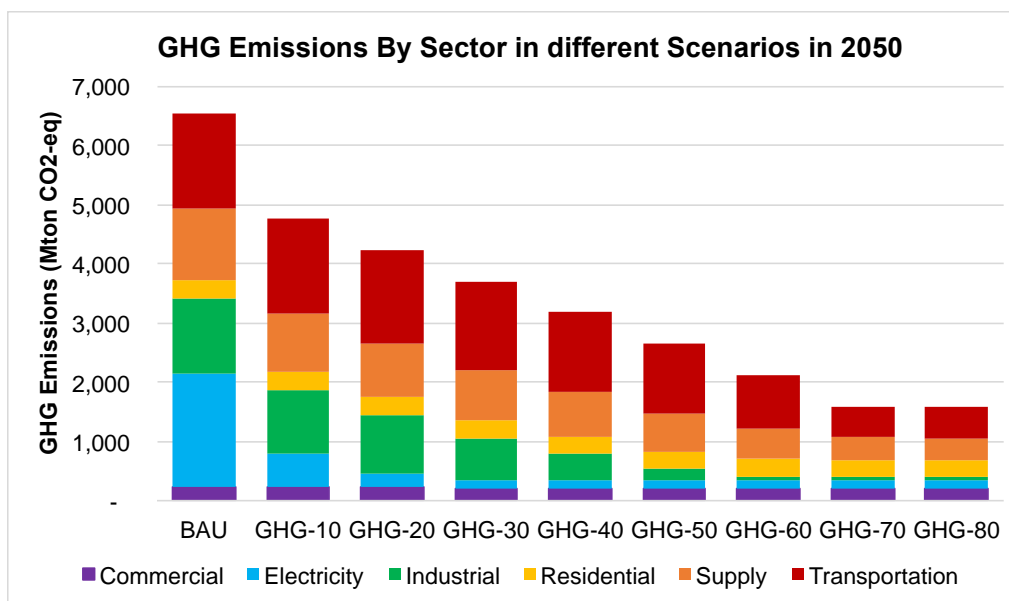


Figure 6. GHG emissions by sector in different scenarios in 2050.

The next sections describe the changes within the two of the most critical energy sectors within the U.S. with respect to GHG emissions: the transportation sector and the electricity sector.

Transportation Sector

The main focus of this work is on the transportation sector. It is also helpful to look deeper into individual transportation sub-sectors to understand the shifts in technology choices, fuel and resource usage that drives these changes which helps us understand the broader underlying GHG emissions results. These results can help us understand how we could achieve deep emissions reductions across the transportation sector.

The transportation sector has the second largest share of GHG emissions in the U.S. (in 2010) and it continues to be a significant source of emissions in all years in all of the scenarios. As a result, the transportation sector is one of the most important sectors in US-TIMES and the model results help us to understand changes in vehicle technology investment and fuel choice decisions as the emissions requirements become more stringent.

Transportation demand in the light-duty sector (VMT, passenger miles) is expected to increase by 38% between 2010 and 2050, at the same time, transportation demand in heavy-duty sector including heavy-duty trucks and buses is expected to increase by 100% in the same period. These projections come from the EPA and AEO (AEO, 2013; EPA, 2014).

Figure 7 depicts the light-duty vehicle fleet mix contributions to VMT in the Reference scenario. The results show that light-duty fleet continue to rely primarily on internal combustion engines and liquid fuels. The bulk of internal combustion engines vehicles are powered by gasoline.

In the Reference scenario, battery electric vehicles (BEVs) represent a small proportion of vehicles in 2020 to 2050 (only about 1% of vehicles). Gasoline plug-in hybrid vehicles (PHEVs) start to show up after 2030 and they contribute to about 17% of total VMT by 2050. There is less than 1% ZEV adoption before 2025 which is primarily due to the existence of ZEV mandate constraint in parts of regions 1,2 and 9. After 2025 BEVs and PHEVs are chosen primarily because they are cheaper for some consumer groups and there is no additional policy in place to push their adoption.

Recall that LDV technology adoption is driven, in part, by heterogeneity in the LDV market. Consumers are subdivided into three risk groups, three annual VMT groups, and four charging infrastructure availability groups as well as the 9 EPA regions. PHEVs and some BEVs are adopted primarily by the early adopter group, though they spread to the early majority group over time. Low range BEVs are only applicable for the consumers with low annual VMT and charging availability (based upon home and work charging). Because this is a fairly low fraction of consumers, BEVs only make up a small portion of total plug-in vehicle sales. These additional factors tend to slow down the adoption of alt-fueled vehicles relative to assuming that vehicle and fuel costs are the primary factors determining adoption.

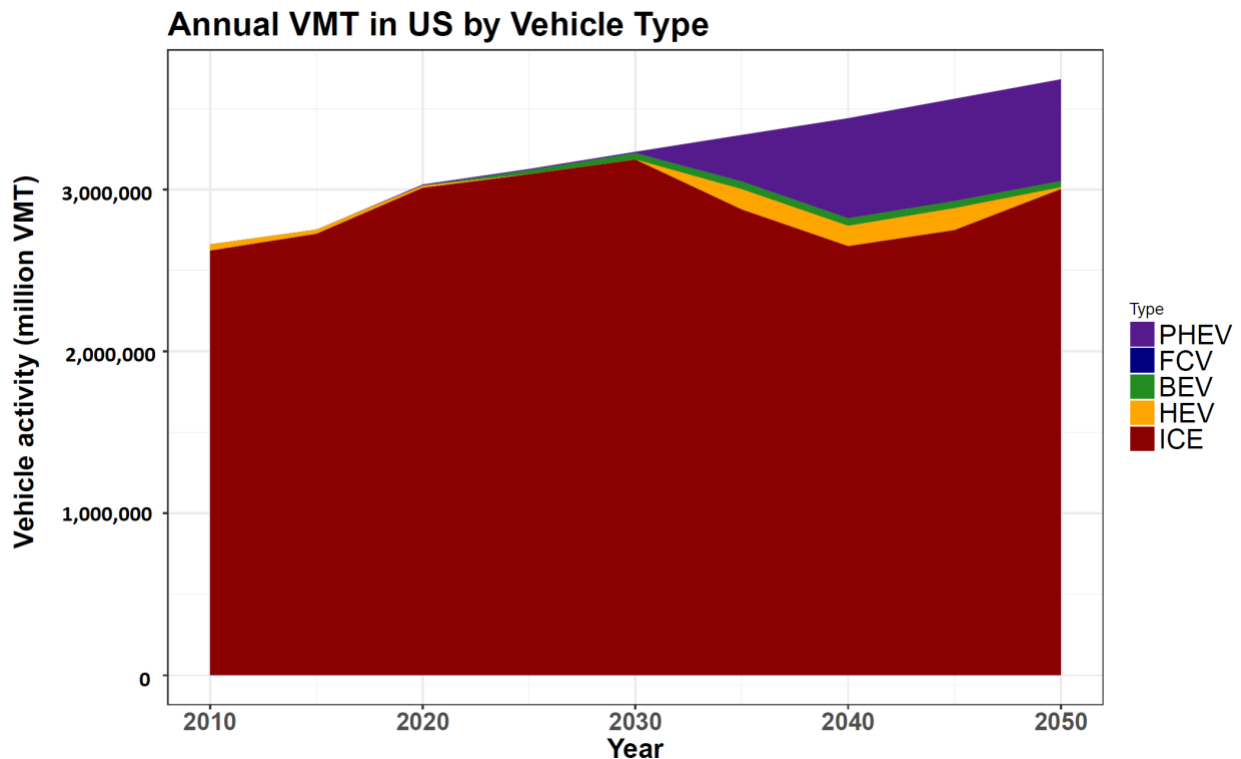


Figure 7. Vehicle activity of light-duty vehicles in the Reference (BAU) scenario.

Figure 8 shows the heavy-duty vehicle fleet mix contributions to VMT in the Reference scenario. The results show that after 2025 we will have a significant fuel cell vehicles (FCVs) and FCVs contribute to about 35% of total VMT in 2050. liquefied natural gas (LNG) and natural gas vehicles are about 13% of total vehicles after 2025 and HEVs which are primarily diesel HEVs are about 18% of total vehicles after 2025. FCVs are mainly short-haul trucks, pick-up trucks and urban buses while vocational trucks and other buses run on CNG. FCVs adoption in the heavy-duty sector in this scenario is relatively substantial. The caveat to these results is that many of the infrastructure issues with hydrogen that limit adoption in the LDV sector are not modeled in HDV sector and are based primarily on economic costs (FCV costs come down with time and abundant low-cost hydrogen from methane reforming).

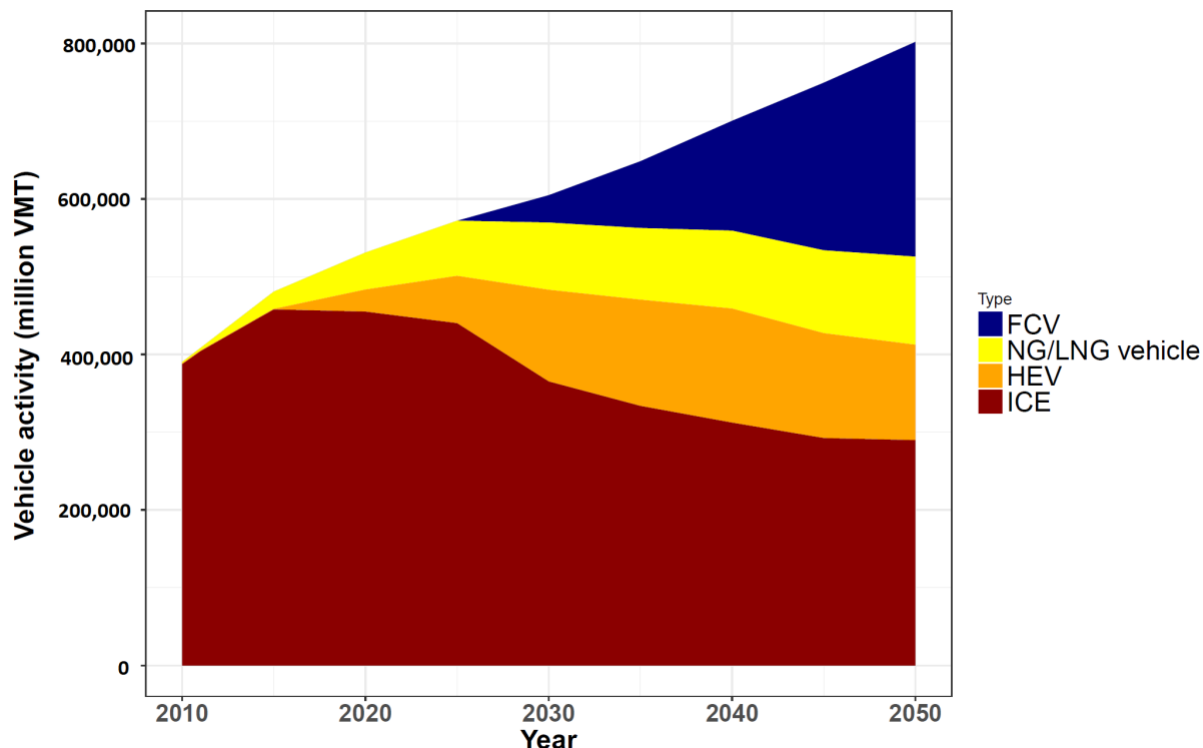


Figure 8. Vehicle activity of heavy-duty vehicles in the Reference scenario.

Figure 9 shows vehicles activity in the presence of 50% carbon reduction cap. We can see HEVs activity increase significantly after 2030 under this scenario and it reaches more than 30% of the total VMT in 2050. At the same time, share of PHEVs in total VMT in 2050 is more than 25% under this scenario. On the top of these vehicles, BEVs contribute to about 10% of the total light-duty activity in 2050.

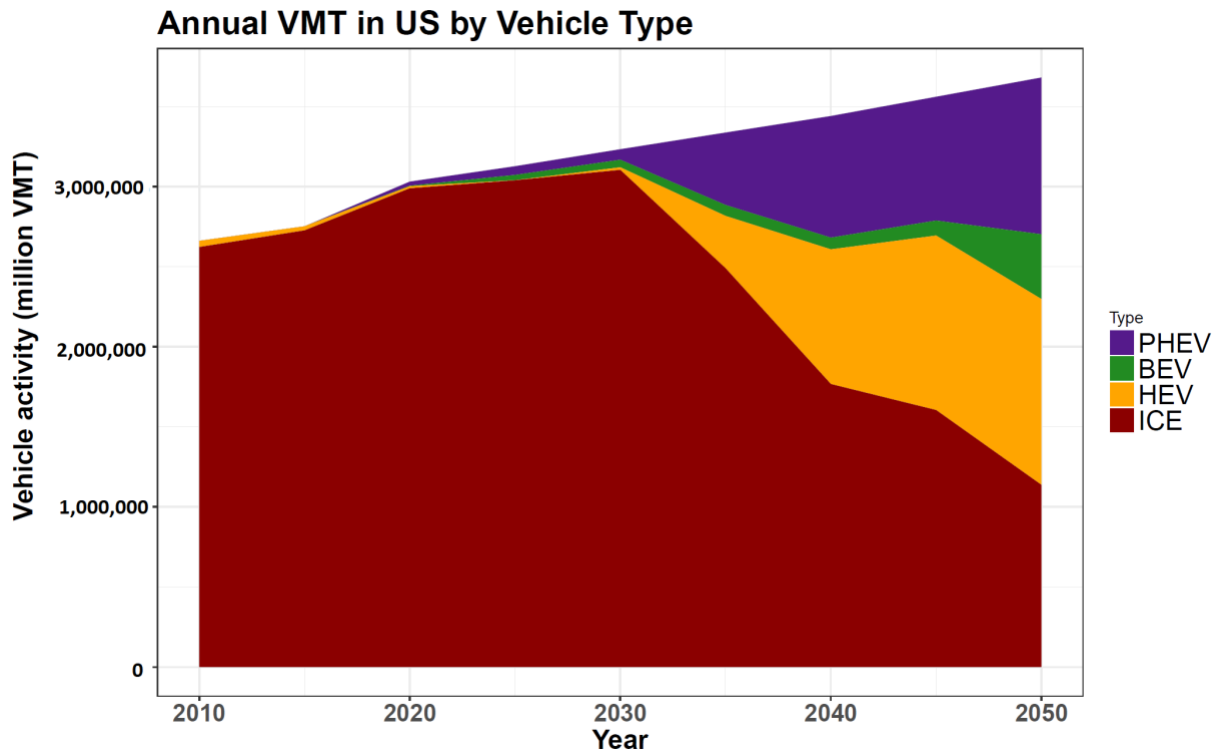


Figure 9. Vehicle activity of light-duty vehicles in the 50% GHG emissions reduction scenario (GHG-50).

As shown in **Figure 10** under 50% carbon reduction cap, FCVs start to show up after 2025 and they contribute to more than 55% of total heavy-duty VMT in 2050. In this scenario, NG/LNG vehicles contribution is about 15% in 2030, however, this share reduces to 3% in 2050 when FCVs share increase. Moreover, HEVs contribute to about 10% of total VMT in 2050 and the rest of 30% is provided by ICEs. We do not see FCVs in light-duty primarily because of assumptions about limited national hydrogen infrastructure availability for light-duty vehicles. This hurts adoption for fuel cell cars and light-trucks, but because infrastructure availability limitations are not currently included in the model for heavy trucks, we see substantial adoption there. This is an area that can be improved in future iterations of the model.

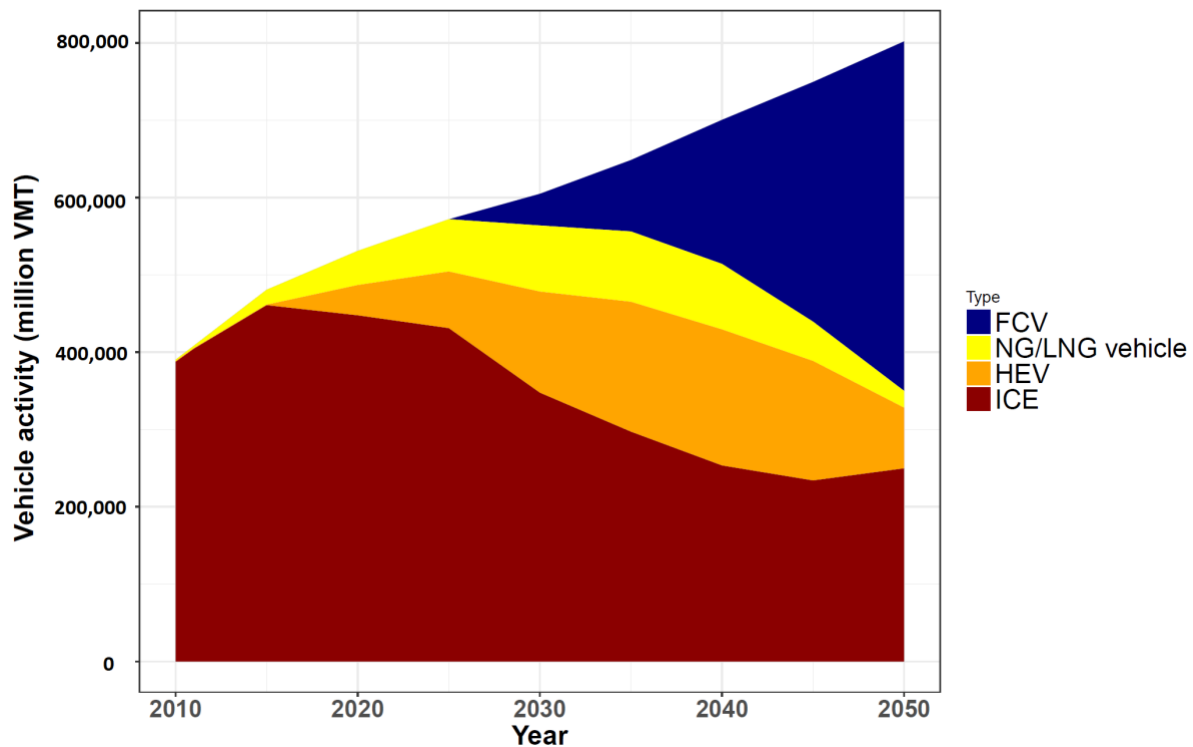


Figure 10. Vehicle activity of heavy-duty vehicles in 50% GHG emissions reduction scenario.

Figure 11 shows the mix of light-duty vehicles for the 70% GHG emissions reduction (GHG-70) scenario. We see a dramatic shift in the vehicle mix starting in 2030 when there is significant growth in PHEVs and BEVs. Also important to note is that in 2050, there are no ICEs and there are only plug-ins, i.e., PHEVs and BEVs. However, there is no FCVs adoption in the light-duty sector. The results show that share of PHEVs is about 40% and BEVs share is 60% in 2050 which shows how the light-duty sector will be significantly decarbonized to help the transportation sector meet the carbon cap. PHEVs are used for segments of the consumer population where BEVs are not ideal (primarily those who do not have access to home and work charging).

As shown in Figure 12, the heavy-duty sector starts to significantly decarbonize after 2025. In order to reach the stringent 70% GHG emissions reduction target in 2050, the model use 100% FCVs to provide VMT. The model does not use electric vehicles in the heavy-duty sector due to their range and payload issues with battery powered heavy vehicles as well as charging and infrastructure issues.

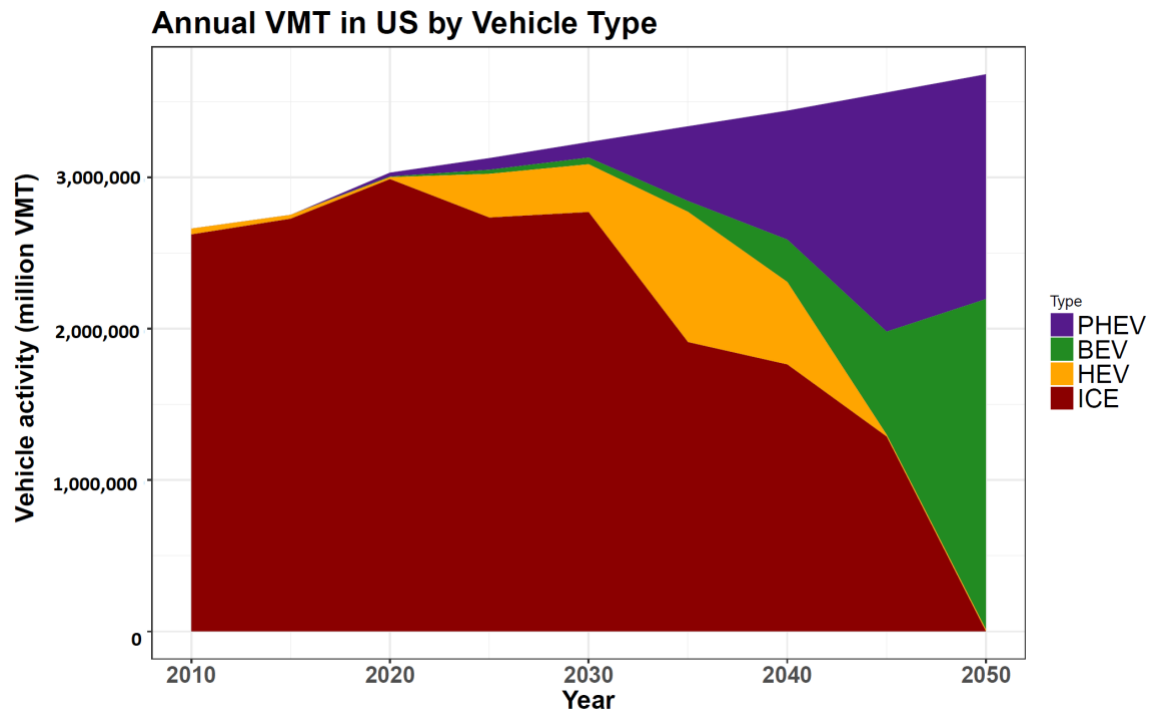


Figure 11. Vehicle activity of light-duty vehicles in 70% GHG emissions reduction scenario.

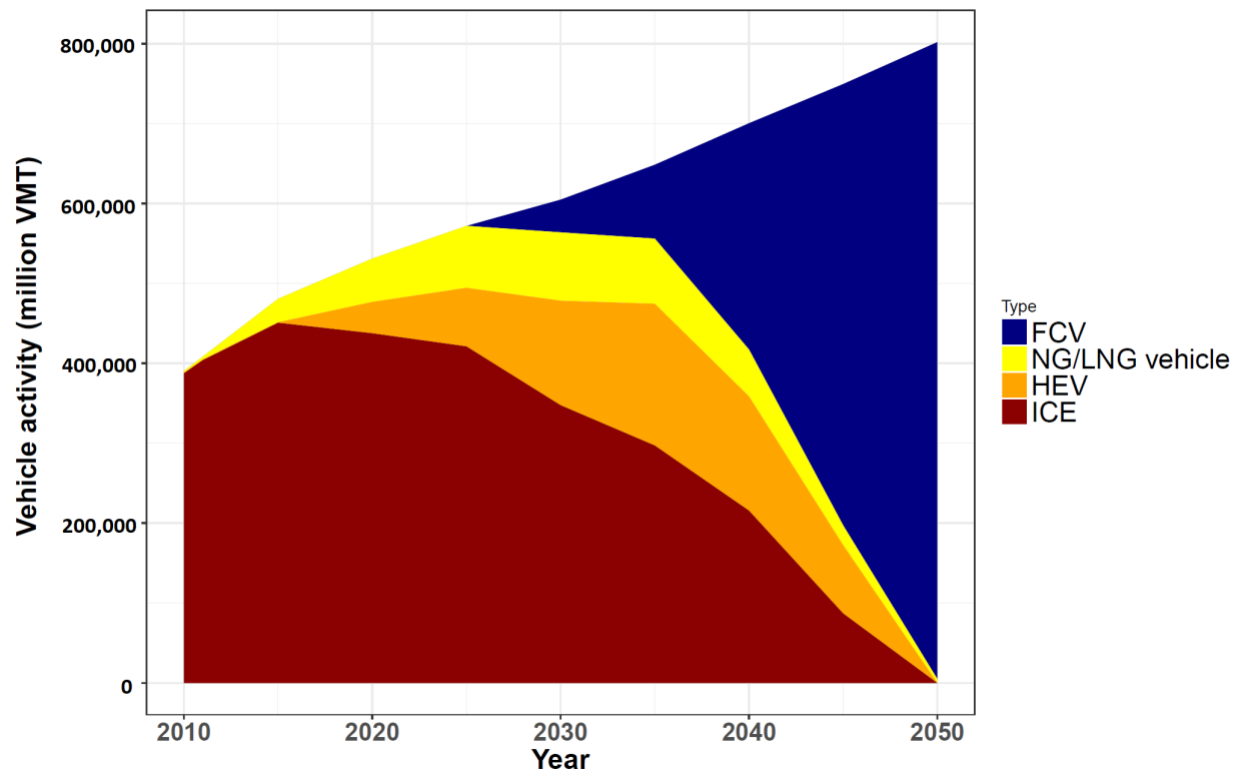


Figure 12. Vehicle activity of heavy-duty vehicles in 70% GHG emissions reduction scenario.

Figure 13 shows how light-duty vehicle activity in 2050 varies across the different carbon cap scenarios (BAU, GHG-10 through GHG-80). The light-duty vehicle mix does not change significantly in 2050 until carbon cap is as stringent as a 40% GHG emissions reduction (GHG-40), which means the model finds enough decarbonization opportunities in other sectors at lower cost than switching in the light-duty sector to meet scenarios up to a 30% GHG emissions cap. It is only in the 40% cap, where costs for decarbonization in other sectors start to approach that of mitigation in the light-duty vehicle sector as we see significant changes in vehicle adoption in this sector. Two key factors are critical in this cap scenario (GHG-40) which yield changes to the light-duty sector: (1) the rising cost of mitigation and (2) the increasing level (stringency) of mitigation.

In these low GHG cap cases (GHG-30 and below), we have about 80% ICEs (ICEs and HEVs) and 20% PHEVs in 2050. However, with having 40% GHG emissions reduction cap we see ICE dominance decreases and it replaces with BEVs, HEVs and PHEVs. With having 70% GHG emissions reduction cap, the model only uses PHEVs and BEVs (40% and 60%, respectively) to satisfy the projected VMT in 2050. The model cannot decarbonize light-duty sector beyond 70% GHG emissions reduction cap as the vehicles mix is the same as 70% GHG emissions reduction cap in the 80% GHG emissions reduction cap.

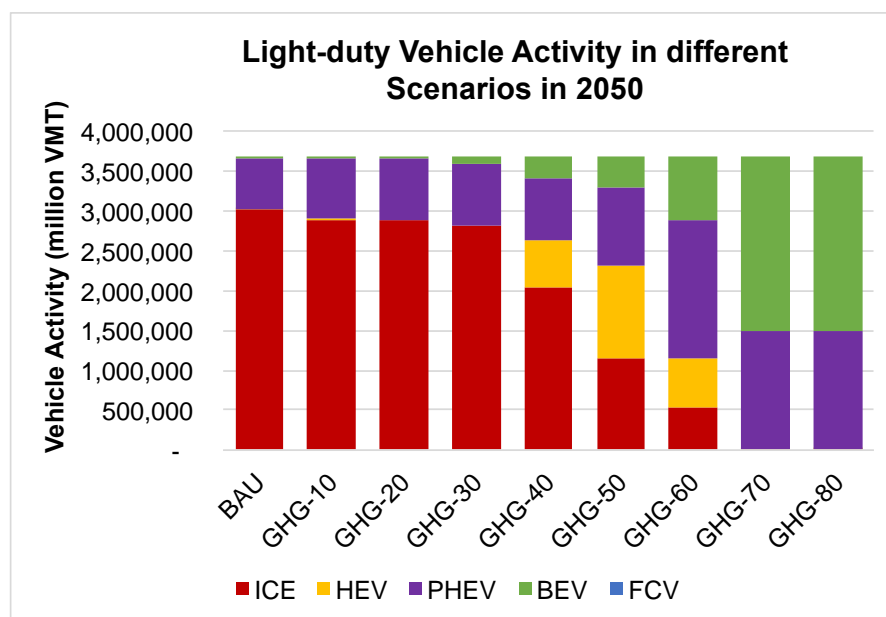


Figure 13. Vehicle activity of light-duty vehicles in different scenarios in 2050.

Figure 14 shows how the heavy-duty sector responds to different carbon caps by showing the breakdown of vehicle types in 2050. Similar to the light-duty sector the model does not change vehicles mix significantly up to 30% GHG emissions reduction cap. It consists of a diverse mix diesel, CNG, hybrid and fuel cell vehicles. At the 40% GHG emissions reduction cap (GHG-40), the model starts to replace more of the combustion vehicles with FCVs and heavy-duty sector is completely dominated by FCVs at the 70% GHG emissions carbon cap (GHG-70). As with the

light-duty sector, the 80% GHG emissions carbon cap (GHG-80) is unable to be met and does not induce any additional changes beyond the GHG-70 scenario, indicating that this is the maximum emissions that can be reduced in the heavy-duty sector (given the assumptions in this model).

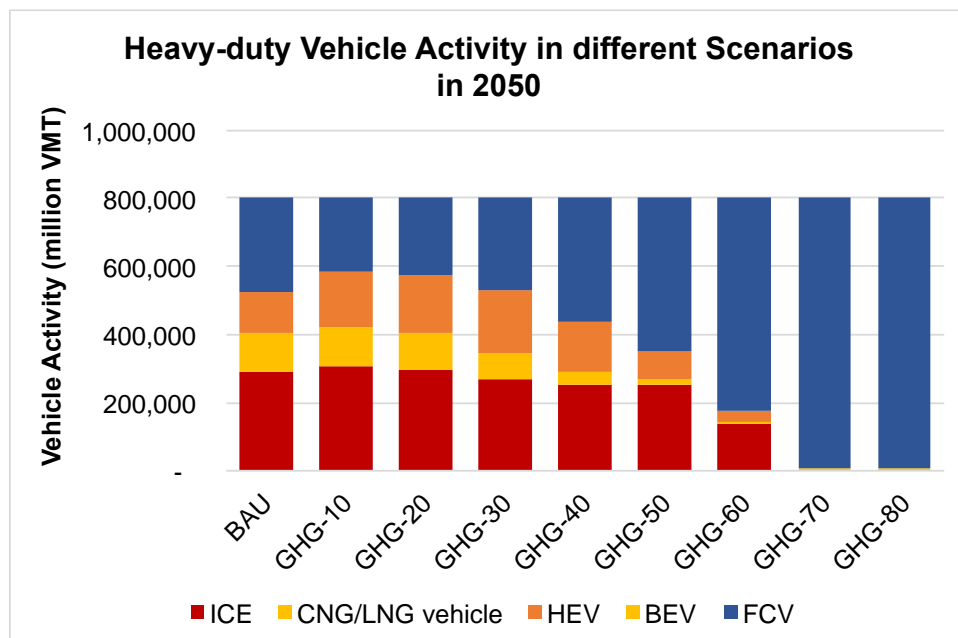


Figure 14. Vehicle activity of heavy-duty vehicles in different scenarios in 2050.

Figure 15 shows fuel consumption in the transportation sector in the reference scenario. Fuel consumption grows by 11% from 2010 to 2020 due to the exogenous increase in activity, however, as the base year stock of vehicles is replaced with new, more efficient vehicles, fuel consumption starts to decrease and fuel consumption in 2050 is about 6% less than 2010's fuel consumption. 90% of transportation fuel in 2010 comes from gasoline and diesel. In the reference scenario, we see natural gas consumption ramps up after 2020 which is mainly used in the heavy-duty sector. We also see hydrogen and electricity emerge after 2030. Hydrogen mainly consumes in the heavy-duty sector but electricity primarily goes to trains and light-duty sector.

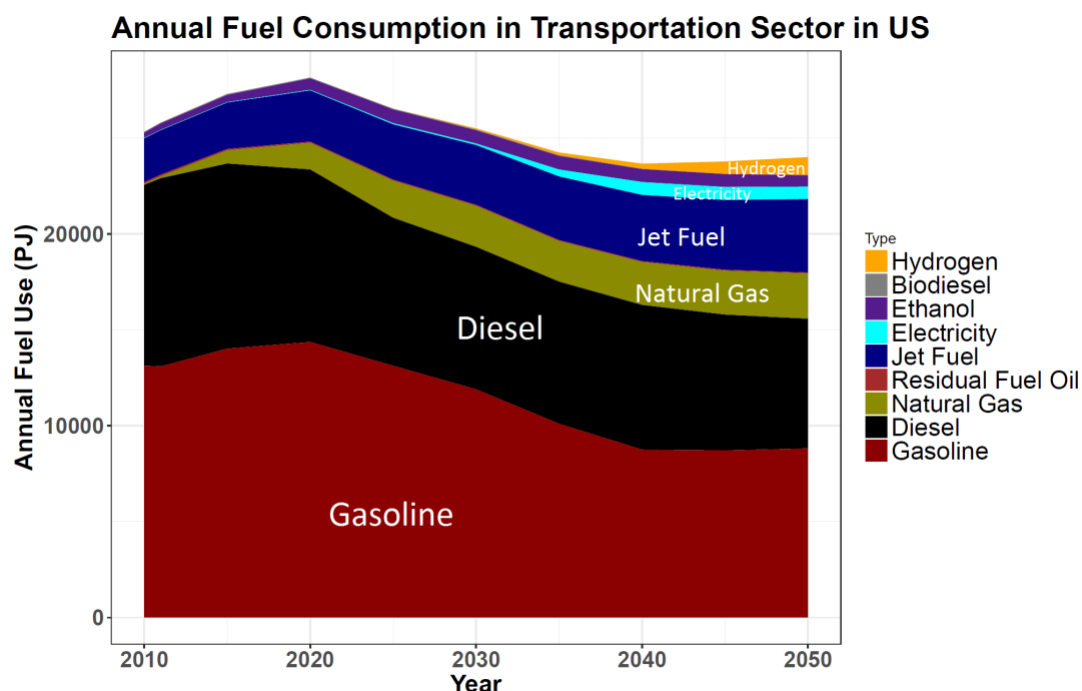


Figure 15. Transportation fuel consumption by type in the reference scenario.

Figure 15 shows fuel consumption in the transportation sector in the reference scenario. Fuel consumption grows by 11% from 2010 to 2020 due to the exogenous increase in activity, however, with replacing new vehicles, which are more efficient than the existing stock, fuel consumption starts to decrease and fuel consumption in 2050 is about 6% less than 2010's fuel consumption. 90% of transportation fuel in 2010 comes from gasoline and diesel. In the reference scenario, we see natural gas consumption ramps up after 2020 which is mainly used in the heavy-duty sector. We also see hydrogen and electricity emerge after 2030. Hydrogen mainly consumes in the heavy-duty sector but electricity primarily goes to trains and light-duty sector.

Figure 16 shows transportation fuel consumption under 50% carbon emissions reduction cap. Transportation fuel consumption decreases from 25,000 PJ in 2010 to 20,000 PJ in 2050 which means total consumption decreases by about 20% in this time period as shown in Figure 4.15. Gasoline and diesel consumption reduction is about 50% between 2010 and 2050 under this scenario. Electricity and hydrogen consumption increases from 21 PJ to 3600 PJ in 2050 in the same time period.

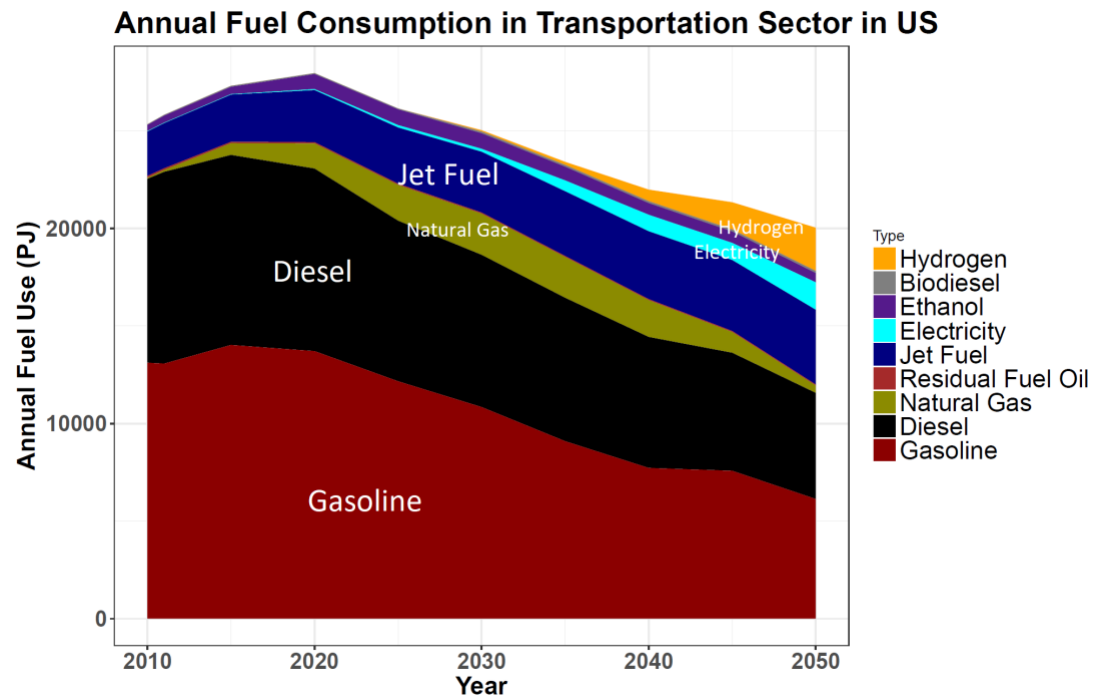


Figure 16. Transportation fuel consumption by type in the 50% GHG emissions reduction scenario.

Figure 17 illustrates transportation fuel consumption in 70% GHG emissions reduction scenario (GHG-70). Similar to the reference scenario fuel consumption increases between 2010 and 2020; however, it decreases by 36% relative to 2010 in 2050, due to significantly higher vehicle efficiency than in the BAU scenario.

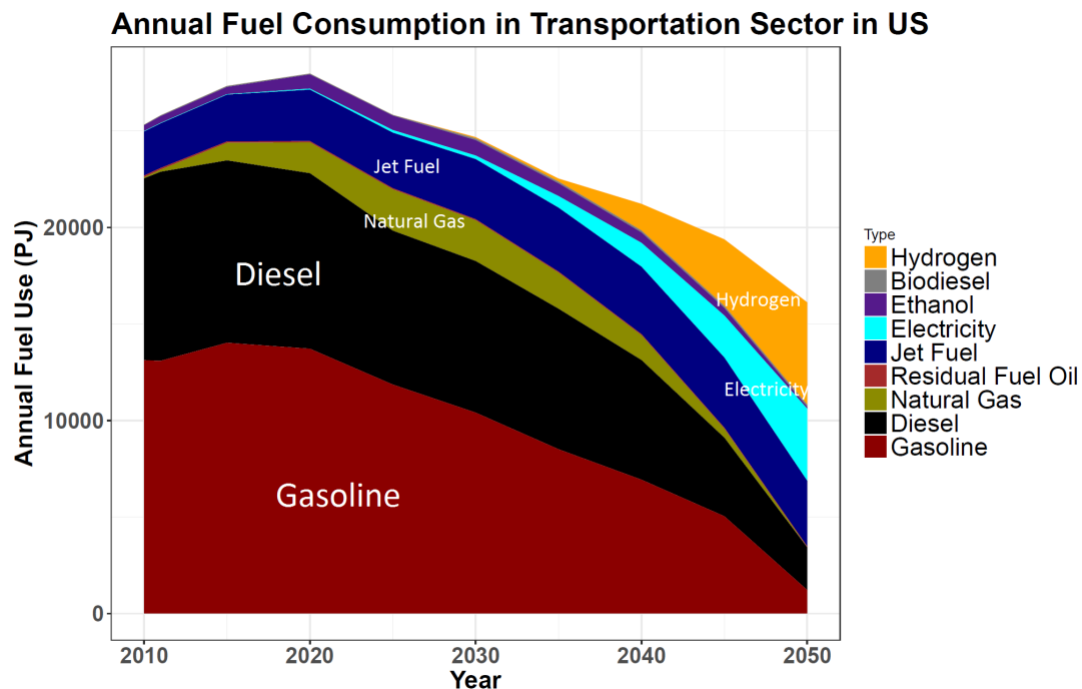


Figure 17. Transportation fuel consumption by type in the GHG-70 scenario.

Gasoline and diesel consumption decrease by 85% in 2050 relative to 2010 because of major changes to the vehicle technology mix in order to meet the carbon cap. Furthermore, over 55% of total transportation consumption in 2050 comes from hydrogen and electricity due to adoption of FCVs, BEVs and PHEVs in the light-duty and heavy-duty sectors. Hydrogen evolves from production via steam reforming to electrolysis from low-carbon electricity over time.

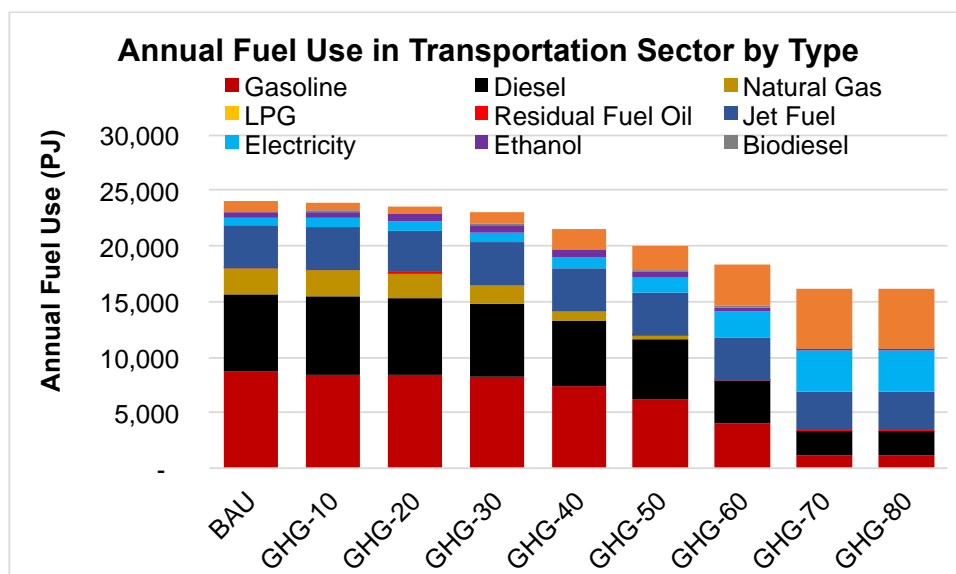


Figure 18. Transportation fuel consumption by type in the 70% GHG emissions reduction scenario (GHG-70).

Figure 18 shows transportation fuel consumption across various scenarios in 2050. Fuel mix and consumption does not change significantly up to GHG-30 scenario, similar to the light-duty and heavy-duty technology mix. This again shows it is cheaper for the model to meet carbon cap by reducing emissions from other sectors. Starting from GHG-40 cap scenario, total consumption is reduced and we see gasoline and diesel are replaced by low-carbon electricity and hydrogen. Total transportation fuel consumption in 2050 in the GHG-70 scenario is 33% lower than the reference scenario.

Electricity Sector

Electricity is another critical component of the energy supply mix and major changes to generation and demand are essential in meeting any carbon cap. As we saw in the previous section, decarbonizing the electric sector is critical in reducing the emissions, because one of the key strategies for reducing emissions is shifting fossil fuel usage from petroleum and diesel to electricity/hydrogen in end use sectors. As electricity demand rises as a result of this electrification, the sector must also re-invest in low carbon technologies.

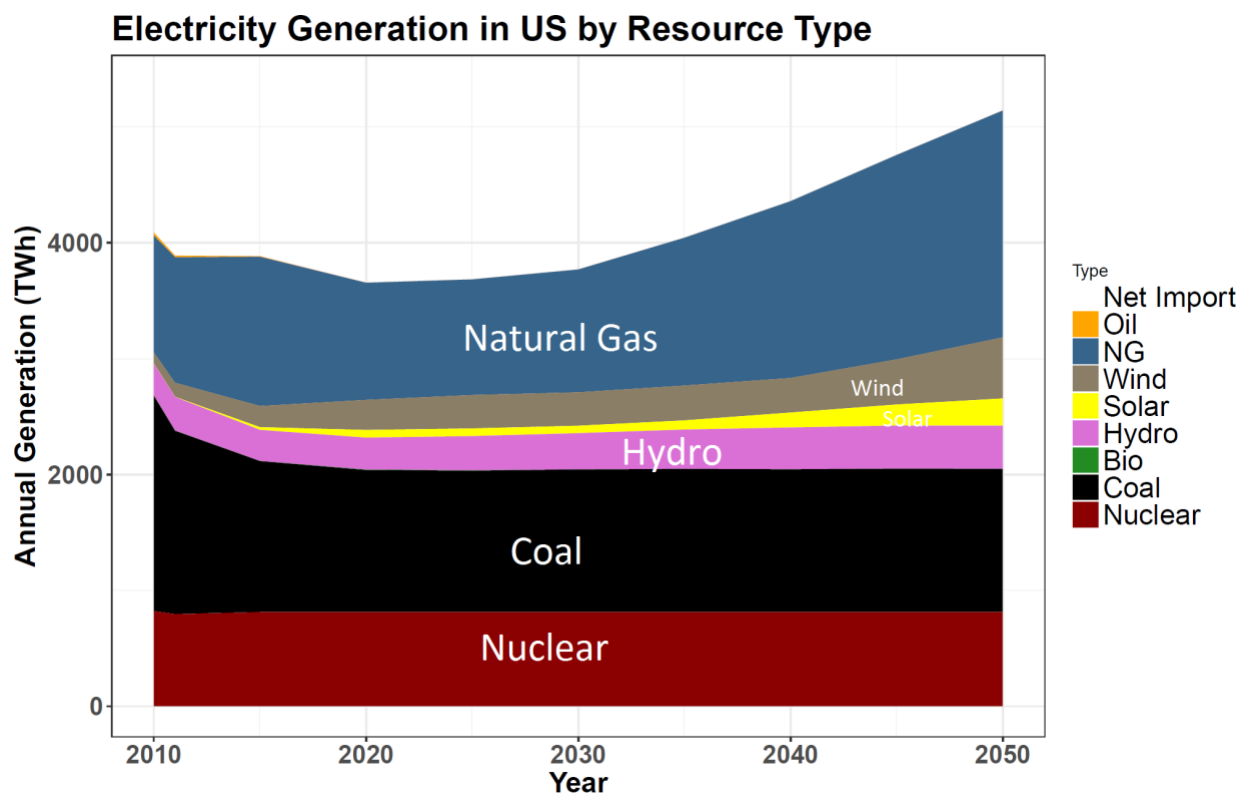


Figure 19. Electricity generation by resource type in the Reference scenario.

Figure 19 shows the annual electricity generation mix from 2010 to 2050 in the Reference (BAU) scenario. Overall electricity usage climbs from 4,100 TWh to 5,200 TWh in 2050, a 25% increase. With respect to the generation mix, coal decreases by 30% between 2010 and 2020 and stays constant up to 2050. Nuclear is held mostly constant throughout the entire 2010-

2050 period. Natural gas increases by more than 90% between 2050 and 2010 and reaches 1,970 TWh/yr in 2050, becoming the main source of electricity generation in 2050 (accounts for about 40% of total generation). The rapid increase in wind and solar power is due to significant reductions in the cost of wind turbines and solar PVs as well as existence of RPS policy in various regions specifically in pacific region (R9). Wind and solar grows to 770 TWh/yr in 2050 which is about 15% of total generation in 2050. Hydro provide about 375 TWh/yr in 2050 which is 7% of total generation in 2050.

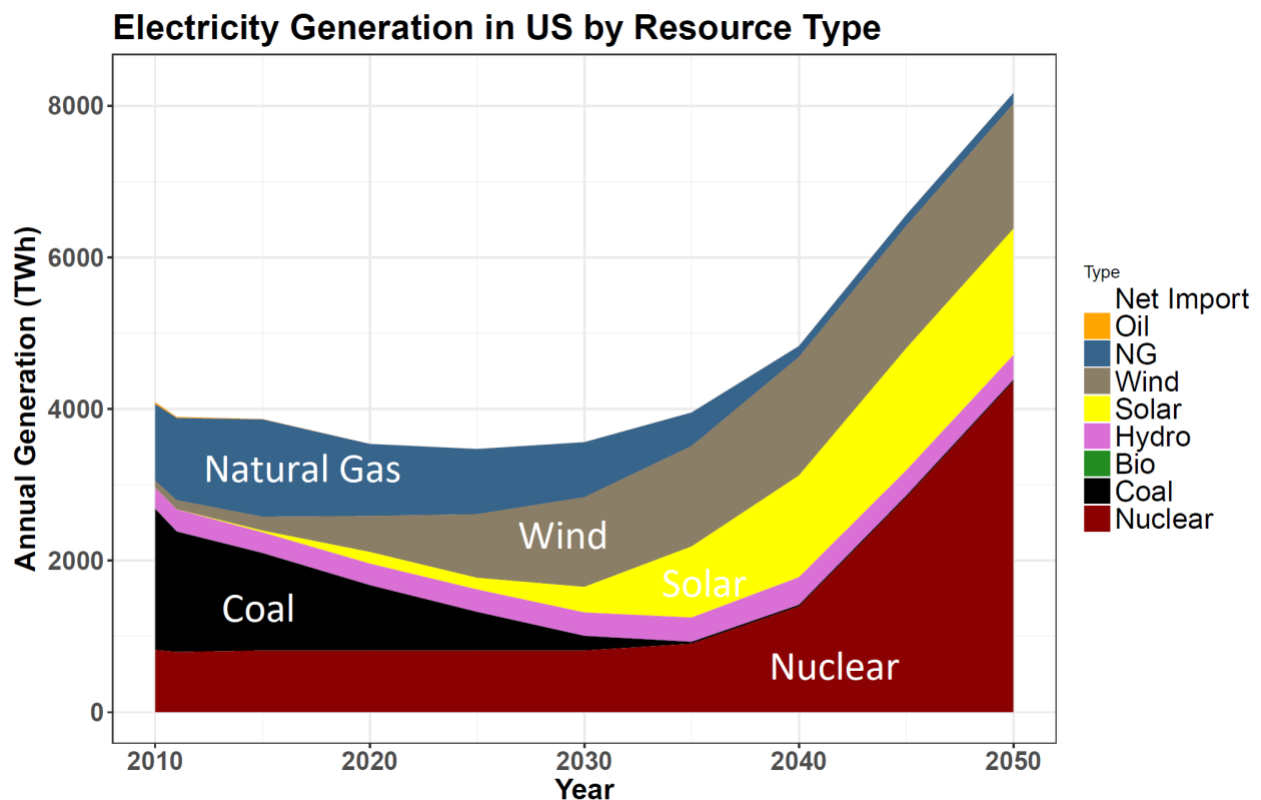


Figure 20. Electricity generation by resource type in the 50% GHG emissions reduction scenario.

Figure 21 shows electricity generation by resource under 50% GHG emissions reduction scenario. In this scenario, total electricity generation increases from 4,100 TWh in 2010 to 8,200 TWh in 2050 which is almost 100% increase which is due to the extensive electrification in different sectors. Coal generation gets to zero by 2035 and natural gas generation decreases by 85% between 2010 and 2035 (from 1000 TWh to 140 TWh). At the same time, nuclear generation increases more than five times between 2010 and 2050. In 2050, almost all of generation (except 140 TWh from natural gas) comes from zero emission sources.

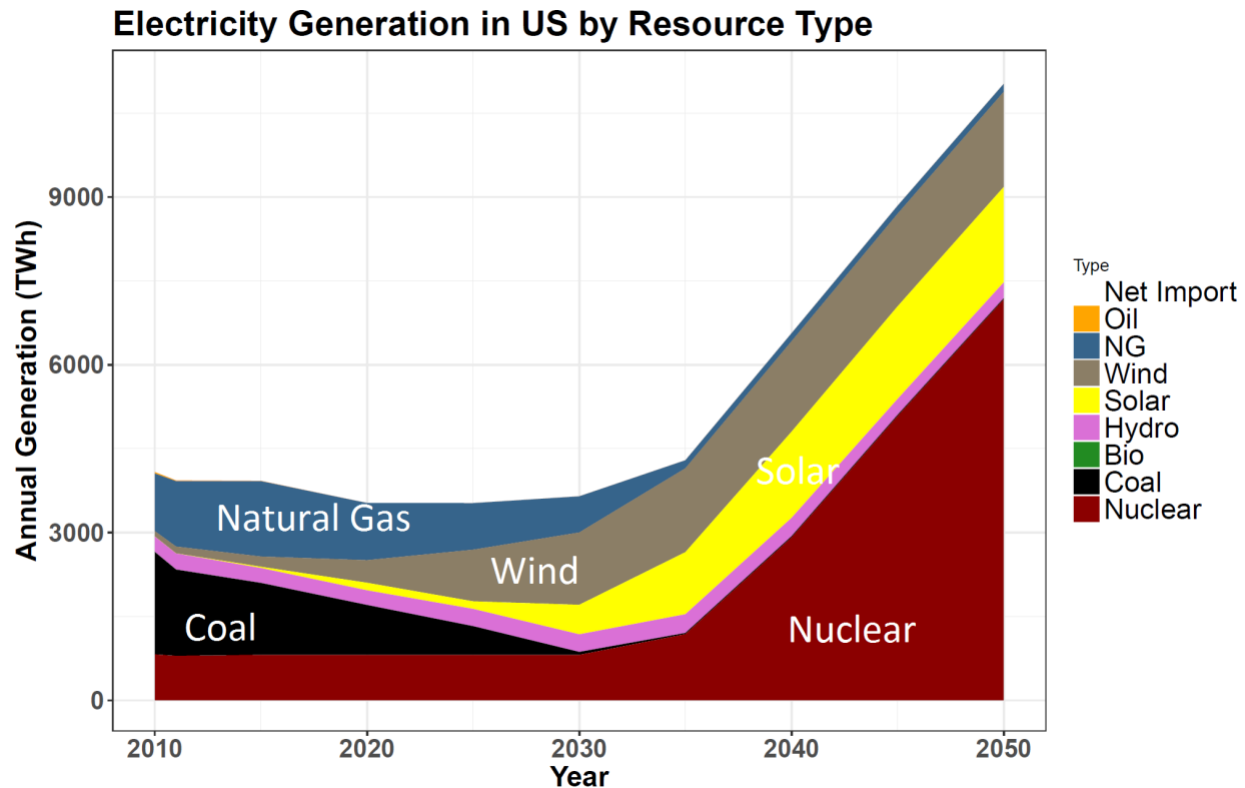


Figure 21. Electricity generation by resource type in the 70% GHG emissions reduction scenario.

Figure 21 shows the generation mix for the 70% GHG emissions reduction scenario (GHG-70). A major difference between GHG-70 and BAU scenarios is the large increase in electricity demand that is needed by 2050. Instead of 5,200 TWh in the Reference scenario, electricity generation in this scenario more than doubles to 11,000 TWh in 2050 (114% more). This is due to significant levels of electrification of end-use appliances and vehicles across all of the end use sectors, residential, commercial, industrial, and transportation. In transportation, hydrogen consumed by the fuel cell vehicles (primarily heavy duty) is produced primarily by low carbon renewable and nuclear electricity.

The model extensively uses nuclear, wind and solar to provide this significant amount of decarbonized electricity. Coal is completely phased out by 2030 and natural gas is mostly phased out by 2035. Nuclear grows to 7,200 TWh/yr in 2050 which is almost 9 times higher than 2010 generation using advanced nuclear plants and contributes to 65% of the total generation in 2050. Solar and wind each generate about 1,700 TWh/yr in 2050 which is about 15% of total generation in 2050 (30% for both wind and solar).

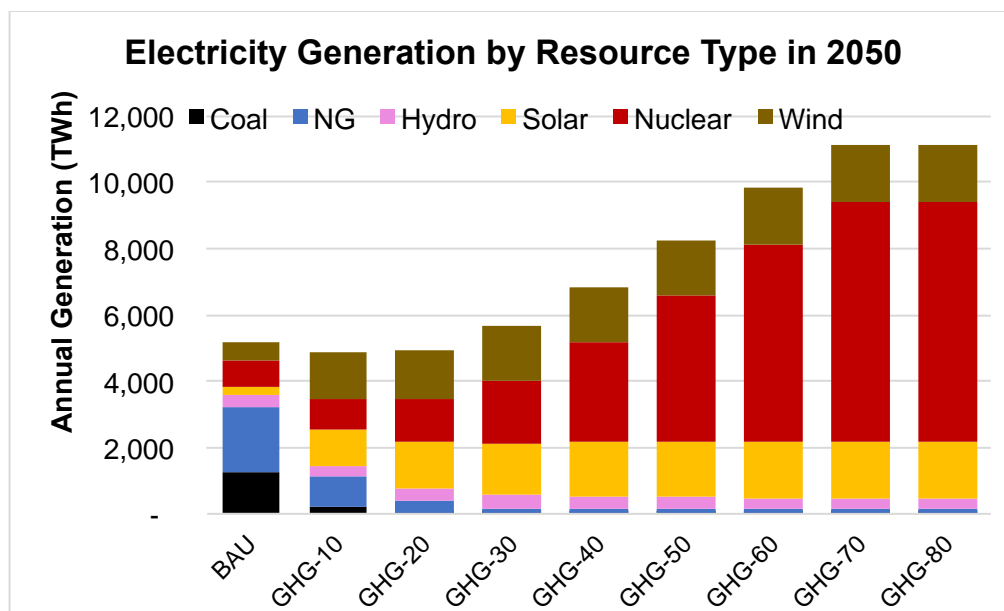


Figure 22. Electricity generation by resource type in 2050 in different scenarios.

Figure 22 illustrates how the electricity generation resource/technology mix changes under carbon caps of varying stringency. It can be seen that the amount of generation does not change significantly until the 30% GHG emissions reduction cap (GHG-30), however, the generation mix changes considerably in the GHG-10 scenario relative to the Reference case. Comparing the Reference and GHG-10 scenarios, coal is almost phased out and solar power grows to 1050 TWh/yr, approximately 4.5 times higher than the Reference scenario. Moreover, wind power grows to 1400 TWh/yr which is almost 2.6 times higher than the Reference scenario. At the same time, natural gas reduces by 55% relative to the Reference scenario. There is a significant increase in nuclear generation where the amount of nuclear power is about 9 times higher than the reference scenario. The limitation on further growth of wind and solar generation beyond the 30% cap is due to the shape of the supply curve of wind and solar resources present in the EPA database. There are significant amounts of relatively low cost resources for wind and solar to exploit, but as these low-cost resources are tapped, installing and operating additional wind and solar generation becomes more costly to where low-cost nuclear power is less expensive for large scale decarbonization. Other scenarios can be run in the future that places restrictions on the expansion of nuclear power and explore the use of more renewables in the national grid. Because the temporal resolution of the model isn't very high (16 time periods per year), the model cannot fully capture the variability and uncertainty in wind and solar generation, but in scenarios with higher wind and solar adoption, the model would need to have demand response, flexible loads or storage in order balance supply and demand properly in a stringent carbon cap scenario.

There is significant synergy between the electricity and end-use sectors in the low carbon GHG-70 scenario. Electricity demand grows very significantly in the decarbonization scenarios (GHG-40 through GHG-70) because of the tremendous level of electrification of the end-use sectors

relies on the availability of abundant low-carbon electricity. This enables vehicles to displace petroleum or natural gas fuels, and utilize limited biomass resources more effectively within the transportation sector. Hydrogen and electricity are essentially fully decarbonized allowing for zero-emission (at the tailpipe and upstream power plant) vehicle operation across the light-duty and heavy-duty sectors.

It also allows the buildings end use sectors (residential and commercial) and the industrial sector to scale back the use of natural gas significantly to use electricity based appliances for space heating, water heating and industrial processes.

Overall, though emissions from the electricity sector go to near zero in these deep reduction scenarios and this increased supply of low carbon electricity is critical.

Project Summary

This report describes the development and use of an U.S. energy system optimization model (US-TIMES) in order to analyze the reductions in GHG emissions that can come about through policy targets. These policy targets induce technology investments and operation in order to satisfy the demand for energy services and environmental policy constraints (notably GHG emission targets).

The model development focused on two key areas within the transportation sector, light-duty vehicles and heavy-duty vehicles. In the light-duty space, we incorporated consumer choice elements into the energy system optimization framework through increasing consumer heterogeneity and adding non-monetary decision factors such as risk and fueling inconvenience. For heavy-duty vehicles, we adopt a segmentation approach and update vehicle cost and performance assumptions from our recent work.

The model is used to project scenarios for low carbon futures from a reference scenario all the way to an 80% GHG reduction target. The electricity sector is the primary sector for reducing emissions at low target levels. The industrial sector is mostly reductions at moderate GHG targets while transportation (vehicles and fuel supply) makes reductions at the highest, most stringent reduction levels.

This result indicates the relative marginal cost of abatement is lowest in the electric sector and transportation has a fairly high cost of abatement, a result that is borne out by many other studies. This result is reinforced, somewhat, by the fact that incorporating other non-monetary factors into the choice calculus that the model uses for its system-side optimization (which already includes consumers' high discount rates for energy efficient purchases) tends to delay widespread adoption of advanced technology, alternatively-fueled vehicles. These retarding factors include technology risk and uncertainty, model availability, infrastructure availability and refueling inconvenience. Therefore, these factors tend to reinforce the relative ranking of transportation (especially passenger transportation purchases by consumers) as a mitigation option with relatively high abatement cost.

Within the light-duty vehicle mix in each of the GHG reduction scenarios, we see changes occur only at more stringent GHG reduction levels (40% and up). This is because of the relatively high "cost" of abatement (i.e., purchases of electric and hydrogen vehicles), especially when including costs such as charging infrastructure availability, risk averseness within the largest consumer segments and limited model availability. Only when the GHG emission reduction targets are very stringent (50% reduction or greater) do we see substantial adoption of ZEV technologies. In the most stringent cases (70% reduction or greater, we have 100% adoption of ZEV or partial-ZEV technologies. In these stringent cases, we see substantial PHEV adoption because of home/work charging availability issues.

We see similar results, though focused on hydrogen fuel cell vehicles, for medium and heavy-duty trucks. Transportation emissions are reduced because of a complementary reduction in emissions from the electric sector (for both EV charging and hydrogen production).

Overall, the development of the US-TIMES model and preliminary analysis shows how an energy system model can be used to analyze the role of vehicle technologies and fuels within a national energy system like that of the United States. This initial study focused on the effect of emissions targets on the transport sector and how the sector responds with adoption of fuels and vehicles.

This model is particularly useful for analyzing cross-sectoral policies like carbon caps and cross-sectoral energy issues like resource competition (e.g., biomass) and synergies (e.g., charging of electric vehicles). Using a cost minimizing model framework, we find that emissions reductions at low cap levels focus primarily on decarbonizing electric sector emissions, and as you increase the stringency of the GHG cap, emissions reductions occur in additional sectors until the transportation sector is decarbonized at the most stringent levels (GHG-60 to GHG-80).

Analysis Limitations and Future Work

Like many models, there are a substantial number of caveats and model and analytical limitations that must be highlighted in order to understand what the results can tell us about the future. This is especially true when the model is as extensive as one that covers a system as complex and large as the entire energy system of the United States.

The primary caveat to the US-TIMES model is that the model outputs are critically dependent on the **input assumptions** that are embedded in the model. We have updated a number of assumptions about vehicle technologies in the light-duty and medium and heavy duty sectors, but have not reviewed all of the assumptions from the EPA U.S. MARKAL model.

Another key caveat is that the primary method by which the model designs the energy system is by **minimizing system cost**. And to the extent that system cost only includes economic costs, the model will ignore other important political, consumer behavior and social barriers that are central in the real energy system, but especially important when considering the adoption of new technologies. This can be seen in some of the results where there is rapid deployment of new low carbon technologies. While this is addressed somewhat with consumer choice in the LDV sector, it is an issue throughout the model.

One of the challenges with a large-scale **linear programming model** is that investments do not show economies of scale (costs can be high at low initial volumes) or endogenous learning (costs and/or performance of technologies can change as a function of adoption levels that occur in the model).

Future work on energy system models always involves the primary work of improving the model via continually updating and refining input assumptions about technology performance and costs.

Other important future elements to be added to this young model could include additional data on truck distributions and mileage to provide better information on the heterogeneity of the truck buying market and consumer type factors that may limit adoption of new technologies (risk factors, infrastructure concerns, etc.). In the future, we could also look at the effects of different national and local policies that could affect adoption of vehicles, infrastructure or other technologies in the transportation sector. Another area of analysis is to focus more on the cost of different emissions scenarios, from a system perspective, at a sectoral level, and finally at the consumer or household level. Some of the elements that we have brought to the CA-TIMES model could also be incorporated into the US-TIMES model, including additional model parameter uncertainty analysis, and learning-by-doing.

References

- AEO, 2013. Annual Energy Outlook Analysis and Projections. U.S. Department of Energy, Energy Information Administration. <http://www.eia.gov/forecasts/aeo/data.cfm>. 2/10/2013
- ANL, 2014. VISION Model. Argonne National Laboratory. <http://www.anl.gov/energy-systems/project/vision-model>.
- Babaee, S., Nagpure, A.S., Decarolis, J.F., 2014. How much do electric drive vehicles matter to future U.S. emissions? *Environ. Sci. Technol* 48, 1382–1390.
- Bandivadekar, A., Bodek, K., Cheah, L., Evans, C., Groode, T., Heywood, J.B., Kasseris, E., Kromer, M.A., Weiss, M., 2008. On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions. Massachusetts Institute of Technology. July 2008
- Brosch, T., Sander, D., Patel, M.K., 2016. Editorial: Behavioral Insights for a Sustainable Energy Transition. *Frontiers in Energy Research* 4, 15.
- CARB, 2009. Attachment B: 2050 Greenhouse Gas Emissions Analysis: Staff Modeling in Support of the Zero Emission Vehicle Regulation. California Air Resources Board. <http://www.arb.ca.gov/msprog/zevprog/2009zevreview/2009zevreview.htm>. 1/10/2010.
- CARB, 2014. CARB EMFAC Database, in: Board, C.A.R. (Ed.). <https://www.arb.ca.gov/emfac/>.
- DeCarolis, J., Daly, H., Dodds, P., Keppo, I., Li, F., McDowall, W., Pye, S., Strachan, N., Trutnevyte, E., Usher, W., Winning, M., Yeh, S., Zeyringer, M., 2017. Formalizing best practice for energy system optimization modelling. *Appl Energy* 194, 184-198.
- DOE, 2013. Transportation Energy Futures, in: Laboratory, N.R.E. (Ed.). http://www.nrel.gov/analysis/transportation_futures/.
- Dong, J., Lin, Z., 2012. Exploring the Paths to One Million Plug-in Electric Vehicles by 2015 Using MA3T Model. Oak Ridge National Laboratory (ORNL).
- EPA, 2014. Assumptions from EPA U.S. 9-Region MARKAL model Database, Washington DC. <http://nepis.epa.gov/Exe/ZyPDF.cgi/P100I4RX.PDF?Dockey=P100I4RX.PDF>.
- EPA, 2018. Greenhouse Gas Inventory Data Explorer. <https://www3.epa.gov/climatechange/ghgemissions/inventoryexplorer/-allsectors/allgas/econsect/all>.
- Greene, D., Plotkin, S., 2011. Reducing Greenhouse Gas Emissions from U.S. Transportation. Pew Center on Global Climate Change.

Heaps, C., 2012. Long-range energy alternatives planning (LEAP) system. Stockholm Environment Institute, Somerville, MA.

IEA, 2016. World Energy Model Documentation. International Energy Agency.

IPCC, 2014. Climate Change 2014: WG3 Mitigation of Climate Change. Intergovernmental Panel on Climate Change.

Kannan, R., Strachan, N., Pye, S., Anandarajah, G., Balta-Ozkan, N., 2007. UK MARKAL Model Documentation. <http://www.ucl.ac.uk/energy-models/models/uk-markal>.

Lenox, C., Dodder, R., Gage, C., Kaplan, O., Loughlin, D., Yelverton, W., 2013. EPA U.S. Nine-region MARKAL DATABASE Database Documentation. U.S. EPA, Air Pollution Prevention and Control Division National Risk Management Research Laboratory.

Lin, Z., Greene, D.L., 2010. The MA3T Model: Projecting PHEV Demands with Detailed Market Segmentation, TRB Annual Meeting 2010. Transportation Research Board, Washington DC.

Loulou, R., Goldstein, G., Noble, K., 2004. Documentation for the MARKAL Family of Models. Energy Technology Systems Analysis Programme.

Loulou, R., Remne, U., Kanudia, A., Lehtila, A., Goldstein, G., 2005. Documentation for the TIMES Model - Part I. Energy Technology Systems Analysis Programme.

McCollum, D., Yang, C., 2009. Achieving deep reductions in U.S. transport greenhouse gas emissions: scenario analysis and policy implications. *Energy Policy* 37, 5580-5596.

McDonald, Z., 2018. Hydrogen Energy Storage for Renewable-Intensive Electricity Grids: A WECC Case Study, Transportation Technology and Policy. University of California, Davis, Institute of Transportation Studies.

Melaina, M., Webster, K., 2011. Role of Fuel Carbon Intensity in Achieving 2050 Greenhouse Gas Reduction Goals within the Light-Duty Vehicle Sector. *Environmental Science & Technology* 45, 3865-3871.

Miller, M., Wang, Q., Fulton, L., 2017. NCST Research Report: Truck Choice Modeling: Understanding California's Transition to Zero-Emission Vehicle Trucks Taking into Account Truck Technologies, Costs, and Fleet Decision Behavior. Institute of Transportation Studies, University of California, Davis.

Morrison, G.M., Yeh, S., Eggert, A.R., Yang, C., Nelson, J.H., Greenblatt, J.B., Isaac, R., Jacobson, M.Z., Johnston, J., Kammen, D.M., 2015. Comparison of low-carbon pathways for California. *Climatic Change* 131, 545-557.

NEMS, 2013. Input Assumptions to the National Energy Modeling System (NEMS), in: Energy, U.D.o. (Ed.).

NRC, 2013. Transitions to Alternative Vehicles and Fuels. The National Academies Press, 2013, Washington DC.

NUSTD, 2013. National U.S. TIMES Dataset. <http://www.energy-modeling.org/nustd.html>.

Pfenninger, S., Hawkes, A., Keirstead, J., 2014. Energy systems modeling for twenty-first century energy challenges. *Renewable and Sustainable Energy Reviews* 33, 74-86.

Ramea, K., Bunch, D.S., Yang, C., Yeh, S., Ogden, J.M., 2018. Integration of behavioral effects from vehicle choice models into long-term energy systems optimization models. *Energy Economics* 74, 663-676.

Schafer, A., 2012. Introducing behavioral change in transportation into energy/economy/environment models, World Bank Policy Research Working Paper. World Bank

Schipper, L., Unander, F., Murtishaw, S., Ting, M., 2001. INDICATORS OF ENERGY USE AND CARBON EMISSIONS: Explaining the Energy Economy Link. *Annual Review of Energy and the Environment* 26, 49-81.

Wei, M., Nelson, J.H., Greenblatt, J.B., Mileva, A., Johnston, J., Ting, M., Yang, C., Jones, C., McMahon, J.E., Kammen, D.M., 2013. Deep carbon reductions in California require electrification and integration across economic sectors. *Environ Res Lett* 8, 014038.

Wilson, D., Swisher, J., 1993. Exploring the gap: Top-down versus bottom-up analyses of the cost of mitigating global warming. *Energy Policy* 21, 249-263.

Yang, C., McCollum, D., McCarthy, R., Leighty, W., 2008. Identifying Options for Deep Reductions in Greenhouse Gas Emissions from California Transportation: Meeting an 80% Reduction Goal in 2050. Institute of Transportation Studies, University of California, Davis. http://pubs.its.ucdavis.edu/publication_detail.php?id=1197.

Yang, C., McCollum, D., McCarthy, R., Leighty, W., 2009. Meeting an 80% Reduction in Greenhouse Gas Emissions from Transportation by 2050: A Case Study in California, USA. *Transport Res D-TR E* 14, 147-156.

Yang, C., Ogden, J., Sperling, D., Hwang, R., 2011. California's Energy Future: Transportation Energy Use in California. California Council on Science and Technology.

Yang, C., Ogden, J.M., 2007. Determining the lowest cost hydrogen delivery mode. *Int J Hydrogen Energy* 32, 268-286.

Yang, C., Ogden, J.M., 2013. Renewable and low carbon hydrogen for California - Modeling the long term evolution of fuel infrastructure using a quasi-spatial TIMES model. *Int J Hydrogen Energy* 38, 4250-4265.

Yang, C., Yeh, S., Zakerinia, S., Ramea, K., McCollum, D., 2015. Achieving California's 80% greenhouse gas reduction target in 2050: Technology, policy and scenario analysis using CA-TIMES energy economic systems model. *Energy Policy* 77, 118-130.